International Measures of Prevention, Application, and Economics of Corrosion Technologies Study







Project Manager
Elaine Bowman, Past President, NACE International, Houston, Texas, USA

Authors
Gerhardus Koch, Ph.D., FNACE, DNV GL, Dublin, Ohio, USA
Jeff Varney, APQC, Houston, Texas, USA
Neil Thompson, Ph.D., FNACE, DNV GL, Dublin, Ohio, USA
Oliver Moghissi, Ph.D., FNACE, DNV GL, Dublin, Ohio, USA
Melissa Gould, M.Sc., DNV GL, Dublin, Ohio, USA
Joe Payer, Ph.D., FNACE, Akron University, Akron, Ohio, USA

Technical Advisory Panel
- Pierre Crevolin, HDIM Protective Coatings, Inc., Edmonton, Alberta, Canada
- Roger Francis, FNACE, RFMaterials, Glossop, Derbyshire, United Kingdom
- Kevin Garrity, FNACE, Mears Group, Inc., Rosebush, Michigan, USA
- Sylvia Hall, Sylvia Hall Engineering (SHE), Hacienda Heights, California, USA
- Richard Kinzie, U.S. Department of Defense Corrosion Office of Policy & Oversight, Washington, DC, USA
- David Kroon, Aegion Corporation, Houston, Texas, USA
- Larry Lee, U.S. Department of Defense Office of Corrosion Policy & Oversight, Washington, DC, USA
- Frank Rampton, Trenton Corporation, Ann Arbor, Michigan, USA
- Doni Riddle, Sherwin-Williams Company, Cleveland, Ohio, USA
- Hiroyuki Tanabe, Dai Nippon Toryo Co., Ltd., Otawara-Shi, Tochigi-Ken, Japan
- David Webster, Worley Parsons Canada Services, Ltd., Calgary, Alberta, Canada

Editor
Gretchen Jacobson, NACE International, Houston, Texas, USA

EXECUTIVE SUMMARY

NACE International initiated the International Measures of Prevention, Application, and Economics of Corrosion Technologies (IMPACT) study to examine the current role of corrosion management in industry and government and to establish best practices.

The global cost of corrosion is estimated to be US$2.5 trillion, which is equivalent to 3.4% of the global Gross Domestic Product (GDP) (2013). By using available corrosion control practices, it is estimated that savings of between 15 and 35% of the cost of corrosion could be realized; i.e., between US$375 and $875 billion annually on a global basis, an astronomical savings. In addition, these costs typically do not include individual safety or environmental consequences. The high cost of corrosion has been known for years; Uhlig performed a comprehensive study in 1949 that revealed a cost of corrosion equivalent to 2.5% of the U.S. GDP.

The Global Impact of Corrosion

The global cost of corrosion is estimated to be US$2.5 trillion, which is equivalent to 3.4% of the global Gross Domestic Product (GDP) (2013). By using available corrosion control practices, it is estimated that savings of between 15 and 35% of the cost of corrosion could be realized; i.e., between US$375 and $875 billion annually on a global basis, an astronomical savings. In addition, these costs typically do not include individual safety or environmental consequences. The high cost of corrosion has been known for years; Uhlig performed a comprehensive study in 1949 that revealed a cost of corrosion equivalent to 2.5% of the U.S. GDP.

The fact that corrosion control provides a cost benefit is a lesson learned over and over again by industry, often too late and following catastrophic events (e.g., accidents, failures, and loss of production). To achieve the full extent of potential savings, it is the conclusion of this study that implementing a Corrosion Management System (CMS) and its integration into an organization's overall management system is mandatory.

A difficulty in promoting corrosion management is that cost savings from corrosion control are difficult to measure; i.e., (i) maintenance costs slowly decrease; (ii) monitoring or inspection costs decrease or inspection intervals increase; (iii) fewer failures save lost production time and/or lost product, decrease injuries, decrease in property damage, decrease in environmental release, improved public relations; and (iv) life extension of the asset can go directly to the bottom-line and/or postpone capital expenditures. All of these can be included in the business case for enhanced corrosion management.

One corrosion management success story is the change in corrosion management strategy and application of innovative technology in the automotive industry globally. Since 1975, the manufacturers have created a coordinated and balanced effort between advances in design, materials, and processing. This was not a quick turnaround, but one of continuous improvement over a relatively long time period of all aspects of corrosion-related design and processing decisions. The transformation in corrosion management strategy by the automotive industry was a decision at the highest levels of an organization, resulting in lower corrosion-related manufacturing costs, lower corrosion-related operating costs, and longer life of automobiles for the buying public.

Corrosion Management System

A CMS is a set of policies, processes, and procedures for planning, executing, and continually improving the ability of an organization to manage the threat of corrosion for existing and future assets. In most cases, this includes 1) optimizing corrosion control actions and minimizing life cycle corrosion costs, and 2) meeting safety and environmental goals.

Substantially reducing corrosion costs (both direct and indirect) requires more than technology; it requires integrating corrosion decisions into an organizational management system. The IMPACT study provides a CMS framework and guideline to integrate corrosion management elements into an organizational management system; alternatively, it can be used to develop a standalone CMS. This CMS framework is considered a core deliverable of this study. This innovative approach is of greatest value in institutionalizing corrosion management within an organization.

Most corrosion professionals currently work within an environment of Procedures and Working Practices, which are in the language of technical contributors (i.e., not financial or operational decision makers). In some cases, corrosion is included within operating plans (e.g., asset integrity management plans), which integrates corrosion with other structural integrity threats. However, only a few organizations link these technical activities and plans to broader organizational management systems elements (e.g., Policy, Strategy, Enablers, Controls, and Measures). Without this link, systemically effective and efficient business decisions are unlikely.

To fully realize the link between corrosion technology and management systems, the following two items should be implemented:

- Broaden the corrosion professional’s competence to include financial optimization of corrosion control investments; this includes use of risk assessment and other tools to monetize the return on investment (ROI) of corrosion control activities. Improved training and education are needed to realize this extension in competence, both for new entrants into the profession and the senior technical professional.
- Broaden the scope of awareness activities and other communications targeted at business leaders and policymakers so that recommended changes to management systems elements are communicated in a language that facilitates business improvement. This ranges from justifying a single corrosion control activity to recommending organizational policy changes. This approach has the added benefit of moving the corrosion professional away from alarmist language and towards enabling sound business practice.

Incorporating Corrosion Management throughout the Asset Life Cycle

Maximizing the effectiveness of corrosion management requires its application over the entire asset life cycle: (i) design, (ii) manufacturing/construction, (iii) operation/maintenance, and (iv) abandonment, decommissioning, and mothballing (ADM). In many organizations, there is a separation between the design/construction group and the operations/maintenance group. In certain industries (e.g., construction industry, pipelines) the design/construction group is rewarded for building the asset with a focus on meeting or beating Capital Expenditure (CAPEX) schedule and budget; and the operations group is left with an asset requiring significant corrosion maintenance Operating Expense (OPEX) activity after it is commissioned for service. Often, the operations group is not consulted for corrosion design considerations. This group can provide valuable input for the long-term cost effectiveness of an asset because they see the problems, but this input is not always heard and can conflict with the management objectives of the project team. In effect, valuable lessons learned are not learned throughout the organization.

A common characteristic of top corrosion management performers, as identified from a survey conducted as part of the IMPACT study, is that corrosion management is an integral part of a formal management of change (MOC) process. Lessons learned (near misses, failures, inspection reports, etc.) are important to formally institutionalize, such that the information is available to those involved in capital projects, operations, as well as top decision makers. This is only possible through a robust MOC process.

Top performers in the survey were nearly twice as likely to measure the cost of corrosion in the design and manufacturing/construction phases. These organizations realize that (i) designing for corrosion control and (ii) quality management in the construction/manufacturing phase are critical to the operation and overall life of an asset. A significant gap was identified as only about half of the total respondents stated that their asset design strategy addresses the following with respect to corrosion: regulations; health, safety, and the environment (HSE); the intended life of the asset; and the functional requirements. So although the top performers consider corrosion in the design phase, there are a significant number of survey respondents whose design strategies do not include corrosion considerations.

The survey revealed that in many cases the operations phase receives the most attention when it comes to corrosion management, because corrosion problems tend to surface during the operating life of an asset. In fact, many of the corrosion problems experienced during operation find their origin in poor design or quality issues during construction/manufacturing.

The survey further indicated that most corrosion management programs (CMPs) do not address ADM. It was found that the petroleum/oil/gas and pipelines industries provide the most consideration for this phase of the asset life cycle, realizing that ADM can pose a significant organizational risk (based on the asset involved) when considering HSE and financial considerations.

Performance Measures and Return on Investment

Based on the survey, the performance measures element of corrosion management consistently provided the lowest score; i.e., measurement of corrosion performance indicators was performed less than 50% of the time based on all but the top 10 performers of the survey respondents (243 respondents). Based on industry discussions, defining specific economic indicators such as Return on Investment (ROI) is not common, which is a major gap in a corrosion management practice.

To meet the corrosion management objectives, different financial tools are available to calculate the cost of corrosion ROI, or net present value (NPV) over part of an equipment's or asset's lifetime or over the entire life cycle. These tools include cost-adding, life-cycle costing, constraint optimization, and maintenance optimization. All of these attempt to answer the question of whether corrosion control or corrosion management is an investment, and not merely a cost.

Most financial tools that are currently used consider only the financial aspect of investing in corrosion control and corrosion management, with little attention given to safety, environmental, and reputational impact. Case studies of U.S. Department of Defense (DoD) projects have demonstrated that ROIs of up to 50 were achieved by using common and improved corrosion control technologies. However, ROIs that provide a total picture of the cost benefit of a project can only be accomplished when considering and monetizing increased safety, minimized impact on the environment, and enhanced reputation.

Buy-In from Top to Bottom

The maximum savings from the impact of corrosion will only be realized by the incorporation of sound corrosion management practices throughout an organization. The organization as a whole must commit to ownership of the CMS systems and processes. The adoption of a CMS into an organization's management system requires buy-in from top to bottom. The technical manager (corrosion/integrity/risk/maintenance), part of middle management, is the likely promoter for a CMS.

Without buy-in at the top, initiatives with corporate-wide impact have little chance of getting off the ground. Buy-in with senior management is necessary to get approval to move forward and garner resources. To ensure the message is effective, organizations require a business case that includes a clear statement of the problem, outlines its impact on the organization, lists the required resources, and includes the outcome in terms of cost reductions, increased productivity, or improved quality.

The management system pyramid developed in this report has different elements. The top three elements are Policy, Strategy, and Objectives. This is the very top of an organization and to institutionalize corrosion management at this level requires full support of senior management; i.e., the organization must commit to ownership of the CMS and its processes. The U.S. DoD has been addressing corrosion control since the mid 1800's (cathodic protection of naval ships was one of the first applications of corrosion control). Although the expenditure for corrosion mitigation in all DoD services was already significant, it took the realization of the cost of corrosion (estimated to be US$20 billion annually in the 2002 Federal Highway Administration [FHWA] study, "Corrosion Cost and Preventive Strategies in the United States") combined with the interest of senior DoD management (the Under Secretary of Defense for Acquisition, Technology and Logistics) to affect a cultural change and a commitment to innovation that permitted corrosion management practices to be institutionalized into an organization with the size and diversity of DoD. Industries and governments worldwide will benefit by studying and implementing this model of success.

Table of Contents

List of Appendices

List of Tables

List of Figures

1 INTRODUCTION

1.1 General

In 2002, the U.S. Federal Highway Administration (FHWA) released a breakthrough study on costs associated with metallic corrosion in a wide range of industries.[1] Results of the study showed that the total annual estimated direct cost of corrosion in the U.S. was US$276 billion – equivalent to 3.1% of the U.S. Gross Domestic Product (GDP). Along with detailed cost analyses, the FHWA study broadly included preventive corrosion control strategies. While this benchmark study is still widely used and has been updated in terms of total annual estimated direct cost of corrosion in the U.S. utilizing inflation, there has been no attempt to extend the study to a more in-depth look at the effects of corrosion as related to overall corrosion management practices.

In October 2014, NACE International initiated the current International Measures of Prevention, Application, and Economic of Corrosion Technologies (IMPACT) study; an initiative to examine the role of corrosion management in establishing industry best practices. The one-year study is being led by NACE International and carried out by DNV GL and APQC with participation from industry and technology partners worldwide.

The IMPACT study (i) updates the global cost of corrosion, (ii) assesses corrosion management practices across various industries and geographies, (iii) provides a template for corrosion management in the form of a Corrosion Management System (CMS) framework and guidelines, and (iv) provides financial tools that can be used for calculating life-cycle costs and return on investment (ROI).

1.2 Approach

The project addresses the general objective to assess how industries and organizations worldwide manage the threat of corrosion and identify gaps. The approach is focused on the concept of integrated corrosion management rather than corrosion control. The report starts with an overview of global costs of corrosion, comparing various industries and geographic regions (Section 2). Section 3 describes in detail the concept of corrosion management, discussing interaction with an organization's existing management systems, and developing guidelines to manage corrosion. An approach is presented to integrate corrosion management into an organization's existing management system. Following the section on corrosion management, a survey conducted to assess and benchmark global practices on corrosion management is described (Section 4). Focus group meetings were held in different parts of the world, the results of which were incorporated into the analysis of the survey results. From the survey results various best practices were derived, and gaps were identified. The results of the survey were also used to benchmark and assess corrosion management practiced in industry and government organizations, as well as global regions (Section 2).

