Corrosion Reduction in Power Distribution

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Abstract – Corrosion can severely impact the safety and reliability of power distribution equipment while imparting significant costs to the end user. This paper will discuss the root cause of corrosion, the monetary effect of early product failures and unplanned outages, and available solutions through equipment design and proper maintenance.

Index Terms — Corrosion, Corrosion Prevention, Power Distribution, Oxidation, Rust, Coatings, Hazardous Locations

I. INTRODUCTION

We have all experienced corrosion in the form of rusting bridges, road salt corroding aluminum wheels and rusting our vehicles, and silver and copper items tarnishing, Fig. 1. These same corrosion processes occur in power distribution equipment, especially in off-shore or near-shore locations, with the potential for causing catastrophic failures. Corrosion is a naturally occurring process that affects virtually all metals, though at different rates. It is the chemical process of the metal returning to its more stable naturally occurring state [1][2].

Corrosion can be a cosmetic issue, but most likely will always impact the function of a device/part/component in a negative way. Power distribution systems not functioning as designed may result in significant safety or performance concerns.

Fig. 1 Examples of common corrosion such as pipeline/bridge structures and bolts rusting [3] and silver tarnishing.

Corrosion can never be stopped, but the rate of corrosion can be slowed down through the selection of proper materials including selection of base materials and coatings. Additionally, a robust maintenance program will help evaluate when corrosion has affected critical functions that can be addressed prior to safe operations being compromised.

II. CORROSION BASICS

Corrosion is the reaction of a metal with its environment, usually in a destructive manner. The corrosion reaction is a chemical and/or an electrochemical process of converting the metal to an oxide, hydroxide, or sulfide.

Understanding the underlying cause of corrosion will help minimize the destructive process, save money, time, and most importantly maintaining the intended safe operation of the equipment. An understanding of the basic types of corrosion will help specify and select the best corrosion protection scheme for the specific pieces of equipment. The different forms of corrosion that can be readily found in power distribution systems, Fig. 2, are discussed below.

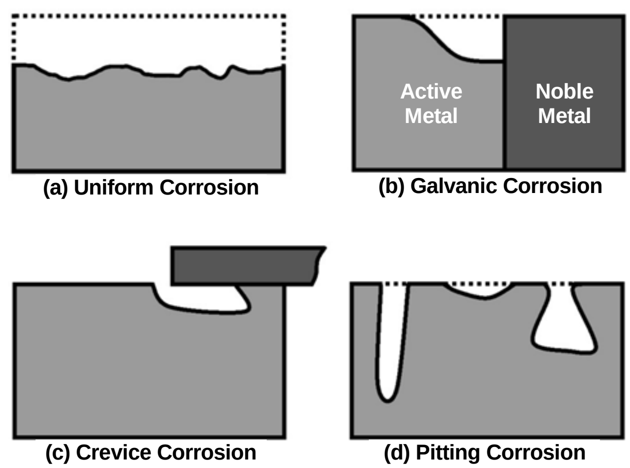

Fig. 2 Schematic representations of selected forms of corrosion, (a) uniform corrosion, (b) galvanic corrosion, (c) crevice corrosion, and (d) pitting corrosion

A. *Uniform Corrosion*

Uniform corrosion or general corrosion (Fig. 2a), occurs where the environment has similar access to all locations of the exposed metal surface, and the resulting corrosion is evenly distributed over this surface at a consistent rate. Atmospheric corrosion is the most prevalent example, including the tarnishing of silver and rusting of iron, Fig. 1. Uniform corrosion is the most common form of corrosion and is especially visible. Though it starts as cosmetic, over time uniform corrosion will eventually result in product failures impacting performance and safety.

B. *Galvanic Corrosion*

Galvanic corrosion, sometimes referred to as bimetallic or dissimilar metal corrosion, occurs when two metals are in electrical contact in the presence of an electrolyte (conductive solution), Fig. 3 [4]. This system creates an electrochemical cell or reaction, Fig. 4. In this system, electrons are allowed to flow through the electrolyte from the anode (metal being corroded) to the cathode (metal being protected). The loss of electrons from the anode material is a process called oxidation, where the anode metal is converted to the metal ion that is dissolved in the solution or to a solid oxide (rust). Equation (1) shows an example of the oxidation or anodic reaction of iron. The reaction at the cathode is dependent on the pH of the solution. In acidic solutions hydrogen ions are converted to hydrogen gas (2), in basic solutions, oxygen is reduced (3).

$$Fe \rightarrow Fe^{2+} + 2e^- \qquad (1)$$

$$2H^+ + 2e^- \rightarrow 2H_2 \qquad (2)$$

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \qquad (3)$$

Fig. 3 Example of galvanic corrosion from the coupling of stainless steel plate with mild steel hardware. [5]

When two metals are coupled, the metal that is corroded is determined by the relationship between the two metal's relative corrosion potential. Table 1 shows selected metals and their relative corrosion potential also referred to as the galvanic series. The more cathodic or noble metal will be protected and the more anodic metal will corrode or be sacrificed.