In Section 6, financial tools that can be used to calculate corrosion cost and ROI over the life cycle of an asset are discussed. These tools include adding corrosion cost, life-cycle costing, and constraint optimization methods.

[1] G. Koch et al. "Corrosion Cost and Preventive Strategies in the United States" FHWA-RD-01-156, March 2002.

Section 7 describes education and training in corrosion as it relates to corrosion management.

Based on the findings in the IMPACT study, strategies for successful corrosion management are presented in Section 8. Information supporting Sections 2 through 7 is provided in the Appendices.

2 ASSESSMENT OF GLOBAL COST OF CORROSION

The purpose of the cost-of-corrosion portion of the IMPACT study is to establish an estimate for the cost of corrosion at a global level utilizing past studies. The current study did not attempt to collect new data or perform any new cost of corrosion analysis beyond using publicly available studies to estimate a global cost of corrosion. Therefore, the cost of corrosion performed within the IMPACT study is limited by the completeness and number of available studies. Appendix A contains the detailed global corrosion assessment.

The global cost of corrosion is estimated to be US$2.5 trillion which is equivalent to 3.4% of the global GDP (2013). By using available corrosion control practices, it is estimated that savings of between 15 and 35% of the cost of corrosion could be realized, i.e. between US$375 and $875 billion annually on a global basis. These costs typically do not include individual safety or environmental consequences. Through near misses, incidents, forced shutdowns (outages), accidents, etc., several industries have come to realize that lack of corrosion management can be very costly and that, through proper corrosion management, significant cost savings can be achieved over the lifetime of an asset. To achieve the full extent of these savings, corrosion management and its integration into an organization's management system must be accomplished by implementing a CMS.

Since the 1950's several countries considered the economic consequences of corrosion. Studies conducted during this time indicated that the cost of corrosion to society was significant. The different approaches used to arrive at this cost included:

- The Uhlig method, which defines corrosion cost as the total expenditure by manufacturing industries and corrosion-protection measures.
- The Hoar method, which estimates corrosion costs for individual industrial sectors, taking into account both direct corrosion cost and spending on countermeasures. In addition to operational costs, the cost of capital can also be included.
- The input/output economic model, used in the 1970's Battelle study, which uses domestic commercial interactions among industries.

To relate the cost of corrosion studies to a global cost of corrosion, a relationship between economic sectors and corrosion costs is needed. Furthermore, the GDP of the economic sectors by country must be known to permit the use of the "percent cost of corrosion by economic sector" within the extrapolation to global corrosion costs.

The studies that were included in the IMPACT study were: India 2011-2012, United States 1998, Japan 1997, Kuwait 1987, and United Kingdom 1970. Each of these studies provided data that could be mapped to the three economic sectors: (1) Agriculture, (2) Industry, and (3) Services. Throughout the global cost of corrosion analysis, the World Bank economic sector and GDP data were utilized.

The economic breakdown for the five countries used in this analysis is shown in Figure 2-1. The United States, United Kingdom, and Japan, with advanced industrial and service economies, are very similar; whereas India, with a significant agricultural economy, and Kuwait, with a significant oil industry, have different profiles. In order to address the economic sectors for different parts of the world, the global economy was divided into economic regions with similar economies (according to World Bank). These were: United States, India, European Region, Arab World (as defined by the World Bank), China, Russia, Japan, Four Asian Tigers+Macau, and Rest of the World. Countries included in each region are provided in Appendix A.

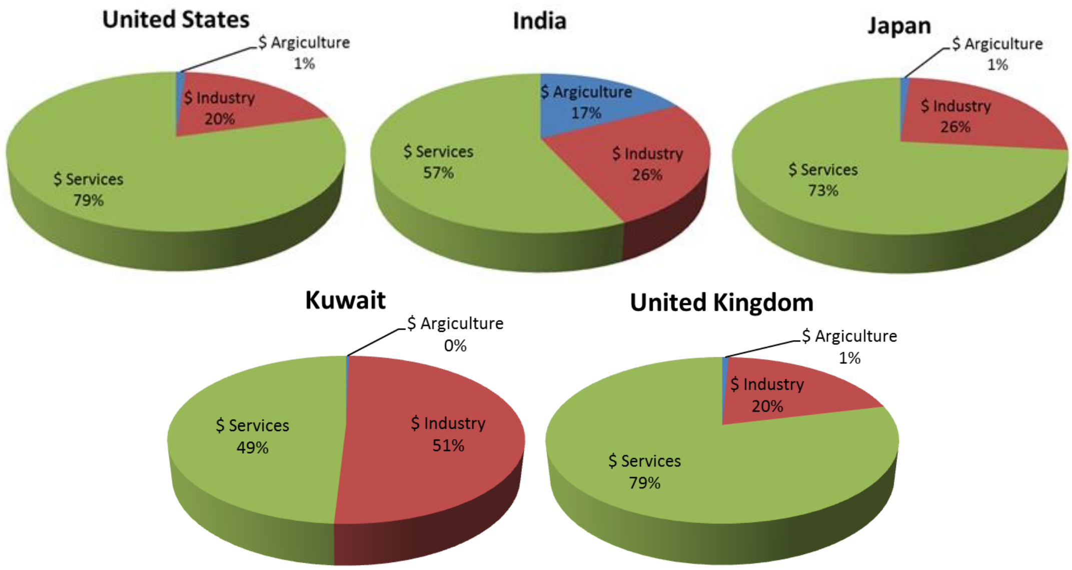


Figure 2-1. Economic Sectors for the five countries used in the Global Cost of Corrosion Study

The global cost of corrosion was assessed by mapping the five available studies to the nine economic regions using Table 2-1. Note that as additional cost of corrosion studies become available, or studies are updated, more detailed and accurate global costs can be assessed.

Table 2-1. Map of Cost of Corrosion studies to economic Regions

Economic Regions	CoC Study used for Region CoC	Agriculture %CoC	Industry %CoC	Services %CoC
United States	United States 1998	1.1	9.3	1.3
India	India 2011	6.1	4.7	3.4
European Region	United Kingdom 1970	1.1*	8.6	2.2
Arab World	Kuwait 1987	9.5	2.2	8.3
China	India 2011	6.1	4.7	3.4
Russia	India 2011	6.1	4.7	3.4
Japan	Japan 1997	1.1*	3.6	0.1
Four Asian Tigers plus Macau	Average of India and Japan studies	1.1*	3.6	0.1
Rest of the World	Average of all studies	3.8	7.4	1.2

* Estimated.

Using Table 2-1 and the GDP for each region divided by economic sector, the cost of corrosion for each country by sector and the total cost of corrosion for each country was determined. The global cost of corrosion is then determined for each economic region by sector by summing the countries in the region (see Table 2-2). The global cost of corrosion is estimated to be US$2,505 billion, which is equivalent to 3.4% of the global GDP (2013). In addition, these costs typically do not include individual safety or environmental consequences. The costs associated with safety and environmental consequences may be difficult to include in an individual country or global cost of corrosion study, but these costs should be considered in an overall management system cost of corrosion for the purpose of decision making and prioritizing projects to be completed within a specific company/corporation.

Table 2-2. Global Cost of Corrosion by Region by Sector (Billion USD 2013)

Economic Regions	Agriculture CoC USD billion	Industry CoC USD billion	Services CoC USD billion	Total CoC USD billion	Total GDP USD billion	CoC % GDP
United States	2.0	303.2	146.0	451.3	16,720	2.7%
India	17.7	20.3	32.3	70.3	1,670	4.2%
European Region	3.5	401	297	701.5	18,331	3.8%
Arab World	13.3	34.2	92.6	140.1	2,789	5.0%
China	56.2	192.5	146.2	394.9	9,330	4.2%
Russia	5.4	37.2	41.9	84.5	2,113	4.0%
Japan	0.6	45.9	5.1	51.6	5,002	1.0%
Four Asian Tigers plus Macau	1.5	29.9	27.3	58.6	2,302	2.5%
Rest of the World	52.4	382.5	117.6	552.5	16,057	3.4%
Global	**152.7**	**1446.7**	**906.0**	**2505.4**	**74,314**	**3.4%**

The above global cost of corrosion is based on available studies that had sufficient sector detail for a global sector analysis to be performed. Previous cost of corrosion studies indicated that between 15 and 35% of the cost of corrosion could be saved by using current available corrosion control practices, i.e. between US$375 and $875 billion globally. The fact that corrosion control can be profitable has been realized over and over again by industry, often following costly business interruptions due to failures of equipment and assets to perform as intended. Cost savings from corrosion control are often not obvious for some period of time; i.e., (i) maintenance costs slowly decrease; (ii) monitoring or inspection costs decrease or inspection intervals increase; (iii) fewer failures save lost production time and/or lost product, decreases injuries, decrease property damage, decrease environmental releases, and improve public relations; and (iv) life extension of the asset. All of these can be included in the business case for enhanced corrosion management. Achieving the most benefit from corrosion control practices is dependent on good business decisions. Therefore, to achieve the full extent of these savings, corrosion management and its integration into an organization's management system must be accomplished by implementing a CMS as outlined in Section 3.

There are problems with using the existing studies to examine savings over time due to implementation of corrosion control practices. For instance, in the United States the cost of corrosion has been estimated to be equivalent to 2.5% of the GDP in 1949 (Uhlig method), 4.5% of the GDP in 1975 (input/output method), and 3.1% of the GDP in 1998 (Hoar method). The problem is that, in general, the studies use different analyses to estimate the cost of corrosion so a direct comparison is not possible. As discussed in Chapter 4, corrosion measures are not well defined or consistently used within the industry as a whole.

One of the most significant success stories in corrosion management is the change in corrosion management strategy and application of innovative technology in the automotive industry. This was a global change involving all of the top manufacturers. Since 1975, the manufacturers have created a coordinated and balanced effort between advances in design, materials, and processing. [2] The automotive industry has moved from (i) minimal corrosion control where the cost of corrosion was primarily maintenance and loss of capital (the life of an automobile was often determined by the corrosion of the body and frame) to (ii) state-of-the-art corrosion control through advance painting/coating technology and use of corrosion-resistant materials, resulting in competitive advantages and warranties against corrosion.

Note that the cost benefit of this transformation is difficult to estimate because different methods were used to provide costs, making the uncertainty of the costs high. Table 2-3 provides the costs available from the two cost of corrosion studies performed in the U.S. that included automotive costs.[3, 4]In 1975, it was estimated that the annual cost of corrosion in the automotive industry was US$6.0 billion, which when adjusted for inflation is equivalent to US$18.6 billion in 1991 dollars. See Table 2-3 for a breakdown of the costs into manufacturing (new car costs) and operating (used car costs). In 1999 the estimated annual cost of corrosion in the automotive industry was US$23.4 billion. The cost of depreciation was 61% of the 1999 cost and was not included in the 1975 study, such that, discounting

2 L.L. Piepho, L. Singer, M.R. Ostermiller, "Advances in Automotive Corrosion Resistance", NACE International, Paper 91407, Corrosion 1991.

3 Greg Moore, "Corrosion Urban Water Industry", Corrosion Challenges Project 2010 – Urban Water. The Australian Corrosion Association In., November 2010.

4 Economic Effects of Metallic Corrosion in the United States, NBS Special Publication 511-1, SD Stock No. SN-003-003-01926, 1978.

depreciation, the 1975 cost would be unchanged at US$18.6 billion compared to US$9.0 billion in 1999. Thereby, the transition in corrosion management strategy produced an annual savings in 1999 compared to 1975 of US$9.6 billion or 52% in corrosion-related manufacturing and operation costs of vehicles. The new vehicle cost of corrosion per unit also decreased by 44% in 1999 compared to 1975. Furthermore, the average age of vehicles increased from 1975 to 1999 by 49% providing an additional significant benefit to consumers.

Global motor vehicle production in 1999 was 56.2 million, or 4.3 times the U.S. production. If the U.S. production is indicative of corrosion-related costs globally, the annual cost savings in 1999 compared to 1975 would be US$41.3 billion.

Table 2-3. Corrosion-Related Costs in the Automotive Industry

	1975	1999
Manufacturing (new vehicles) [US$ billion in 1999 dollars]	3.1	2.5
Operating (used vehicles) [US$ billion in 1999 dollars]	15.5	6.5
Total [US$ billion in 1999 dollars]	18.6	9.0
Total Production (Vehicles)	9,000,000	13,000,000
Corrosion Cost of Manufacturing (US$ Cost per Vehicle)	344	192

This transformation in corrosion management strategy by the automotive industry was a decision at the highest levels of an organization, resulting in lower corrosion-related manufacturing costs, lower corrosion-related operating costs, and longer life of automobiles for the buying public.

Maximizing savings due to the impact of corrosion will only be realized by the incorporation of sound corrosion management practices throughout the organization. In the remainder of the IMPACT study, corrosion management is discussed and a CMS is detailed that, if implemented, would permit a significant portion of these savings to be realized.

3 CORROSION MANAGEMENT SYSTEM FRAMEWORK

A CMS is the documented set of processes and procedures required for planning, executing, and continually improving the ability of an organization to manage the threat of corrosion for existing and future assets and asset systems.

Managing the threat of corrosion requires consideration of both the likelihood and consequence of corrosion events. For the purposes of this report, the consequence, or impact, of corrosion is considered the potential or actual monetary loss associated with the safety, environment, or asset integrity. This value is typically quantifiable when considering lost revenue, cost of repairs, and clean-up costs, as applicable. Other aspects of corrosion impact include deterioration of an asset to the point where it is no longer fit for its intended purpose (e.g., lost future production).

In general, corrosion threats should be mitigated to a point where the expenditure of resources is balanced against the benefits gained. One outcome of this is that a financial analysis might conclude that a technically sound corrosion mitigation action is unjustified. To determine whether a corrosion management investment is appropriate, it can be compared to the potential corrosion consequence through an ROI analysis. ROI is a benefit (or return) of an investment divided by its cost. For corrosion management, the costs may include inspection and other maintenance costs and the benefit of ROI is not always measured in financial gains, but in the avoidance of safety or integrity costs. Some risks are hard to monetize including reputation and societal costs. The ROI for corrosion management can be linked to the risk-management concept of As Low As Reasonably Practicable (ALARP).

It must be noted that there are uncertainties in quantifying both the likelihood and consequences of corrosion. These uncertainties include both data and models (models can include analytical expressions. numerical models, and expert opinions/mental models). Therefore, additional mitigation measures (also sometimes referred to as defense in depth) are often taken that are beyond the calculated ROI.

One way to visualize the benefit of combining corrosion technology-specific activities with management system elements is through a two-by-two matrix shown in Figure 3-1. With poor corrosion technology and a weak management system, corrosion is neither controlled nor managed (i.e., it is unsafe). With sound corrosion technology, corrosion is controlled but not optimized (i.e., it is expensive). A mature management system without sound corrosion technology cannot be effective (i.e., it is unsound). Combining a mature management system with sound corrosion technology is ideal in that it results in an effective and efficient management of a degradable asset.

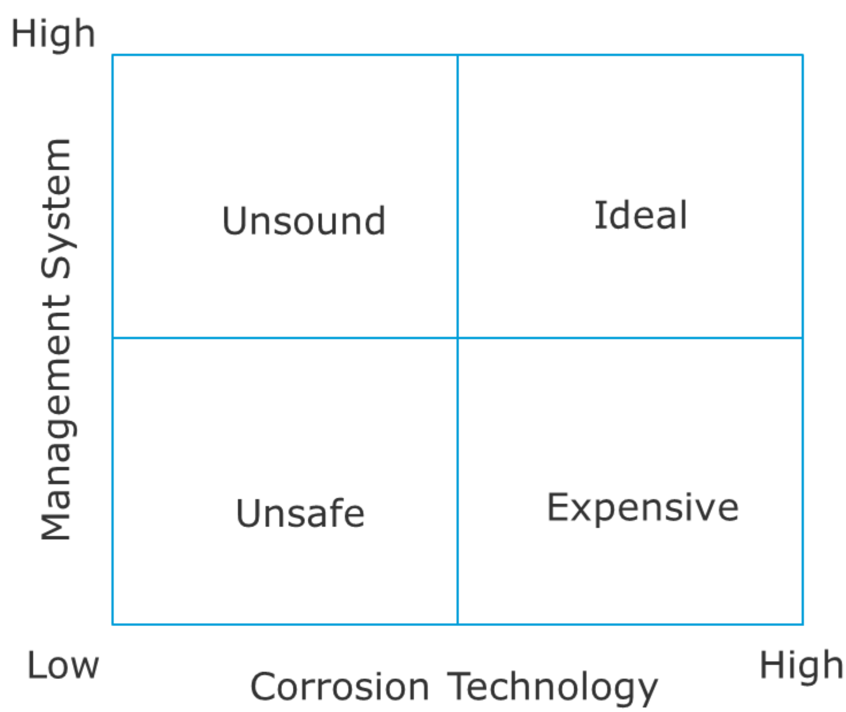


Figure 3-1. A Two-by-Two Matrix Illustrating the Benefit of Combining Sound Corrosion Technology with a Mature Management System

Investing in corrosion management activities such as inspections and maintenance may not prevent all corrosion events because the likelihood of failure is rarely zero. Additionally, the consequences of corrosion events, when they occur, may be compounded due to system-related issues such as lack of training, not following procedures, inadequate emergency response, etc. Therefore, investing in a CMS to frame the corrosion activities with the system elements necessary for planning, execution, and continual improvement should be considered as part of the ROI.

3.1 General Description

Due to the need to manage the threat of corrosion throughout an asset's life cycle and by different groups within an organization, a CMS is unlikely to be a standalone management system. More commonly, a CMS takes on the form of components embedded within an existing well-defined management system framework. A CMS should be part of an organization's asset integrity management system (AIMS) designed to specifically manage the threat of corrosion as well as the other non-corrosion-related threats to the assets or asset systems. For example, the diagram in Figure 3-2 illustrates the interrelation of the various organizational management systems for a pipeline company, into which the CMS is incorporated. These organizational management systems that address important topics such as safety, quality, structural integrity, and environment often already exist within many organizations. For organizations without management systems, creating one would normally have higher priority than implementing a standalone CMS. The applicable standards and recommended practices, which apply to the various management systems, are included in parentheses in the diagram.

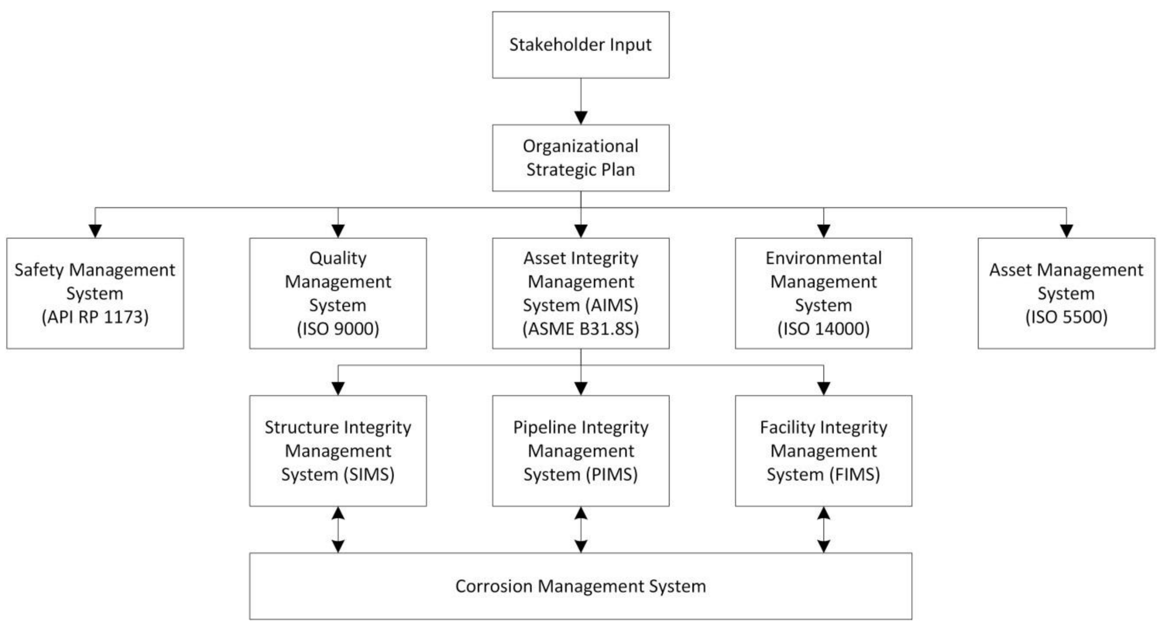


Figure 3-2. Interrelation of Organizational Management Systems - Pipeline Example

Figure 3-3 illustrates the interaction between CMS and other organizational management systems broken out in standard management system elements and the corrosion-specific elements. The diagram shows two major management categories: (i) management system elements that address all threats (including corrosion), and (ii) corrosion-specific elements. The management system elements, at the top of the hierarchy triangle, comprise Policy, Strategies, Objectives and Enablers, Controls, and Measures. The Enablers, Controls and Measures Element contains sub-elements that apply to all management system elements, including corrosion, such as organization, resources, risk management, training and competency, management review, and continuous improvement (the complete list of these sub-elements is given in the diagram). The corrosion-specific elements address implementation through plans and procedures and working practices.

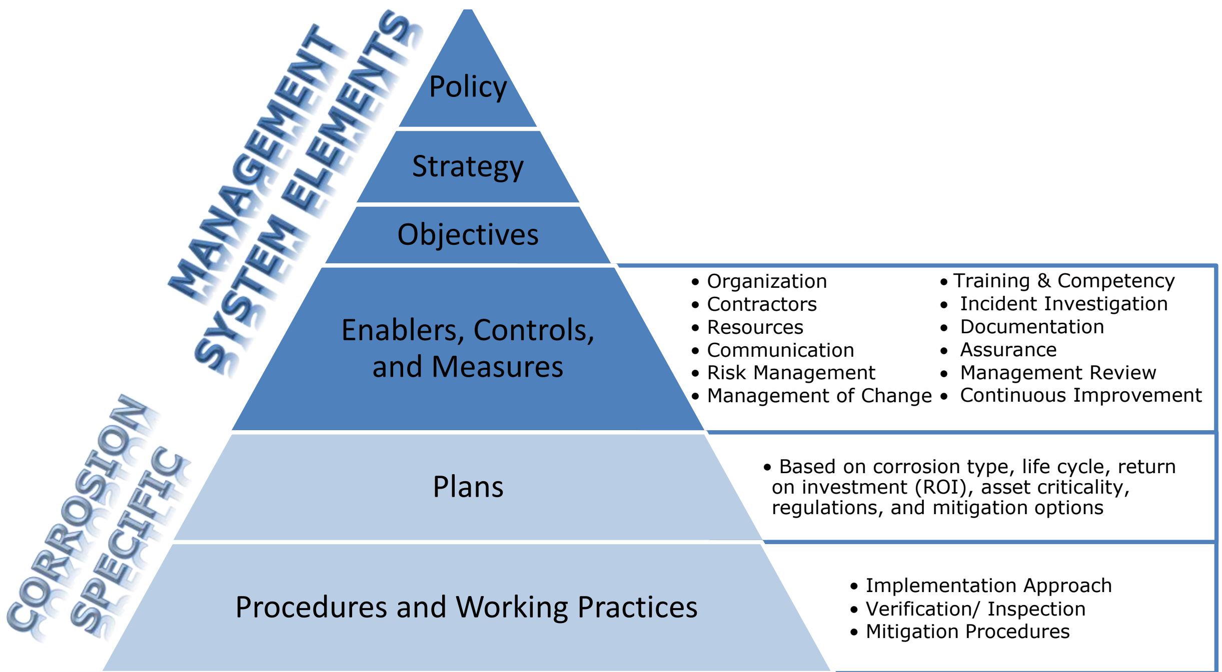


Figure 3-3. Hierarchy of General and Corrosion-Specific Management Elements

Figure 3-4 shows how corrosion management fits into the framework of an overall management system through the standard management system elements. The diagram in the figure shows the risk-based corrosion planning process, similar to ISO 31000, *Risk Management - Principles and Guidelines*, which incorporates threat assessment and prevention or mitigation options. This type of analysis, which fits into the lower two segments of the management triangle, requires an in-depth technical knowledge of the potential or existing corrosion mechanisms and the available options for mitigation. The process can also serve as input to a complete risk-based decision process that includes associated consequences and context as described in Section 3.2.2.5. However, other types of corrosion planning processes may also be utilized depending on the type of industry, regulatory compliance, the required reliability, and return on investment (ROI) considerations.

It is important to note that regardless of the type of corrosion planning process, the personnel, plans, procedures, and work practices are controlled and optimized through the standard management system elements. For example, training and competency of personnel performing corrosion assessments or determining prevention or mitigation options should be defined and consistently applied through the management system. Additionally, communication paths and applicable forms or documentation can be standardized and continuously improved through the management system.

The CMS plans must be communicated to all relevant stakeholders to the level of detail appropriate to their participation or business interests in the delivery of the plans.

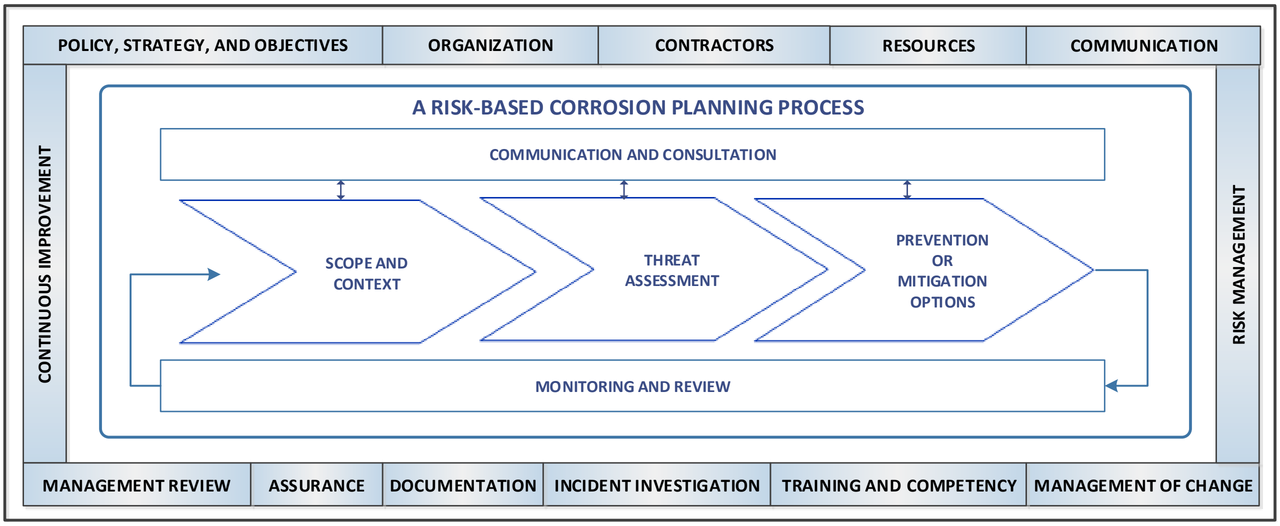


Figure 3-4. CMS Framework (Based on ISO 31000)

The implementation details of the management elements depend on several factors including:

- The corrosion type observed or expected.
- The life cycle of the asset or asset systems.
- ROI.
- The criticality of the asset or asset systems.
- The applicable regulatory requirements.
- The available mitigation options.