Typically the corrosion is more aggressive near the junction of the two metals due to lower electrical resistance and a short electrolyte path. The galvanic

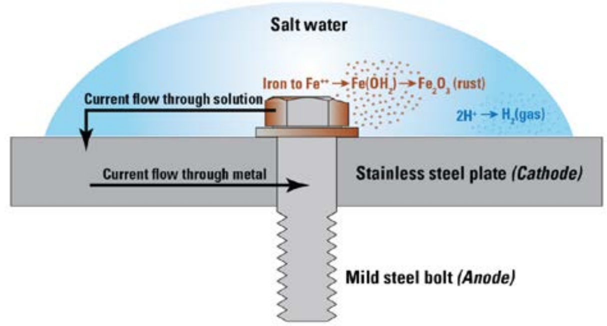

Fig. 4 Schematic description of a galvanic corrosion cell.

corrosion reaction is dependent on the conductivity of the electrolyte and the cathode to anode area. Higher conductivities and cathode to anode area ratios will produce more aggressive attacks.

An example of an intentional galvanic corrosion reaction is galvanized steel. The steel is more noble or cathodic to the zinc coating (anode), Table 1. The zinc coating will be sacrificed (corrode) and the underlying steel will be protected. This is sometimes used as a method of corrosion protection known as sacrificial anode cathodic protection. However, once the zinc coating is completely sacrificed, it no longer protects the underlying steel material and corrosion will proceed rapidly.

Driving the galvanic reaction in the opposite direction by applying a voltage to the system is a corrosion protection technique called cathodic protection. This technique is rarely used in electrical distribution systems and is thus outside the scope of this paper.

TABLE I
GALVANIC SERIES

Platinum	Noble (Cathode)
Graphite	↓
Gold	
Titanium	
Silver	
Stainless Steel 316 (passive)	
Stainless Steel 304 (passive)	
Nickel	
Monel	
Bronze	
Copper	
Brass	
Lead	
Cast Iron	
Mild Steel	
Aluminum	
Galvanized Steel	
Zinc	
Magnesium	Active (Anode)

C. *Crevice Corrosion*

Crevice corrosion, Fig. 5, occurs in small sheltered gaps or cracks. Corrosion can proceed in a crevice formed between two metal parts, between a metal and a non-metal part, or due to a design flaw.

The gap will accumulate moisture and slowly the solution will become more and more corrosive due to the dissolution of the metal as well as the concentration of chlorides and a lowering of the pH from the hydrolysis of the chlorides (4). The corrosion reaction will eventually become auto-catalytic as more chloride is drawn into the crevice thus, becoming more acidic due to hydrolysis reaction further corroding the metal. Galvanic corrosion, discussed above, can exacerbate this attack.

$$Fe^{2+} + 2H_2O + 2Cl^{-} \rightarrow Fe(OH)_2 + 2HCl \qquad (4)$$

Factors that influence crevice corrosion include material interactions such as metal to metal or metal to non-metal and include crevice geometry such as gap size, depth, and surface roughness. The environmental factors such as pH, temperature, halide concentration and availability of oxygen can also have a significant impact on the aggressiveness of crevice corrosion.

Fig. 5 Examples of crevice corrosion. Left, a corroded bolt showing the telltale necking effects of crevice corrosion as well as some significant uniform corrosion.

D. Pitting Corrosion

Pitting corrosion is very similar to crevice corrosion in that it is a localized attack. A drop of corrosive fluid or even water will create a localized galvanic cell, Fig. 4, where the center of the droplet is the anode with potentially a very large cathode. This localized area will start to corrode and eventually develop into a pit. Once the pit forms it acts as a self-serving crevice and corrosion can progress rapidly, inducing the same chemical mechanisms as described above in crevice corrosion.

Stainless steels and nickel alloys can be especially susceptible to pitting corrosion, Fig. 6. These alloys rely on passivated oxide films for corrosion resistance. These films can be compromised by chloride (Cl^{-}), sulfates ($S_2O_3^{2-}$), fluorides (F^{-}), and iodides (I^{-}).

Fig. 6 Examples of pitting corrosion damage.

III. MONETARY EFFECTS OF PRODUCT FAILURES AND UNPLANNED OUTAGES

Corrosion is one of the largest single expenses in the US economy, yet it rarely receives the attention it requires.[6] The annual cost of corrosion globally is estimated to be $2.5 trillion per year. This figure is based on a calculation method used by NACE (National Association of Corrosion Engineers) using a fixed percentage (3.4%) of the GDP.[7] This cost includes only direct costs as indirect costs related to safety or environmental consequences are difficult to measure. However, these costs should still be considered in the overall corrosion preventative strategy.

In a recent study conducted by the Executive Branch and Government Accountability Office, researchers found that by preventing corrosion instead of treating it as it happens, the annual cost of corrosion could be reduced by as much as 40%.[8]

Using corrosion control practices provides a cost benefit as well as avoids failures which can result in catastrophic events.

A. Factors which Effect Corrosion Costs

Although costs differ in relative significance from industry to industry, several generalized elements combine to make up the total cost of corrosion. The highest costs of corrosion are business interruptions that occur when equipment and assets fail to perform as intended.

Direct costs will include costs that are directly related to corrosion and can be placed into two main categories (1) design, manufacturing, and construction and (2) costs related to corrosion management.

The design, manufacturing, and construction costs include:

- Material selection
- Protection technologies
- Costs related to labor, equipment, and overhead

Corrosion Management related costs include:

- Corrosion related inspection
- Corrosion related to maintenance
- Repairs due to corrosion damage
- Material costs related to replacement of corroded components
- Labor costs related to replacement of corroded components
- Inventory costs for backup material
- Rehabilitation and refurbishment

Indirect costs include:

- Environmental clean-up
- Litigation costs
- Downtime/loss of production

B. Corrosion by Industry

Based on a survey conducted as research for this paper (Appendix A), over 90% of the people surveyed operate in harsh environments in the Water/Wastewater, Oil & Gas, and Chemical industry and had corrosion concerns. Of that same group, more than 88% of them agreed that corrosion is a concern in their power distribution equipment, however roughly 72% preferred to address electrical maintenance issues in 3-5 year intervals.

According to a study conducted by EPRI (Electric Power Research Institute of the US) more than half of all unplanned power outages are due to corrosion.[9] This falls in line with several other studies which have shown that generally half of all failures within an industry segment tend to be corrosion related.

According to a 2002 study conducted by the U.S. Federal Highway Administration (FHWA) the top 5 industries affected by corrosion are utilities, transportation, production and manufacturing, government, and infrastructure, Table 2.

TABLE 2
DIRECT CORROSION COSTS BY INDUSTRY IN U.S.

Industry	1998 Costs	2013 Costs
Utilities	$47.9B	$197.8B
Transportation	$29.7B	$122.6B
Production and Manufacturing	$17.6B	$73.0B
Government	$20.1B	$83.2B
Infrastructure	$22.6B	$93.5B
Total	$137.9B	$570.0B

In this study, the US GDP from 1998 ($8.79 trillion) was used, the US GDP for 2013 was $16.77 trillion, by using the calculation method from NACE of 3.4%, the direct cost of corrosion in the US is roughly $570 billion.

1) *Utilities*: For this study, utilities included gas distribution, drinking water and sewer systems, and electrical utilities. The annual direct cost due to corrosion is estimated to be roughly $197.8 billion, Fig. 7.[10]

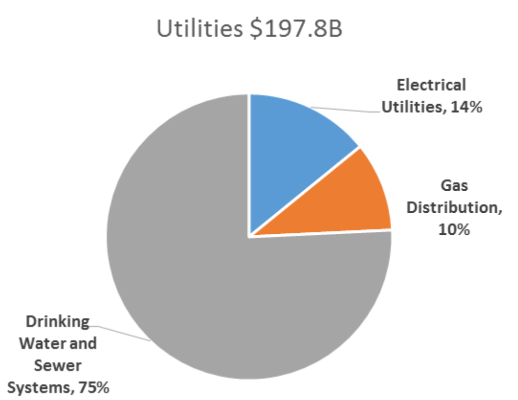

Fig. 7 Utilities cost stemming from direct costs of corrosion.

a) *Drinking Water and Sewer Systems:* There are nearly 15,000 Publicly Owned Treatment Works in the United States. In these facilities, chlorination is the most common means of disinfection. Chlorine is known to contribute significantly to the environments corrosive nature. Another main contributor includes hydrogen sulfide (H2S) which is produced as waste breaks down. H2S usually leaves a white crystalized residue on anything within close vicinity. Overall the direct cost of corrosion in drinking water and sewer systems is estimated to be $148.4 billion.