The final level of the CMS elements (Figure 3-3), i.e. of corrosion-specific processes and documentation, includes the procedures and working practices that result from the corrosion plans. These include the implementation approach, verification, inspection, and mitigation procedures. For example, if re-coating is the mitigation option selected during the corrosion planning process, the associated procedures and work practices may include surface preparation, coating application, and post-coating inspection.

To maximize effectiveness, the CMS must manage the threat of corrosion at each of the significant stages of an asset's life cycle, from design to decommissioning, as shown in Figure 3-5. Additionally, the CMS's continual improvement processes allow for review and improvement not only over the life of a specific asset, but also over the life cycles of an organization's similar assets. In this context, the term "asset" describes individual assets, types of assets, or asset systems that an organization builds, acquires, or enhances.

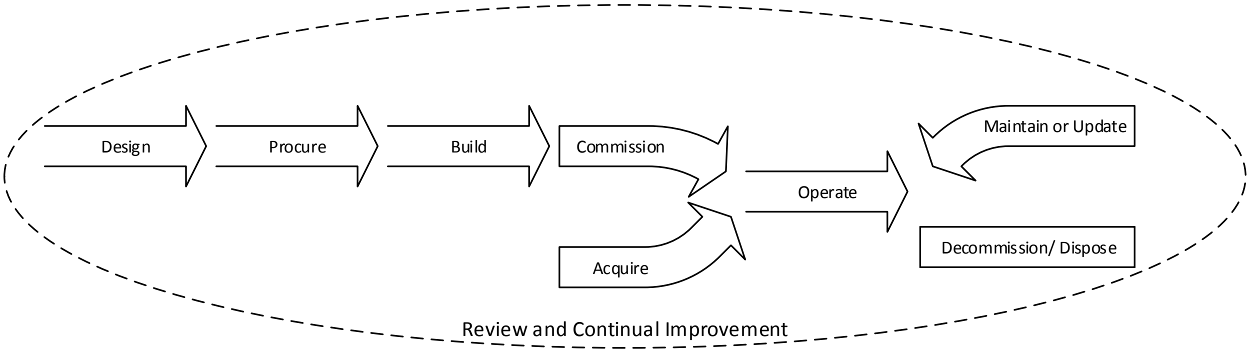


Figure 3-5. Corrosion Management over the Life Cycle of the Asset

3.2 Corrosion Management System Elements

The framework for a CMS is based on a series of central elements to ensure the effectiveness and consistency and communication of corrosion management processes. The implementation of corrosion management in a consistent and holistic manner in all stages of asset integrity management is an area where many organizations have identified the need for improved guidance. The following sections highlight the elements necessary for the development and implementation of an optimized CMS.

3.2.1 Corrosion Management Policy, Strategy, and Objectives

The corrosion management policy includes the principles and requirements used to manage the threat of corrosion over the life cycle of assets and asset systems. The corrosion management policy must be aligned with the organization's mission and values through the organizational strategic plan. The policy lays the foundation for the corrosion management strategy, or long-term plan for managing corrosion over an organization's assets and asset systems by way of specific and measurable objectives.

During the development of the corrosion management policy, strategy, and objectives, the internal and external context, or environments in which the organization seeks to achieve its objectives, must be considered. Examples of external context include the regulatory environment and the organization's perceived reputation, while examples of internal context include an organization's culture as well as internal standards and business models.

Although corrosion management policy, strategy, and objectives may be contained in standalone documents, they are ideally grouped with the policies, strategies, and objectives used to manage other threats to an organization's assets or asset systems.

Some organizations understand the importance of the commitment of upper management. A national oil company (NOC) participant in one of the Middle East focus group meetings conducted during the IMPACT study said:

> *"Corrosion management is of paramount importance to senior management and is a tool to manage asset integrity. The company is structured in asset groups and each has asset standards to follow. The CEO signs an asset management policy."*

A senior manager of a major pipeline company in India said:

> *"Companies should have a robust corrosion management system comprising approved policy, plans, and targets; strategy; processes and procedures; controls and checks; structures; professionals; and resources."*

3.2.2 Enablers, Controls, and Measures

3.2.2.1 Organization

An optimized CMS requires defined and documented roles and responsibilities throughout an organization with respect to corrosion management. The defined roles and responsibilities should include personnel involved in the development, implementation, review, and continual improvement of the CMS, as well as personnel performing corrosion assessments and determining and prioritizing corrosion prevention and mitigation activities. Often, the roles and responsibilities are communicated internally through the use of organizational charts. Additionally, any applicable external personnel, such as contractors or consultants, should also be included in the organizational charts.

3.2.2.2 Contractors, Suppliers, and Vendors

When utilizing contractor services, the organization is responsible for verifying that the contractor services meet or exceed the requirements of the CMS. Additionally, the contractor(s) should be held responsible for meeting or exceeding the requirements of the CMS as defined by the organization. The same considerations should be applied to the qualification of any subcontractors used by the contractor.

Many organizations are indeed struggling with rolling out corrosion management principles to contractors, suppliers, and vendors. This is underscored by a comment made during a Middle East focus group meeting:

> *"There are no clearly defined roles and responsibilities in the execution of CMP (corrosion management plan) – rollout to facilities and contractors is not being done."*

3.2.2.3 Resources

The organization should commit to determining and providing the resources required for developing, implementing, and continually improving the CMS. Resources include staffing, infrastructure, and equipment, such as inspection tools or repair equipment. Staffing requirements may be met by providing a combination of organization staff and contracted personnel; however, the organization must commit to ownership of the CMS and its processes.

Allocation of appropriate resources to deliver programs, which are consistent with the CMS, must be ensured. This is accomplished by allocating proper budgets, setting achievable staffing levels, and developing and implementing training programs to ensure the right amount and the right competence levels of staffing.

Resourcing is found to be a problem in implementing corrosion management. Quotes made during a focus group meeting in China reflect a problem that most organizations have admitted to:

> *"We are missing the expertise to build corrosion SME (subject matter expert) teams. Non-experts cannot easily find hidden corrosion issues."*

> *"There is a shortage of corrosion experts to hire in China. We have to look for 3rd party experts; often is not local, so it creates inefficiencies and delays."*

3.2.2.4 Communication

The organization must create processes to establish and maintain internal and external communication processes associated with corrosion management. These processes include identification of the stakeholders and information that require communication. Channels should exist to allow communication to flow from management to project/field personnel and vice versa.

Internal Communication

Internal communication processes facilitate awareness of the CMS and corrosion processes throughout the organization, including awareness and understanding of the CMS policy, objectives, plans, processes, and procedures. Communication links management, employees, and other internal stakeholders and allows employees to give feedback and provide possible solutions to issues.

It is of particular importance to open up and maintain internal communication between all levels in the organization, as well as across the organization, since this is one of the means to incorporate corrosion management into an organization's management systems.

Key internal communication processes include communication of the following:

- Roles, authorities, and responsibilities.
- Best practices.
- Learning opportunities from ongoing activities, near-misses, and incidents, both internal and external.

Often information is not shared across an organization as is evidenced by a quote made during one of the focus group meetings by a staff member of a NOC:

> *"There is a problem with communications; there are no communication protocols. If a corrosion engineer has an issue with corrosion and uses central engineering services, the solution/response goes only to the facility that had an issue – not to all who may have the issue or could have it."*

External Communication

External communication processes facilitate awareness, understanding, and acceptance of the CMS by contractors and other external stakeholders. As with internal communication, these processes include identification of the stakeholders and information that require communication. Additionally, the organization should make visible points of contact and exchange information regarding corrosion management with external stakeholders. This may include members of the public, regulators, industry organizations, emergency responders, and law enforcement. Adequate training in communication to external stakeholders is essential.

For contracted personnel, achieving buy-in of the CMS is crucial to the overall management of corrosion for an organization's assets and asset systems. This is why clear communication of the CMS, expectations of the contractor, and responsibilities of the contractor within the CMS framework are essential.

Key external communication processes include communication of the following:

- The CMS activities and processes to be conducted or reviewed by the external organization, including scope, boundaries, and applicable standards and procedures.
- Roles, authorities, and responsibilities.
- Best practices.
- Learning opportunities from ongoing activities, near-misses, and incidents.
- MOC, including key contacts and elevation plans for technical and non-technical inquiries.
- Approval processes for subcontracting or other contractual changes.

The importance of external communication is very important when the business is politicized and the media misrepresents the organization, as is evidenced by comments from the water distribution industry made during one of the group forum meetings:

> *"Management is very reactive to media/political winds."*

3.2.2.5 Risk Management

The risk management process coordinates activities to direct and control an organization with regard to risk. In the case of a CMS, the organization needs to establish, implement, and maintain documented processes and procedures for the ongoing identification and assessment of corrosion risks, as well as the identification and implementation of necessary control measures throughout the life cycle of the assets or asset systems.

A risk management approach is well suited to corrosion management where the final plan must include specific tasks and actions required to optimize costs, risks, and performance for assets and asset systems having a wide range of safety, environmental criticality, and business importance.

The ISO 31000 standard provides a useful reference in terms of the components and basic requirements for a consistent approach to risk management, but in general terms the organization's methodology for risk management needs to be:

1. Proportional to the level of risk under consideration.
2. Defined with respect to its scope, nature, and timing to ensure it is proactive rather than reactive.
3. Include where appropriate the assessment of how risk can change over time and service life.
4. Provide the classification of risks and identification of those risks that are to be avoided, eliminated, or controlled by asset management.
5. Be consistent with the organization's operating experience and the capabilities of mitigation measures employed.
6. Provide the monitoring of required actions to ensure both the effectiveness and timeliness of their implementation.

In terms of corrosion as a specific threat to the asset integrity or lifetime, the planning process described in Figure 3-4 is a crucial step conducted by corrosion experts to establish the probability of credible corrosion-related events and the various options for mitigation to achieve the integrity or lifetime objectives of that specific asset. To complete the "risk picture," the credible consequences of a failure or event as a result of this corrosion mechanism need to be determined. The type or context of the consequence will vary according to the asset type and criticality, but consideration should be given to safety, environment, reputation, and business loss. Applicable regulations or organization procedures may also require a "reverse" risk management process whereby the consequence criticality of a specific asset is determined first and then the corrosion threat analysis is only conducted for those assets with unacceptably high consequences.

Similar risk pictures will normally be established for other types of threats and then decisions about future investment and plans for asset management will be made based on the (risk) classification of a specific threat. ISO 31010 – *Risk Assessment Techniques*, which is a supporting standard to ISO 31000, provides guidance on the selection and applications of systematic techniques for risk assessment.

3.2.2.6 Management of Change

The MOC process is used to control, evaluate, and verify technical and non-technical changes to the corrosion management processes, CMS, assets, or asset systems. Each MOC request must be reviewed by appropriate subject matter experts to evaluate the effect of each proposed change or suite of changes based on the significance of the change, the need, technical basis, and expert evaluation of the risk associated with the change. Utilizing this information, authorization to proceed with the change should be determined.

It is critical that the MOC is effectively documented and communicated to all impacted parties throughout the organization.

3.2.2.7 Training and Competency

The organization is responsible for ensuring and documenting that personnel whose roles fall within the scope of the CMS have an appropriate level of competence in terms of education, training, knowledge, and experience. Training and competency requirements are applicable to both the organization's staff and contractor personnel.

The organization should develop a process for training personnel on the organization-specific CMS processes and procedures. Additionally, competency evaluations for personnel, such as certifications, internal or external written or oral examinations, demonstrations of competence, previous job experience, or on-the-job evaluations, should be defined, implemented, and documented. It is important to consider the needs for re-training and evaluations, as well as the difference between training requirements for new and experienced personnel.

It is important to attract young and new talent and create an attractive career path for them. Several larger companies do have extensive training programs, but even the best programs have gaps:

> *"New graduates work with mentors for 10 to 15 years and have goals (CMAPs). On the not so good side, it was pointed out that mentors of people responsible for corrosion may not have any knowledge of corrosion themselves."*

> *"The company offers and underwrites advanced degrees, courses, and certifications, and they have internships."*

Moreover, globally and across industries it is a battle to create an attractive career path for engineers as shown with one quote from an employee of a Middle East NOC:

> *"The field of corrosion is not made to be that appealing within the company, especially for young people. If someone in the corrosion group performs very well, they are made an attractive offer to move to another group. Salaries also favor moving out of a specialized group like corrosion control."*

Furthermore, it is essential that corporate knowledge stays with the company; however, often corporate knowledge disappears when senior staff leave. A quote by a senior engineer in a U.S. water distribution company underlines this concern:

> *"I have very specialized knowledge (water quality, chemistry, and corrosion) and have been in the business for 30 years. There's no one being trained to replace me, and I am concerned about that."*

3.2.2.8 Incident Investigation (Lessons Learned)

Learning from both internal and external events is critical to the continuous improvement of a management system. Formal and consistent processes, such as incident investigations, are used to verify that a continuous improvement loop is in place to learn from events. In this context, "incident" is used to describe an undesirable event that affects the CMS, corrosion process, asset, or asset systems.

Examples of incidents include unintentional failure of an asset due to corrosion or failure to follow a defined CMS process or procedure. The goal of an incident investigation is to identify necessary improvements to the CMS, corrosion processes, or procedures. These improvements must be evaluated using the MOC process, communicated throughout the organization, and reviewed by management for effectiveness.

3.2.2.9 Documentation

An organization is responsible for assembling, managing, and maintaining the documentation and records required to support and continually improve the CMS. The term "document" refers to plans or instructions for what actions will be performed; examples include the CMS policy, strategy, objectives, plans, procedures, and inspection forms. Alternately, a "record" refers to proof of compliance with a document's requirements at a specific time. Examples of records include training records, corrosion inspection reports, and meeting minutes.

A needs analysis may be performed to determine which records and documents should be retained, both for regulatory or legislative reasons, as well as to conform to an organization's requirements.

3.2.2.10 Assurance

The corrosion management plans (CMPs) and work processes need to be audited periodically to ensure that they are being followed and adhered to and that they remain effective and consistent with the CMS strategy and objectives.

The audits can be performed by either the organization's own staff or using a third-party consultant. The audit reports can serve as major input to the management review and continuous improvement process.

3.2.2.11 Management Review

A management review is an important aspect of a management system that demonstrates commitment from the organization for implementing, reviewing, and continually improving the management system and associated processes and documents. Management reviews are carried out at the optimized frequency determined by the organization to promote the continuing effectiveness of the CMS, examine current issues, and assess opportunities for improvement.

Typical information inputs for management reviews include:

- Findings from non-conformances, incidents, and failures, both internal and external.
- Status of preventive and corrective actions.
- Follow-up actions from previous management reviews.
- Changes in the organization's operational environment that could affect the CMS including the requirements for additional or revised resources or changes to applicable regulations or standards.
- Audit results, both internal and external.
- Overall performance in terms of key performance indicators (KPIs).
- Opportunities for improvement.

Typical outputs of the management reviews include:

- Changes to policy, strategy, or objectives associated with the CMS.
- Reallocation or supplementing of resources.
- Changing organizational details, including staffing or responsibility updates.
- Corrective and preventative measures.
- Changes to the CMS processes, procedures, or documents.

A process should be implemented to track the completion of any required actions determined during the management review.

3.2.2.12 Continuous Improvement

In addition to formal processes that affect continuous improvement, including incident investigations and management reviews, informal opportunities, such as employee concerns and impromptu feedback, should be utilized in an appropriate manner to improve the CMS as well as the corrosion processes and procedures. Continuous improvement can be used to evaluate both the effectiveness of the CMS and its continued relevance to the organization's goals and objectives. Improvements may take the form of changes to the overall policy, strategy, or objectives, or the individual elements of the CMS and their associated processes and procedures.

3.3 Implementation of the CMS Framework

The previous sections describe the general approach toward developing and implementing a corrosion management framework. In Appendix B, a guidelines document is presented that can be used to implement a CMS framework. The guidance document can be used as a standalone document as well as part of an organization's overall management system. Most organizations have management systems in place, in which case incorporation of corrosion management into the existing management systems is the preferred approach.

Primarily, two specific groups of personnel will be impacted during the implementation of a CMS: management and corrosion specialists. Management, driven by an awareness of the potential threat of corrosion, will be responsible for:

- Demonstrating commitment to corrosion by establishing policies and strategies and setting goals and objectives.
- Maintaining clear descriptions of the required roles and responsibilities.
- Aligning authority for the corrosion specialist with the identified risk level.
- Developing and tracking measurable goals for corrosion-related risks.
- Securing an appropriate budget for implementing corrosion-related plans.

Alternatively, corrosion specialists, driven by the principles of ALARP, will be responsible for determining the optimum mitigation approach to achieve the acceptable level of risk by:

- Assessing the level of risk in absolute terms, where higher risks justify additional expenditure on controls.
- Determining the magnitude of the potential consequences to rank the risks accordingly.
- Verifying that the proposed and existing corrosion control measures are consistent with industry best practice.
- Evaluating the reliability of the corrosion control technologies, including conservative assumptions for new/novel technologies.
- Knowing the cost of additional corrosion control measures.
- Comprehending the degree to which the existing assets or asset systems are inherently safe.
- Understanding the performance of existing corrosion controls, especially compared to the expectations of their performance.

3.4 Corrosion Research and Development

Corrosion research has played a critical role in developing the technical framework and underpinnings for corrosion mitigation activities. Research has also assisted organizations in identifying new threats that did not become apparent from past operating experience. However, corrosion research and development (R&D) has the greatest business impact when aligned with an organization's business strategy. Without this alignment, R&D can either be too operationally focused or disconnected from value-creation for an organization.

Operational R&D focuses narrowly in scope and time because day-to-day troubleshooting drives it. Within the management system pyramid of Figure 3.3, operational R&D usually falls within the "Procedures and Working Practices" of a business unit. Value creation is incremental because deliverables need short-term ROI, and project size is restricted by available discretionary funds within operational budgets. Operational R&D within "Plans" of the management system pyramid tend to have corporate funding, which justifies use of centralized funds, which fall outside of an operating unit budget and facilitates implementation of deliverables across the organization.

The corrosion industry is replete with examples of unanticipated failures (steam generator cracking, pipeline stress corrosion cracking, etc.). Long-term, applied research (or strategic research) helps develop new knowledge that can sustain an organization by anticipating new risks and creating solutions. Long-term research may not fit into the procedures and work plans of an organization precisely because it is aimed at anticipating and mitigating disruptive scenarios.

Basic research adds to a scientific body-of-knowledge and sets the overall paradigm within which corrosion professionals conduct their activities. However, both basic and long-term applied research provide an organization tools to deal with unanticipated risks and should be considered in the strategic part of the overall organizational management pyramid (Figure 3-3).

R&D is strategic if it aligns with a management system element of the CMS pyramid, which ties to operational knowledge found in lower parts of the pyramid, including a strategic element that allows an assessment of business impact to define and justify specific R&D activities. This allows prioritization of R&D funds across an organization. Most importantly, aligning R&D with organizational strategy enables value creation (i.e., positive ROI). Including management system elements within R&D has the further benefits of introducing governance to include roles and responsibilities, collaboration between functional areas, relevance to operational needs, and measurement of research benefits.

A further consideration for including business-oriented contributors to R&D is that deliverables can include both technical and business innovations. For example, the concept promoted in this report to move from corrosion control to corrosion management is innovative because it creates value by doing something new.

4 BENCHMARKING

In order to gain insight into global corrosion management practices across several industries, a survey was prepared and sent out to a broad range of industries. The industries surveyed ranged from aerospace and aviation to chemical, petro chemical and oil and gas across the world. The main objectives of the survey were to assess, where possible, the corrosion management practices in the various industries and organizations, and to identify and understand any gaps or shortcomings in what is considered best practice.

It is critical to understand the business and work processes being performed to manage corrosion costs across the asset life cycle. In turn, this can be used to assess the benefits of differing levels of corrosion management practices and help to identify potential best practices for other organizations to adopt.

The study followed a parallel self-assessment survey and interview process that resulted in key observations and findings (Figure 4-1). Interviews were accomplished in (i) a series of regional focus group discussions and (ii) individual interviews with subject matter experts (SMEs). The focus groups allowed for open dialog about a specific industry's corrosion management practices, business needs, challenges, and opportunities to support future improvement. The individual interviews with SMEs allowed for more in-depth discussions concerning an individual organization.

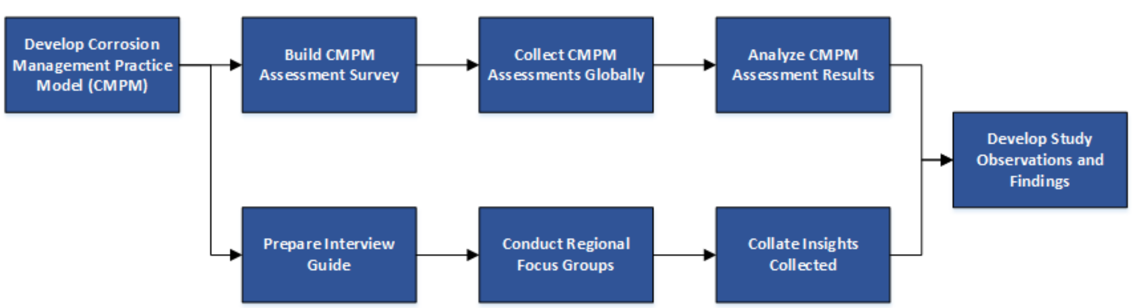


Figure 4-1. Survey Study Flow Diagram

4.1 Building the Survey

4.1.1 Corrosion Management Practice Model

The Corrosion Management Practice Model (CMPM) was developed to provide a repeatable framework for assessing the structure, approach, and features that comprise a CMS within an organization. Corrosion management practices were identified across nine management system domains (see Table 4-1) and aligned to Figure 3.3. The survey was developed to examine corrosion management practices in each of these domains over the life cycle of assets to be managed – design, manufacturing/ construction, operations/maintenance, and abandonment.

Table 4-1. CMPM Domains

Domain	Link to Corrosion Management Elements (Figure 3-3)	Description
Policy (including Strategy and Objectives)	Policy, Strategy, and Objective Elements (top three in triangle)	Policies, associated strategies and objectives to address business needs (including regulatory, legal, environmental and societal)
Stakeholder Integration	Enablers, Controls, and Measures Element	Alignment to stakeholder needs, performance monitoring, and compliance
Organization		Structure, interaction model, and internal/external engagement (vendors/suppliers)
Accountability		Roles, responsibilities, and resource allocation
Resources		Competencies, training and development, and formalization of job and work requirements
Communication		Awareness, knowledge management, and lessons learned
Corrosion Management Practice Integration		Integration into work processes, alignment to quality and other disciplines, and incident tracking/resolution
Continuous Improvement		Improvement identification, prioritization, selection, and change management
Performance Measures		Quantifiable indication, such as KPIs, to assess and to measure how well an organization or individual is achieving desired goals

Seventy questions were asked across the CMPM domains and asset life-cycle phases; see Appendix C.

Using the structure of the CMPM, each CMS practice was converted into a single assessment question with a range of pre-set answer options (see Appendix C). The answer options typically ranged from (i) no, the organization does not perform that practice or have the capability, (ii) to successively higher levels of capability or proficiency (see example in Table 4-2).

The resulting assessment survey was then piloted with a number of organizations to ensure understanding and ease of completion. A web-based survey tool was then set up to allow direct entry by participating organizations via a provided URL.

Table 4-2. Example Survey Question and Answer Set

Example of CMPM Practice Alignment to Survey Question/Answer	
Practice from CMPM	The corrosion management strategy is linked to organization strategy.
Survey Question	Is your corrosion management strategy linked to your organization's overall strategy?
Answer Options	a) No b) Yes, but to technical requirements only c) Yes, but to business performance only d) Yes, comprehensively
Scoring	Scoring ranges from "0" Baseline to "1" Best Practice a) 0 b) 0.5 * c) 0.5 * d) 1.0

* Weighting of intermediate answers can vary depending on the question and options.

4.1.1.1 Engagement of Participants

The study project team engaged with global partners to help generate awareness of the CMPM self-assessment survey and promote participation (see Table 4-3). Each of the global partners agreed in advance to identify candidate organizations and support completion of the self-assessment survey.

Table 4-3. Listing of Global Partner Organizations

Global Partner Organizations
Association of State and Territorial Solid Waste Management Officials [United States]
Australasian Corrosion Association [Australia]
American Water Works Association [United States]
DECHEMA Institute [Germany]
Exova [U.K., global locations]
India Academy of Engineering [India]
Indira Gandhi Centre for Atomic Research [India]
Institute of Oceanology [China]
International Union Painters and Allied Trades [United States & Canada]
Japan Society of Civil Engineers [Japan]
Petronas [Malaysian]
Saudi Aramco [Saudi Arabia]
U.S. Department of Defense [United States]
University of Science and Technology Beijing [China]
University of Calgary [Canada]

To support confidentiality, each global partner was assigned a set of participant codes they could distribute so that each participating organization could remain anonymous if desired as part of their self-assessment survey response. As self-assessment survey participant responses were received, the global partners assisted in the resolution of incomplete submissions or validation issues identified by the study team.

The self-assessment survey (Appendix C) was made available to participants over a three-month period to allow as many potential organizations to contribute. At the end of that period the survey was disabled to allow validation of the entire data set and subsequent analysis of the results.

4.1.1.2 Validation of Submissions

All submitted self-assessment surveys were processed through a professional data validation process. This included both logical and statistical validation steps to identify any anomalies. Each validation issue was then communicated back to the global partner if a participant code was used, or directed to the submitter for clarification. Any data with validation issues that did not reach resolution were omitted from the final data set.

Validation occurred in three stages:

1. Upon submission of a survey.
2. Once a large pool of surveys had been submitted.
3. When the survey collection period ended.

When a survey was submitted, initial validation of the survey by itself was performed. This considered completeness and the logical patterns of answers across related questions. Resolution of any issues was then worked immediately. Once a large pool of survey submissions was in place, an initial view of statistical validation was conducted to identify anomalies across the participants. Again, identified issues were worked immediately. When the survey was closed and collection completed, the full data set then went through additional statistical analysis and issues were resolved as described above.

A total of 721 self-assessment surveys were started by participants, but only 267 passed the full validation process. Many of those that did not pass validation did not include key data necessary for reasonable inclusion into the data set. After numerous unsuccessful attempts to reconcile the validation issues, those submissions had to be excluded. While those submissions were not included, the study team did compare analysis results with and without those submissions and saw no appreciable change in the results. This gives greater confidence that the results reported in the remainder of this report are relevant and accurate.