Protecting electrical infrastructure within treatment faclities is vital as nearly 2% of total U.S. electricity use goes towards moving and treating water and wastewater.[11] Disrupted power at treatment processes and pumping stations can not only be extremely costly, but can also have devastating impacts on drinking water and wastewater services within a community such as water contamination, discharge of untreated sewage and sewage backup.

b) *Electrical Utilities:* Most power stations burn fossil fuels such as coal and natural gas to generate electricity.[12] Others use nuclear power, however cleaner renewable sources such as hydroelectric, wind, and solar are increasing in recent years. The direct cost of corrosion is estimated to be $27.7 billion, Fig. 8. As power plants look to increase effciencies and lower maintenance costs, corrosion prevention becomes critical.

Fossil fuel plants tend to experience corrosion issues when they have buried storage tanks for fuel and underground piping systems. In such an instance galvanic corrosion can be problematic due to improper joining of disimilar components.

For electrical systems, those buried underground can experience corrosion due to the content of the soil as well as in transitions to above ground areas due to the difference in electrolyte. In coal burning power plants, the process itself creates large amounts of ash which can be corrosive. Additionally, systems near the scrubber area can be affected by hydrochloric acid which is produced during the cleaning process where there is combination of water, sulphur dioxide and limestone.

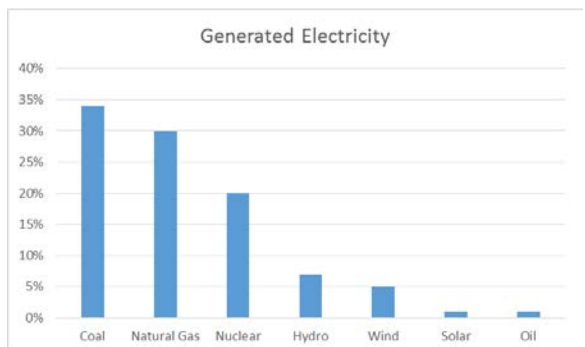

Fig. 8 Direct costs of corrosion for power generation utilities.

c) *Gas Distribution:* Nation wide there are about 272,000 miles of high-strength steel pipe ranging from 20 inches to 42 inches in diameter transmitting natural gas.

Distribution pipelines move large amounts of natural gas thousands of miles from the producing regions to local distribution companies. The pressure of gas in each section of line typically ranges from 200 psi to 1,500 psi. As a safety measure, pipelines are designed to handle much more pressure than is ever actually reached in the system.

Compressor stations are located approximately every 50 to 60 miles along each pipeline to boost the pressure that is lost through the friction of the natural gas moving through the steel pipe.

Metering stations measure the flow rate of the gas in order to monitor the performance of the gas, particularly in areas where custody transfer takes place.

The major threat for a buried gas transmission pipeline is external corrosion which can affect the structural integrity of the pipeline.

For electrical infrastructure, protection is typically needed at compression stations and metering stations. Because both of these are considered a hazardous location, extra precaution should be taken. Electrical systems are typically compromised in areas where there is a transition from underground to above ground due to a reaction that occurs when a metal is exposed to two separate environments.

All in all, the direct costs of corrosion for gas distribution is roughly $19.8 billion annually.

2) Production and Manufacturing, Fig. 9:

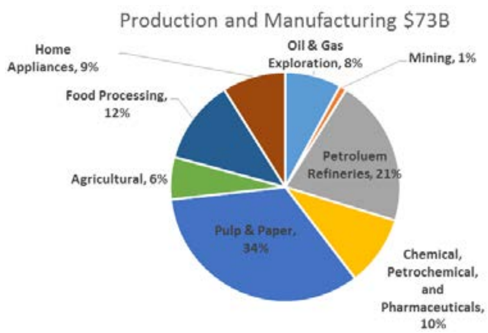

Fig. 9 Direct costs of corrosion for production and manufacturing.

a) *Pulp & Paper:* The United States is the largest consumer of paper in the world and produces roughly 24% of the world's paper. The vast majority of processes include a bleaching procedure in order to whiten and brighten pulps for paper. This creates wastewater containing chlorinated compounds such as dioxins. Combine that with the high heat and humidity produced during manufacturing and the end result is a very corrosive environment. The direct cost associated with the pulp and paper industries totals to approximately 24.8 billion.

b) *Chemical, Petrochemical, & Pharmaceutical:* The chemical industry includes manufacturing facilities that produce bulk or specialty compounds from chemical reactions between organic and/or inorganic materials. Many of the chemicals used in these processes can be corrosive on their own or corrosive when combined with other substances.