4.1.2 Demographics of Participating Organizations

Of the 267 validated CMPM self-assessment submissions, 243 contained information to permit the distribution across industry and geography (see Table 4-4).

Table 4-4. Distribution of Respondents According to Industry and Geography*

	Aerospace & Automotive	Airline, Logistics, & Transportation	Chemicals	Construction	Electronics & Instrumentation	Energy & Utility	Environmental	Government/Military	Machinery & Machinery Equipment	Metals, Mining, & Steel	Petroleum/Oil/Gas	Pipelines	Water-Potable	**Total**
Asia	3	10	21	5	3	4	0	0	20	2	61	3	0	**132**
Australia	0	0	0	0	0	0	0	2	0	0	7	1	5	**15**
Europe	0	0	0	0	0	0	0	0	0	0	2	0	0	**2**
Middle East	0	0	0	0	0	0	0	0	0	0	2	0	0	**2**
North Ameri	4	0	3	0	1	3	3	21	0	4	31	12	10	**92**
Total	**7**	**10**	**24**	**5**	**4**	**7**	**3**	**23**	**20**	**6**	**103**	**16**	**15**	**243**

Note: * The respondents in several industry classifications and geographies were too low to develop statistically significant trends.

4.1.3 Analysis of Collected Self-Assessments

The study team performed a series of analyses on the self-assessment survey results including frequency analysis, capability score analysis, cross-tabulation analysis, and correlation analysis. From these a set of observations was generated that is discussed in the remainder of this report.

For each type of analysis performed, a comparison across geographical regions and industries was performed to identify differences.

It is important to consider the quality or validity of self-assessment data. In both self-assessments and facilitated assessments, organizations often take more credit for capabilities the first time they take an assessment. This may be because they do not want to reveal their limitations or lack of in-depth internal evaluation of their capabilities and processes. Hence, it may be assumed that the scores generated in the current study are generally higher than the actual current state. Despite these limitations, the trends shown in the overall observations and findings are valid and useful to the corrosion management and engineering community. In addition, the low number of participants in certain industries and geographies limit the ability to develop statistically significant trends.

4.1.3.1 Frequency Analysis

Frequency analysis looked at the distribution of answers for each question in the survey. From this it provided a snapshot of the global capability and also regional and industry comparisons. In the example provided in Table 4-5, approximately 90% of organizations link their corrosion management strategy to their organization’s strategy, but only 23% do this comprehensively for both technical and business requirements.

Table 4-5. Example of Frequency Analysis

Question	Answer	Frequency (all)	Percentage (all)
5. Is your corrosion management strategy linked to your organization's overall strategy?	No	28	10
	Yes, but to technical requirements only	130	49
	Yes, but to business performance only	15	6
	Yes, comprehensively	62	23

4.1.3.2 Capability Score Analysis

Each answer option in the survey was assigned a capability score to allow calculation of a comparison score by participating organization, region, and industry. The scores reflect the successively higher levels of capability or proficiency based on answers selected. From this a set of heat maps (e.g., Figure 4-2) and radar plots (e.g., Figure 4-3) were generated to depict areas where more advanced capabilities and proficiencies exist. Scores for each CMPM practice range from 0 to 1, with 0 reflecting no capability and 1 reflecting the highest level of capability based upon the provided answer options. Figure 4-2 (heat map) provides question number, general area of question, and score for all questions in each management system element for each life-cycle category. Color provided with the score is green (high score), yellow (medium score), and red (low score). The heat map has a significant amount of data, but is hard to read except at a high level (green is good and red is bad). Figure 4-3 (radar plot) shows only the score for each management system element. These graphs have less data than the heat maps, but are easier to view, especially when comparing multiple data sets (up to five data sets are compared in graphs in Sections 4 and 5). The heat map in Figure 4-2 provides an aggregate score for each question for all respondents. It indicates that abandonment is the weakest of the life-cycle phases, while managing and developing resources and good performance measures are the weakest CMS domains. Strengths for the aggregate of all respondents include integration into business processes, continuous improvement, and communication. Except for the life-cycle phases (not included as a breakdown), Figure 4-3 provides the same conclusions as discerned from Figure 4-2. In Figure 4-2 aggregate scores for each management system domain is given. In the remainder of the report, radar graphs are used to present data.

	Management System Element								
	Policy	Stakeholder	Organization	Accountability	Resources	Communicati	CMP Integration	Continuous	Performance
Entire Lifecycle	2 Policy 0.4	5 Strategy Linkage 0.5	11 Respons. Linkage 0.5	15 Roles & Res. Defined 0.6	22 Staff. Lvl Identified ##	29 Comm. Import. CM Prac. ##	35 Process Defined 0.6	40 Improvemen t Identified ##	1 Lowest Total Cost 0.4
	4 Strategy 0.5	6 Plan Linkage 0.5	12 Interactions 0.5	16 Roles & Res. Document. 0.3	23 Staff. Lvl Budget ##	30 Vertical Comm. ##	36 Process Documented 0.6	41 Improvemen t Funded & Staffed ##	1a Measure Cost 0.4
		9 Standards Compliance 0.6	13 CM Group Supporting 0.4	17 Roles & Res. Communic. 0.6	24 Competen. Defined ##	31 Comm. b/n Groups ##	37 Process Communic. 0.6	42 Org. Mgmt of Change Process. ##	7 Perf. Monitored & Reported 0.3
		10 Standards Non-Compliance 0.4	14 Managing Supp./Vend 0.5	18 Roles & Res. Integrated 0.5	25 Assignment of Prof. ##	32 Capturing Lessons Learned ##	38 Process Aligned & Embedded 0.4	43 Compliance w/ Org MOC ##	8 Perf. Metric Integration 0.4
				19 Org. Understand. 0.4	26 Competen. - Work Proc. ##	33 KPIs ##	39 Process Incl. Risk Mgmt 0.7		44 Perf. Measure Tracking 0.4
				20 Lead. Eng. & Owner. 0.6	27 CM Training ##	34 Comm. Ext. Stakehold. ##			
				21 P.O.C for Ext. Stake. 0.4	28 Mech. Transfer Know. ##				
Design	45 Strategy Addresses 0.4	46 CM Plan Design 0.5	48 Prof. Interaction 0.4	49 Prof. Involv. Supp/Vend 0.5		52 CM Plan Address Ext. Stakehold. ##	53 Design System & Solutions 0.6		
		47 CM Plan Integration 0.4		50 Prof. Supp/Vend Ovrsight 0.4			54 Supp/Vend. Reviewed 0.6		
				51 Design Approval Acct. 0.6			55 Econ. / Cost Effect. Design 0.6		
Manufacturing / Construction	56 Strategy Addresses 0.4	57 CM Plan Manufact. 0.3	59 Prof. Interaction 0.3	60 Commiss. Approval Acct. 0.5			61 CC Practices Awareness 0.5		
		58 CM Plan Integration 0.3							
Operations / Maintenance	62 Strategy Addresses 0.4	63 CM Plan Operations 0.5	65 Prof. Interaction 0.4	66 Maint. Acct. 0.4			67 CC Practices Applied 0.6	69 Reliance on Indus. Stand. ##	
		64 CM Plan Integration 0.4					68 Supp/Vend Audit 0.4		
ADM	70 Strategy Addresses 0.2	71 CM Plan Abandon. 0.4	73 Prof. Interaction 0.3	74 ADM Prep Acct. 0.4			75 CC Practices Applied 0.5		
		72 CM Plan Integration 0.3					76 Supp/Vend Audit 0.5		

Figure 4-2. Example of Capability Heat Map (Aggregate Score for All Participants)

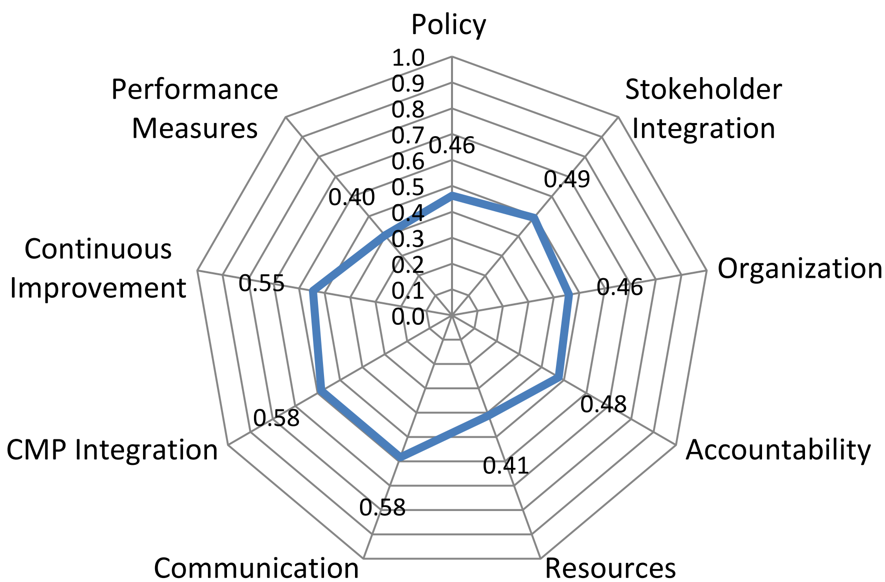


Figure 4-3. Example of Radar Plot or Spider Diagram (Aggregate Score for All Participants)

4.1.3.3 Cross Tabulation and Correlation Analysis

Cross tabulation and correlation analysis took the trends and patterns from both the frequency and capability score analyses and looked for alignment. Insights gathered during the regional focus group discussions were also incorporated.

During these analyses the study team looked at different filtered views of the data set to gain additional insights. For instance, the top 10 scoring organizations were compared to all other organizations to identify any significant variances and evaluate why they exist.

A set of observations was developed and evaluated, resulting in key study findings. These are discussed in the remainder of this section.

4.2 Regional Focus Group Discussions

Concurrent with the surveys, focus group discussions were held in selected parts of the world. These focus group meetings were held to gain further insight into corrosion management philosophies and practices of targeted industries or industry groups. The primary goal of the focus group meetings was to understand identified gaps that exist in specific industry segments. The focus group meetings were held in:

- The Middle East (Oil and Gas).
    - NOCs in Saudi Arabia and Abu Dhabi.

- India (Chemical, Oil and Gas, and Pipelines).
    - Mumbai and New Delhi.
- China (Shipbuilding and Marine Ports).
    - Shanghai.
- Malaysia (Oil and Gas).
    - NOC.
- U.S.A. (municipal drinking water).
    - Los Angeles, California.

The focus group discussions were moderated by NACE International following similar survey protocols.

The focus group meetings were basically conducted in the form of an open forum discussion about a specific organization's corrosion management approach. The objective was to provide a forum for talking about the daily realities of corrosion management and engineering within their organizations, and identify any potential best practices in place. The focus group discussions were guided by an outline developed by the study project team (see Table 4-6) and conducted by NACE staff.

Table 4-6. Focus Group Discussion Guide

Focus Group Discussion Guide
1. CORROSION MANAGEMENT OVERVIEW
• Where corrosion management exists within your organization
• A history of your corrosion management practices and how they have evolved
• How corrosion management objectives and measures are established
• How you forecast, measure, and control the cost of corrosion
2. CORROSION MANAGEMENT PRACTICES
• What corrosion management standards, processes, guidelines, systems, and tools exist
• How compliance to the items above is managed
• How corrosion management interacts with other disciplines (risk management, quality management, audit/compliance)
• The role of corrosion management with suppliers and vendors
• Determination of return on investment (ROI) for corrosion management practices
3. CORROSION MANAGEMENT COMPETENCIES
• Identification, documentation, and communication of corrosion engineering competencies
• Identification and funding of required corrosion engineering staff
• Education, training, and career development of corrosion professionals within your organization
• How experience and knowledge are shared between corrosion professionals
4. LESSONS LEARNED AND ADVICE
• Strengths and weaknesses of corrosion management program
• Lessons learned from corrosion management
• The future of corrosion management within your organization

Observations and insights from the focus groups were compiled and incorporated with the self-assessment survey analysis.

4.3 Survey Results

Table 4-4 shows the responses by geography and industry. The responses by geography showed North America (U.S., Canada, and Mexico) and Asia (India, China, and Malaysia) had the most respondents, with 91 and 133, respectively. Europe and the Middle East had only two respondents each.

With 99 respondents, the petroleum/oil/gas industry had the most returns with the remaining industries ranging from four to 24. The ability to make statistically significant statements concerning corrosion management practices based on geographies and industries is limited by the number of responses received. Nevertheless, geography and industry practices were compared based on the available data. Because benchmarking is key for companies comparing practices among geographies, industries, and peers, the benchmarking capability from this study will continue. It will be possible for companies to perform a corrosion management self-assessment for the first time or perform a re-assessment of their practices through a continuing program sponsored by NACE International.

4.3.1 General Observations

The response to one of the initial questions, whether a specific organization has a corrosion management strategy, is shown in Figure 4-4 (recall that the number of respondents is low for some geographies [Table 4-4]). The figure shows the responses according to geography. The graph shows that only a low percentage of the survey participants responded with having no strategy. The majority however, limit corrosion management to technical requirements only with the Middle East companies scoring 100%. The percentage of companies claiming to have a comprehensive corrosion management strategy is relatively low; only Asian, Australian and North American respondents indicated that they have a comprehensive corrosion management strategy. By far the majority of respondents indicated that their organization's CMP is limited to technical aspects only. This would indicate that most CMPs are not integrated throughout an organization's overall management system.