The petrochemical industry includes facilities that manufacture substances from raw hydrocarbon materials such as crude oil and natural gas.

The pharmaceutical industry formulates, fabricates, and processes medicinal products from raw materials which often times include base materials and compounds which are corrosive.

In total this sector's annual direct costs total $7.3 billion. This figure does not include costs associated with operation and maintenance as a detailed study of individual companies would be required in order to collect the data.

c) *Petroleum Refining:* There are currently 139 petroleum refineries in operation across the U.S. supplying more than 18 million barrels of refined petroleum daily.[13] Total corrosion-related direct costs add up to a yearly total of $15.3 billion.

3) *Infrastructure:* Infrastructure in this study was divided into the following sectors: highway bridges, gas and liquid transmission pipelines, waterways and ports, hazardous materials storage, airports, and railroads. The annual direct cost in this category is estimated to be $93.5 billion, Fig. 10.

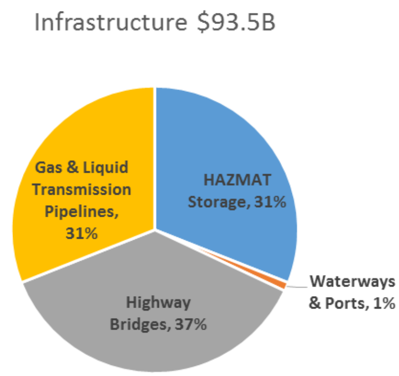

Fig. 10 Direct costs of corrosion for infrastructure.

a) *Gas and Liquid Transmission Pipelines:* The primary factor affecting the life span and reliability of pipelines transporting energy sources through the country is corrosion. Today there are more than 2.4 million miles of transmission and distribution pipelines carrying natural gas, crude oil, and hazardous liquids.

According to ASM International, approximately 25% of all pipeline failures, including all pipelines (both unprotected and improperly protected), carrying hazardous liquids were due to corrosion. Of those failures 65% were due to external corrosion, 34% were due to internal corrosion, leaving a 1% miscellaneous category.[14]

b) *HAZMAT Storage:* According to the United States Environmental Protection Agency, as of July 2015, there are approximately 561,000 underground storage tanks (USTs) which store petroleum or hazardous substances. Leaking USTs can lead to contamination of ground water which supplies drinking water for nearly half of all Americans. In 2016 it was found by the EPA that 83% of USTs in the US exhibited moderate or severe corrosion, however only 25% of owners were aware of a corrosion issue.[15]

IV. AVAILABLE SOLUTIONS THROUGH EQUIPMENT DESIGN AND PROPER MAINTENANCE

Proper specification and selection of electrical products in highly corrosive environments will reduce long term cost and reduce risk of failure. Several decisions need to be made when selecting electrical equipment that will be subject to corrosion as addressed earlier in this paper. These decisions include answers to the following basic questions:

- Where will the equipment be placed and what corrosive elements are most likely to be present?
- What types of material finishes and coatings are available in the equipment that can slow down the corrosion process?
- What equipment design options are available that can be selected in the specification process to aid and extend the corrosion free life cycle of the equipment?
- What is the recommended maintenance of the equipment selected for installation, and is there a robust maintenance program available to ensure said maintenance is implemented?

A. Equipment Placement

Placement of electrical distribution equipment is a significant factor in warding off elements of corrosion, Fig. 11. Choosing a location that is protected from elements of wind, rain, excessive vibration, and exposure to corrosive chemicals is a best first defense in corrosion resistance.

Fig. 11 Severe corrosion of a bolted enclosure.

B. Material Finishes

Vast improvements have been made in materials, coatings, and finishes in recent years. Conduit outlet bodies, cable & cord fittings, junction boxes and enclosures, motor control & circuit breakers, local control stations, panel boards, switches, luminaires, and plugs & receptacles can be made available from fiberglass reinforced polyester materials, from low copper (<0.1%) aluminum, from ferrous and malleable irons, from different grades of stainless steel, and from engineered plastics.

The corrosion resistance of these materials can be enhanced by specialty coatings, including the electrostatic application of a thick powdered epoxy or urethane, specialty paints, and the application of polyvinyl chloride (PVC). While various coating systems can provide enhanced corrosion protection the coating consistency and adhesion are critical to the performance of the coating. Improper adhesion of a coating can actually increase corrosion. Table 3 describes several corrosion inducing chemicals and materials/finishes designed to resist them. This is provided as a general guide, for specific chemical resistance please check with the product manufacturer to ensure proper material selection for your specific environment.

TABLE 3
GENERAL GUIDE TO CORROSION RESISTANCE*[16]

Chemical Atmosphere	**Stainless Steels**	**Low Cu Aluminum**	**Cast Iron**	**PVC Coating**	**Epoxy Powder Coating**	**Fiberglass reinforced Polyesters**
Marine/Saline	C	B	D	A	A	A
Acidic	B	D	B	A	A	C
Basic	B	D	B	A	A	B
Organic Solvents	A	A	B	A	A	A

*Ratings: A – Excellent, B – Good (minor effect, slight corrosion or discoloration, C – Fair (moderate effect, not recommended for continuous use), D – Severe Effect (not recommended for any use)

C. Base Material Selection

Ferrous iron, for example, offers great strength and is economical. Ferrous cast irons when electrochemically coated with a deposit of zinc plating or a hot dip galvanize finish will resist the corrosive effects of alkalis, many organic compounds, neutral and slightly acidic solutions, and chemically neutral brines.

Aluminum, when its alloy contains a minimal amount of copper of less than 0.0004%, will resist marine atmospheres, sulfur gasses, and ammonium nitrate. Limiting the copper content in aluminum will stave off corrosion due to galvanic action.

Polyvinyl Chloride (PVC) coated galvanized rigid steel conduit systems provide excellent structural strength as well as superior corrosion protection. The coating is able to withstand environmental elements such as sunlight exposure, extreme temperatures, humidity, salts and acids. PVC coated GRC also has the widest range of use where pH levels and chemical resistance are concerned. In areas where weight is a concern, PVC coated aluminum is an option.

Certain fiberglass reinforced polyesters are specifically formulated for use in the harshest corrosive environments.

Stainless steel has a high resistance to rust, and numerous grades of stainless steel are used in Industry. The most commonly used grades of stainless steel are 302/303, 304, 316 and 316L. Grade 304 provides an acceptable resistance to corrosion, however the additional chromium content of 316, and 316L provide a greater corrosion and oxidation resistance. Both 316 and 316L contain on average 2-3% molybdenum, also adding to their corrosion resistance. Grade 316L has a lower carbon content (.03%) than 316 (.08%) allowing for greater corrosion resistance when welded.

D. Equipment Design Options

There are practical things that should be considered for specification for enhanced resistance to corrosion in the selection of electrical equipment used for power distribution.

1) Breathers and Drains: Breathers and drains, Fig. 12, serve to fight corrosion by not allowing buildup of condensation and moisture inside the hazardous rated or outdoor rated enclosure. It is a misnomer to believe that sealing up a metal enclosure as tight as possible from the outside elements will prevent the onslaught of corrosion – in fact quite the opposite is true. The breather and drain combination serves to allow the power distribution enclosure to "breathe".[17] Condensation occurs commonly in areas where wide temperature and air moisture content swings are present. Condensation is the reverse of evaporation. Unchecked, condensation will build up in sealed metal enclosures and can cause corrosion induced equipment failure.

Fig. 12 Examples of breather and drain used to control moisture inside enclosure systems

2) *Space Heaters:* Where practical, space heaters, Fig. 13, can be used to introduce a slightly elevated ambient temperature. This induces a positive pressure outward, and has the dual effect of "drying" out any unwanted moisture by increasing the internal enclosure temperature above the dew point.

3) *NEMA 4 Gasketing of Enclosures:* Many if not most hazardous location enclosures today are equipped with an O-Ring gasket that provides NEMA 4 moisture ingress protection, Fig. 14. Whereas it is a good idea to have the enclosure "breathe" it is not a good idea to openly allow water and moisture to penetrate the enclosure corroding the internal components. For this reason, a machined groove and fitted O-ring can be provided.