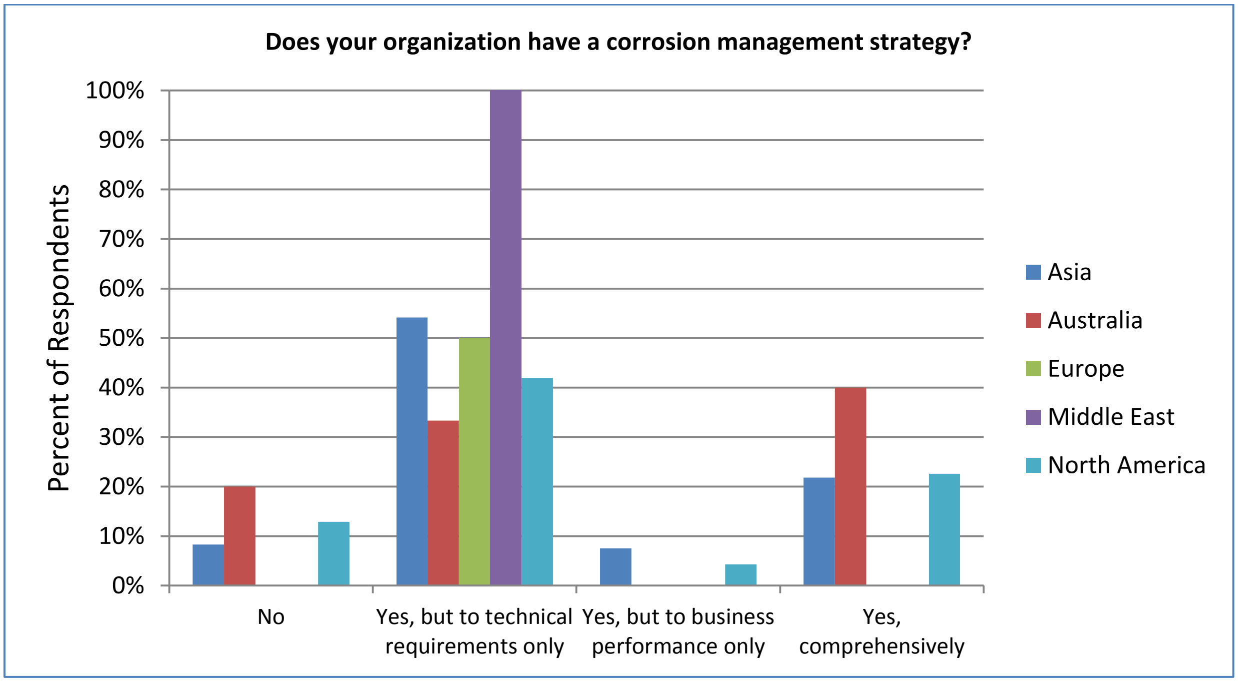


Figure 4-4. Corrosion Management Strategies

For the three geographical regions shown in Figure 4-5, there is a link between (i) corrosion management strategy integrated into the organizational strategy and (ii) corrosion management performance integrated into organizational performance metrics (both relatively high for these regions). The link between integration of corrosion management strategies and corrosion management performance into the overall organization is obvious. This says that strategies and performance should be linked. Certainly this must be true for a robust CMS.

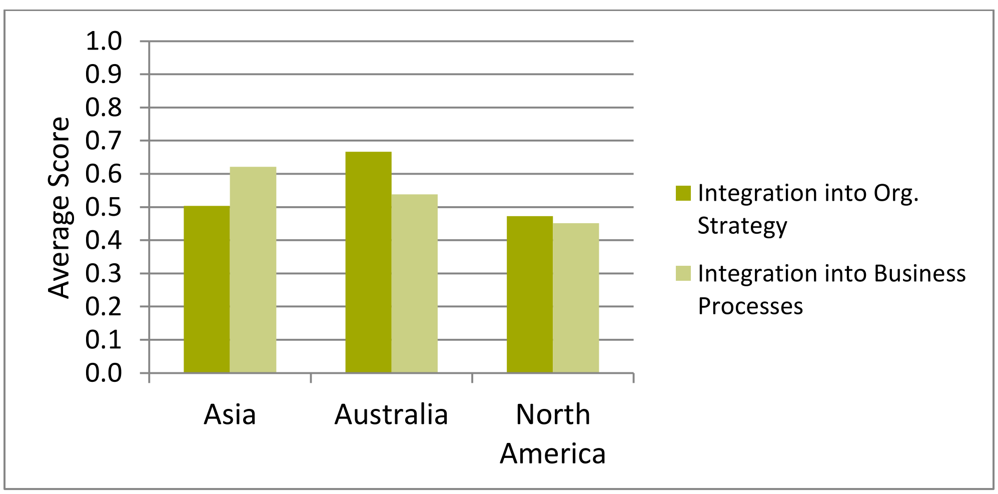


Figure 4-5. Corrosion Management Strategies and Performance for Three Geographic Regions

Figure 4-6 shows the average total scores by industry. The highest possible score was 76. The figure indicates that the industries with the highest scores were (i) petroleum/oil/gas, (ii) pipelines, (iii) airlines, logistics, transportation, and (iv) chemicals. These industries scored approximately 40 or just over 50% of the total possible score. Figure 4-7 shows the average total scores by geography. Asia and Australia had the highest average scores (40 and 38, respectively) of the five geographies examined. In reviewing these data it must be recalled that certain industries and geographical regions had limited participation and the scores may not represent entire industries or regions (Table 4-4). Europe and the Middle East had only two respondents to the survey.

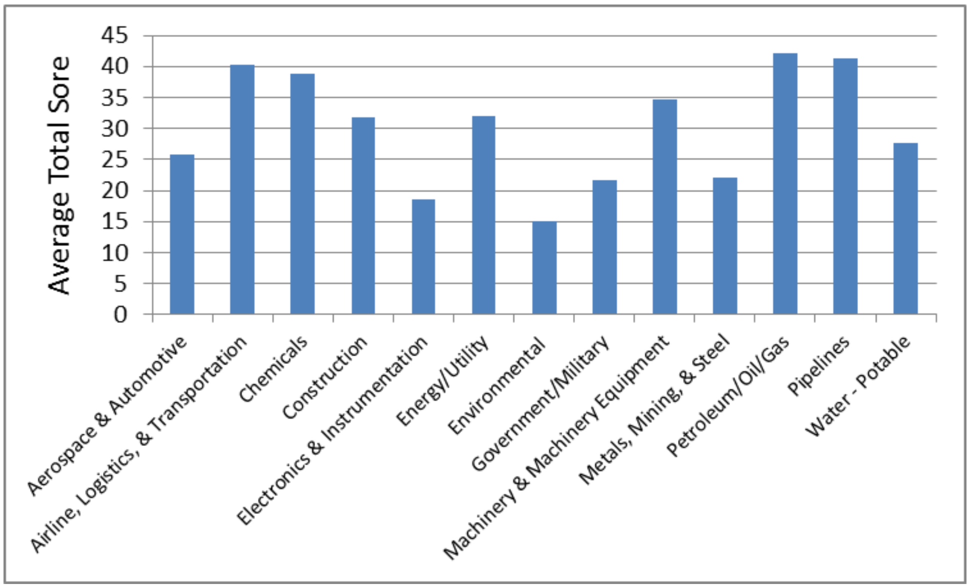


Figure 4-6. Total Survey Scores by Industry

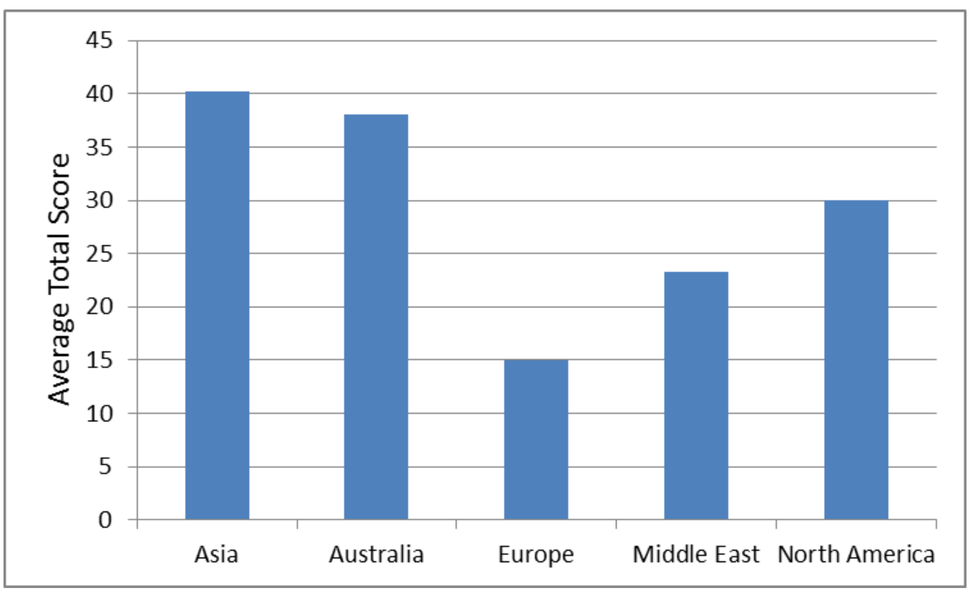


Figure 4-7. Total Survey Scores by Geography

The petroleum/oil/gas and pipeline industries scored the highest in continuous improvement but stated that their CMS could use improvement to better understand the cost of corrosion (Figure 4-8). Continuous improvement activities ensure that an organization recognizes that there is an ability to improve. While petroleum/oil/gas and pipeline industries were top performers in continuous improvement practices, the recognition that more could be done shows that corrosion management in these industries is still developing. Moreover, in order to truly understand the costs, these industries understand that there is a necessity for improvement.

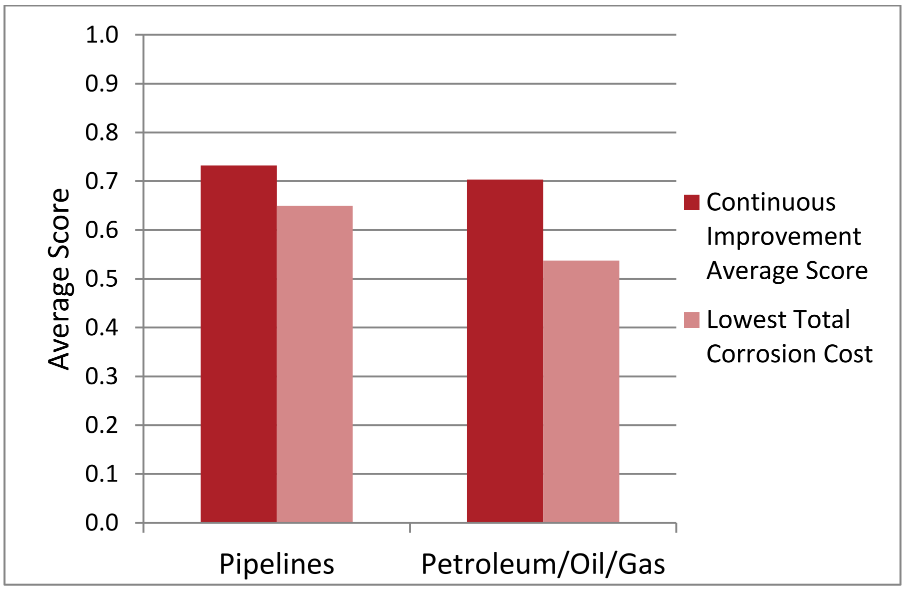


Figure 4-8. Continuous Improvement and Need to have Better Understanding to Achieve Lowest Total Corrosion Cost for Pipeline and Petroleum/Oil/Gas Industries

Figure 4-9 shows the average scoring by geography. It should be noted that Asia, Australia, and North America show similar scores and trends, while the Middle East and Europe responses generally deviate from this pattern (recall that there are only two respondents for each of these geographies). All geographies show low scoring for performance measures. This would indicate that regardless of whether a CMS is in place, there is little measure of the effectiveness of the program.