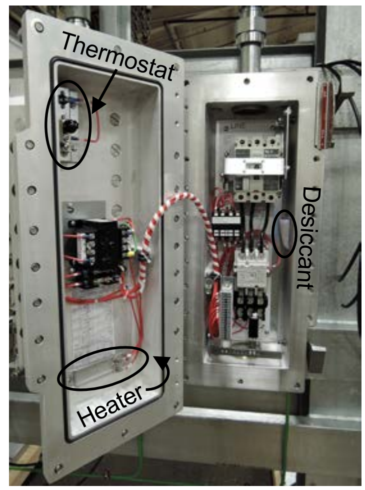

Fig. 13 Enclosure with heater, thermostat and desiccant pack for moisture control.

Fig. 14 Enclosure with a NEMA 4 gasket to minimize ingress of moisture.

4) *Thread Lubricants:* A preventive maintenance program should always include the practice of using an approved thread lubricant, Fig. 15, when mating the metal surfaces together of any hazardous location equipment, helping to inhibit the advance of corrosion between these ground joints or threaded joint flame path surfaces.

Fig. 15 Proper use of thread lubricants can help to inhibit corrosion on threaded joints.

5) *Use practical methods to shelter equipment from weather:* Consider the use of a rooftop when specifying an outdoor motor control center that will be placed in a hazardous location, Fig. 16. This is a simple way to slowdown the advances of corrosion in otherwise exposed power distribution motor control.

Fig. 16 Use of shelters can help to minimize environmental exposure leading to reduced corrosion. Reprinted, with permission, from [17]

6) *Bolts and screws, proper torque of equipment, electrical connections or fasteners per manufacturer recommendations:* Now a National Electric code (NEC) requirement in 2017. Whereas improperly torqued lugs, nuts, and screws combined with elements of corrosion will lead to early failures. Article 110. 14(D) requires that a calibrated torque tool now be used when torqueing lugs, bolts, or fastening screws of any electrical equipment where a manufacturer's torque value is recommended.[18]

Stainless Steel bolts driven into aluminum castings can eventually cause bolt seizure if not adequately lubricated. These bolts are at risk for "breaking off" upon routine opening of the door of the enclosure, rendering the equipment unsafe without the ability for all cover bolts to be installed and torqued correctly. Modern equipment designs have reduced the number of bolts needed in EP power distribution and motor control, Fig. 19.

Fig. 19 A clamped enclosure with minimal bolts allowing for improved ease of access for preventative maintenance.

E. Robust Preventive Maintenance Program

1) *Corrosion Preventative Strategies:* By creating a Corrosion Prevention Strategy, organizations are able to properly implement corrosion prevention technologies and strategies which will lead to overall cost-savings as well as implement design practices that increase reliability and safety, conserve materials and energy, and reduce costs.[19]

Preventive strategies in non-technical areas:

1. Increase awareness of the considerable corrosion costs and potential savings.
2. Change the misconception that nothing can be done about corrosion.
3. Change policies, regulations, standards, and management practices to increase corrosion cost-savings through sound corrosion management.
4. Improve education and training of staff in recognition of corrosion control.

Preventive strategies in technical areas:

5. Advance design practices for better corrosion management.
6. Advance life prediction and performance assessment methods.
7. Advance corrosion technology through research, development, and implementation.

2) *Inspection and Maintenance Program*: Using the preventive strategies, discussed above, a basic inspection and maintenance program can ensure equipment is operating properly and that any corrosion is addressed prior to failure.

Some simple housekeeping techniques that should be included in the inspection/maintenance program are:

- Twist the stopcocks on all breather/drains on turnarounds, if available
- Cycle breakers, switches, and lubricate properly
- Use approved lubricants when replacing covers on enclosure bodies
- Use proper torque tools (now a code requirement) when attaching and reattaching any screw, nut, lug, or bolt
- Be sure only properly trained personnel are servicing/operating the equipment
- Proper use of desiccant packs can provide moisture and therefore corrosion protection. Desiccant packs do need to be maintained otherwise will they will exacerbate corrosion issues
- Select equipment that will provide maintenance free use for an extended maintenance cycle. It is not uncommon today for maintenance MRO cycles to be extended – buy good stuff that lasts

V. CONCLUSIONS

Corrosion never stops! Most metals are mined as ores (oxides, sulfides, carbonates, etc.) and are processed into the metals we use in our electrical distribution systems. Every year, day, minute, and second these metals are trying to return to their most stable state: the ores from which they were mined, this is the corrosion process. Corrosion is most readily revealed as an aesthetic issue, but can quickly progress to a state when intended function is compromised. When this occurs significant costs can be accrued mainly due to unplanned outages, but more importantly safe operations can be at risk.

While the science of corrosion is quite well known and understood, limiting the impact of corrosion is much more of an art. Understanding the underlying principles of corrosion along with the equipment to be protected, the installation environment and the risk of product failure will help to prescribe an appropriate corrosion protection scheme composed of material selection, coating selection, and sheltering equipment. Equally important to the proper corrosion protection scheme is a robust maintenance program. Preventative maintenance will ensure your equipment is functioning as designed as well as provide early indication of potential product failures limiting unplanned outages.

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VIII. VITAE

Jesse W. Taylor is a Senior Advanced Chemical Engineer at Eaton's Crouse-Hinds business. He is responsible for developing new technology platforms, and assists new product development and sustaining efforts from a chemistry perspective. Jesse earned a Ph.D. in inorganic chemistry from Syracuse University, Syracuse, NY and a B.S. from Hartwick College, Oneonta, NY. His research in the areas of alternative fuels, catalysis, polymers, and harsh and hazardous electrical products has led to numerous patents, patent applications, and peer reviewed publications.

Kenneth W. McFarland has been with Eaton's Crouse-Hinds Business for 37 years and has vast experience in product application solutions in the Petroleum and Chemical Industry. Ken is currently a Field Application Specialist with Eaton's Crouse-Hinds and is responsible for major project specifications in the Western United States with Engineering Procurement Contractor (EPC) businesses. Ken holds a B.S. Degree from San Jose State University, San Jose, CA in Business Administration-Marketing.

Stephanie Ellis is the Marketing Manager for Robroy Industries and has been with the organization for 7 years. Stephanie also acts as Director for Corrosion College which is a 2 day education course on corrosion and corrosion prevention methods. Corrosion College was established in 1996 and is accredited by Purdue University, Kilgore College, American Institute of Architects, and PDH Engineer. Stephanie holds a bachelor's degree from Stephen F. Austin State University and holds a Corrosion Technologist Certification from NACE (National Association of Corrosion Engineers.)

IX. APPENDIX A
SURVEY QUESTIONS AND STATISTICAL DATA

1. What is your role in the use of power distribution equipment?
    a. Installer / Contractor
    b. Maintenance
    c. Engineer
    d. Supervisor / Owner
    e. Other (please specify)

2. What is the size of your company?
    a. <50 employees
    b. 50 – 100 employees
    c. 100 – 500 employees
    d. >500 employees

3. What is your primary industry?
    a. Wastewater Treatment
    b. Oil Refinery
    c. Food Processing
    d. Pharmaceutical
    e. Chemical
    f. Pulp or Paper
    g. Mining
    h. Other (please specify)

4. Do you use, specify, install equipment in harsh and hazardous locations, e.g. off-shore, near-shore, chemic, mining, refining etc.?
    a. Yes
    b. No

5. Is corrosion an issue for you with installed hazardous location power distribution equipment?
    a. Yes
    b. No

6. Do you or your company use any specific materials or material finishes to address the challenges associated with electrical equipment corrosion? (Select all that apply)
    a. Stainless steel
    b. Paint powder coatings
    c. PVC-coated
    d. Specialized iron alloys
    e. Aluminum
    f. Hot dip galvanizing
    g. Non-metallic Including glass reinforced polyester
    h. Other (please specify)

7. What is your desired maintenance frequency on electrical distribution products?
    a. Work on the equipment on a 1-year interval after installation
    b. Work on the equipment on a 3 to 5-year interval after installation

8. What is your current maintenance inspection cycle?
    a. Inspect every 6 months
    b. Inspect every 6-18 months
    c. Inspect every 18 months – 3 years
    d. Inspect every 3-5 years
    e. Inspect every 5 years or greater

9. Monetary Effects – Costs of unplanned outages: Please estimate the percentage that costs increase in a typical project for unplanned outages (vs. planned)?
    a. Greater than 50%
    b. Greater than 100%
    c. Greater than 150%

10. Monetary Effects – Costs of unplanned outages: Please estimate the average total cost increase of unplanned outages?
    a. Less than $250K
    b. $250K to $2M
    c. $2M to $10M
    d. Greater than $10M

11. Monetary Effects – Costs of unplanned outages: Please estimate the increase in labor costs for unplanned outages (vs. planned)?
    a. Greater than 50%
    b. Greater than 100%
    c. Greater than 150%

12. Monetary Effects – Costs of unplanned outages: Please estimate the increase in replacement material costs for planned vs unplanned outages
    a. Greater than 50%
    b. Greater than 100%
    c. Greater than 150%

Number of participants: 105

Number of qualified end user participants solicited: 1450