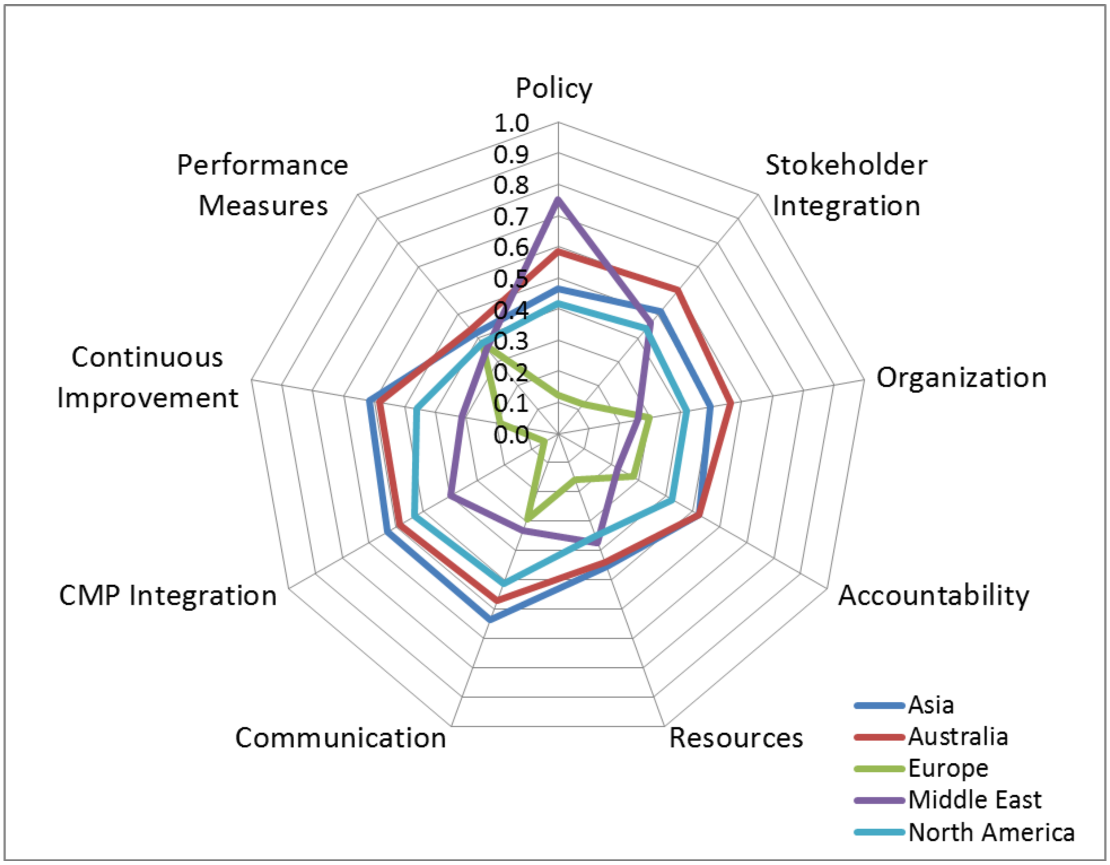


Figure 4-9. Radar Plot Showing Average Scoring by Geography

4.3.2 Practices of the Top Performers in the Survey

The top performers based on the survey were those companies that had the top total average scores. From these top performers, common themes were extracted from the survey questions and identified as the "best practices" for CMSs based on the self-assessment surveys. Typical drivers for a company to implement a CMS would include financial impact, environmental risks, safety issues, regulations, failures, public awareness, etc. Regardless of the motivation, it is obvious that corrosion issues have worked their way into the awareness of senior management in these top-performing organizations, such that critical aspects of a CMS are in place.

Top performers in the survey had several aspects of their corrosion program in common. The following are critical to a successful CMS. First and foremost, (i) corrosion management policy is integrated with the organization's policy, (ii) CMS is available for the entire organization and linked to the organization's strategy, and (iii) organizational leadership is actively involved in corrosion management. In addition, (i) corrosion management processes are well-defined, well-documented, and well-communicated and (ii) corrosion management roles and responsibilities are defined, documented, communicated, integrated into work processes, and understood across the organization.

The primary corrosion-related performance metrics of the top performers in the survey are regularly evaluated, monitored and reported to all management levels, and instances of noncompliance are resolved by organization-wide management. This is a weak area for many of the other survey respondents.

A critical common aspect of the top performers is that corrosion management is an integral part of a formal MOC process; (i) improvements are identified, assessed, and prioritized, (ii) improvements comply with their organizational MOC practices, and (iii) improvements are funded, staffed, and measured for intended results. This observation clearly shows that the top-performing organizations evaluate and improve their corrosion management practices as an integral part of operations. This is important, as a change in the corrosion management practices often has a significant impact on how the organization designs, constructs, operates, or retires an asset impacted by corrosion. Lessons learned (near misses, failures, inspection reports, etc.) are important to formally institutionalize, such that the information is available to those involved in capital projects, operations, as well as top decision makers. This is only possible through a robust MOC process. Closely related is the importance of institutionalizing various forms of knowledge transfer processes in order to allow corrosion competencies to be disseminated.

Corrosion engineers have long discussed the importance of designing for corrosion and the lost opportunities for corrosion quality management during construction. The top performers identified in the survey were nearly twice as likely to measure the cost of corrosion in the design and manufacturing/construction phases.

Other aspects that were common to top performers based on the survey were:

- Corrosion management interactions are reflected in the organization structure.
- A Corrosion management group exists that supports the entire organization.
- The cost of corrosion is measured in design and manufacturing/construction phases.
- Corrosion management competencies are defined as part of a career path for corrosion professionals and training is provided for both internal and external resources.

Further details of top performer practices are discussed below.

- The top 10 performers identified in the survey either had a corrosion management policy for at least part of the organization or the entire organization and asset life cycle.
- The top 10 performers identified in the survey were over three to five times as likely to have both (i) a corrosion management strategy for the entire organization and an asset life cycle and (ii) a comprehensive corrosion management strategy linked to their organizational strategy (Figure 4-10).

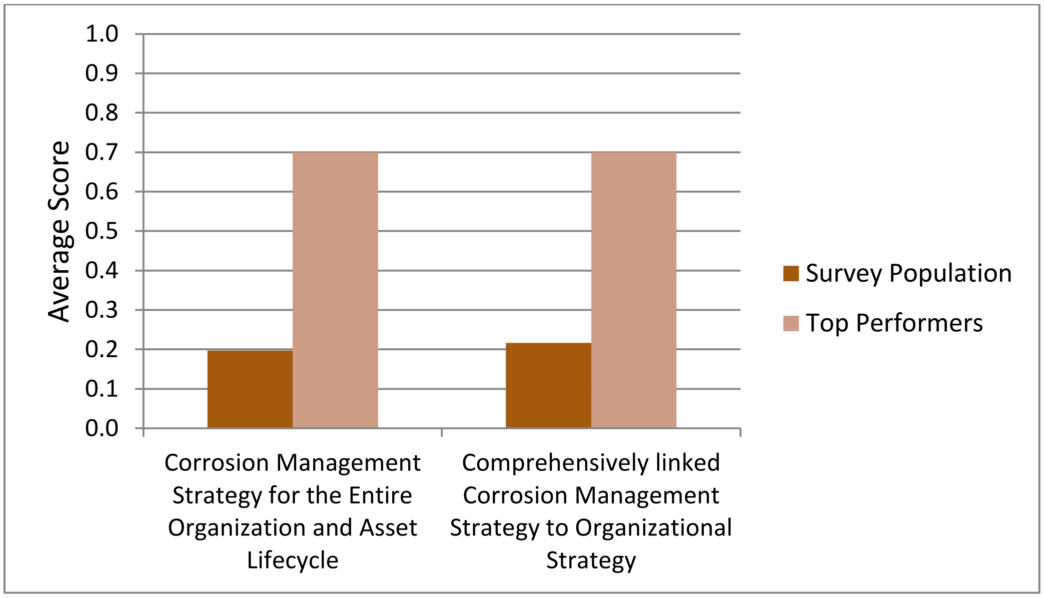


Figure 4-10. Linking Corrosion Management Strategy with Organizational Strategy

- All of the top 10 performers have corrosion management processes that are well-defined, well-documented, and well-communicated.
- The top 10 performers identified in the survey were three to five times more likely to have corrosion management roles and responsibilities (i) defined, (ii) documented, (iii) communicated, (iv) integrated into work processes and (v) understood across the organization (Figure 4-11).

  All (100%) of the top performers had well-defined roles and responsibilities related to corrosion management. Furthermore, all of the top performers communicated and integrated these roles and responsibilities throughout the organization. This is clearly one of the primary principles of a best practice CMS.

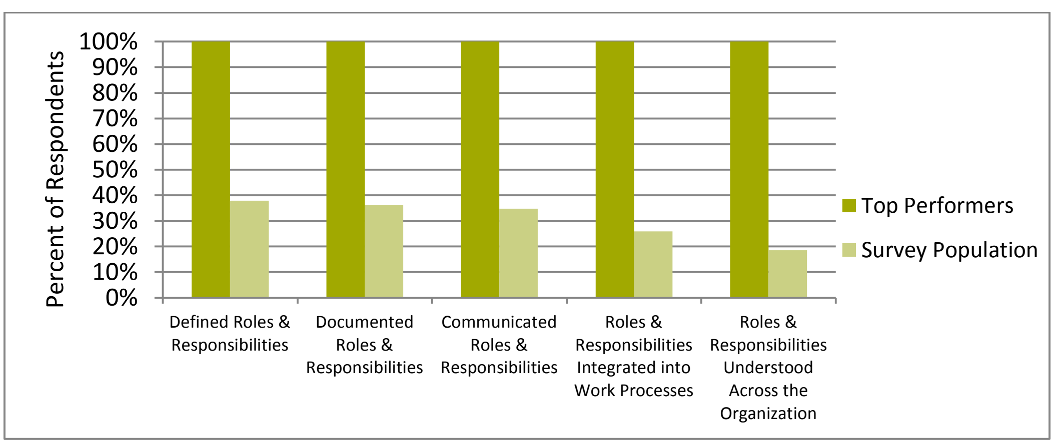


Figure 4-11. Roles and Responsibilities in Corrosion Management

- The top 10 performers identified in the survey had corrosion management interactions reflected in the organization structure (Figure 4-12). For a CMS to be effective, integration into the overall organization and management system is critical. In addition, nine of the top 10 performers indicated that organizational leadership is actively involved in corrosion management.

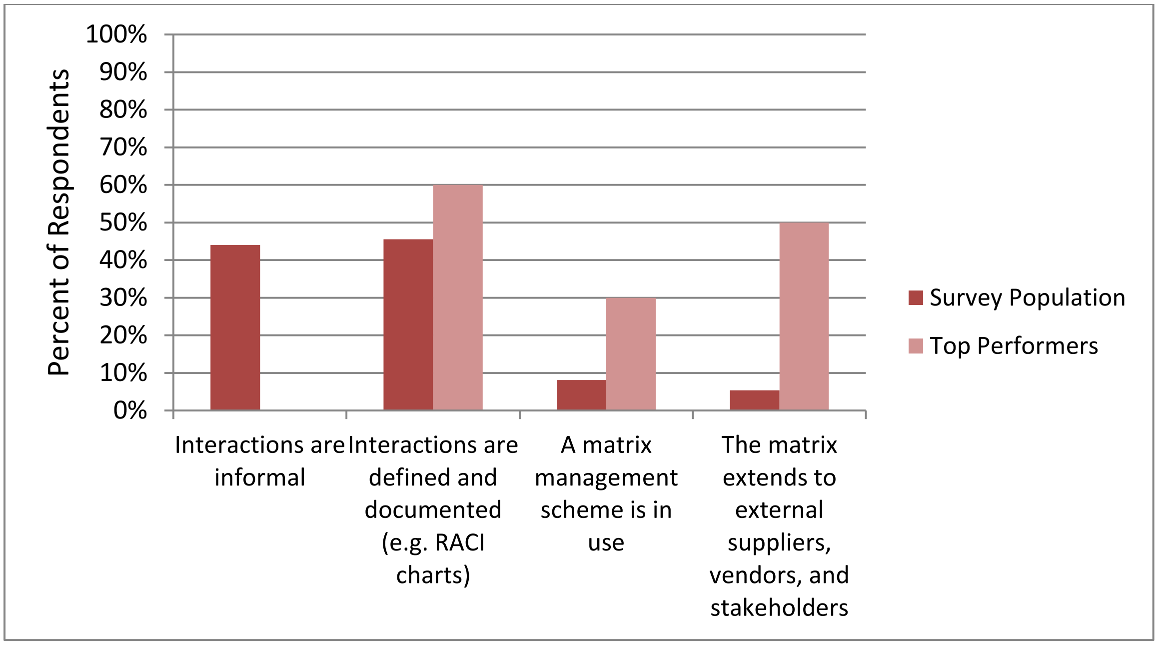


Figure 4-12. Corrosion Management Interactions are Integrated into the Organizational Structure

- The top 10 performers identified in the survey were nearly seven times more likely to have a corrosion management group that supports the entire organization (Figure 4-13).

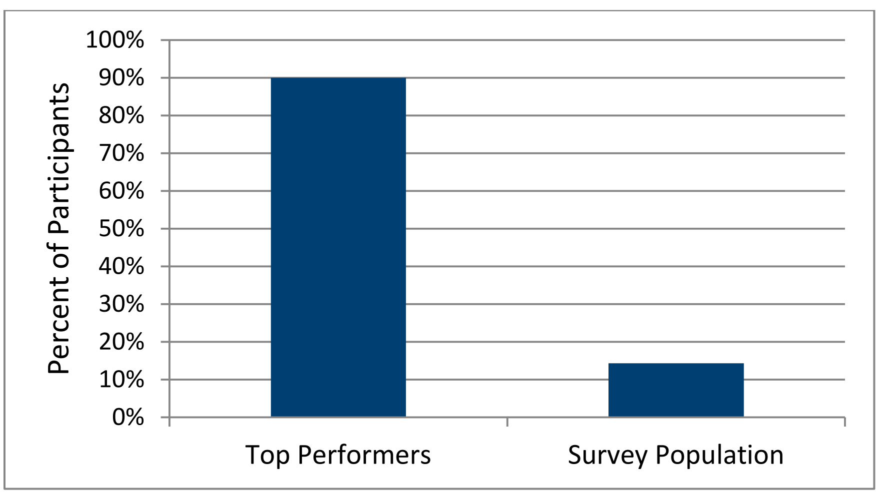


Figure 4-13. Existence of a Corrosion Management Team to Support Entire Organization

- The top 10 performers identified in the survey were nearly twice as likely to measure the cost of corrosion in the design and manufacturing/construction phases (see Figure 4-14). Proper consideration to corrosion management in design and manufacturing/construction phases can significantly decrease operation and maintenance cost over the life of the many assets. Often, the primary cause of failures or operating problems resulting in unscheduled maintenance and lost production has its roots in design-related inadequacies concerning corrosion issues or quality management during construction.

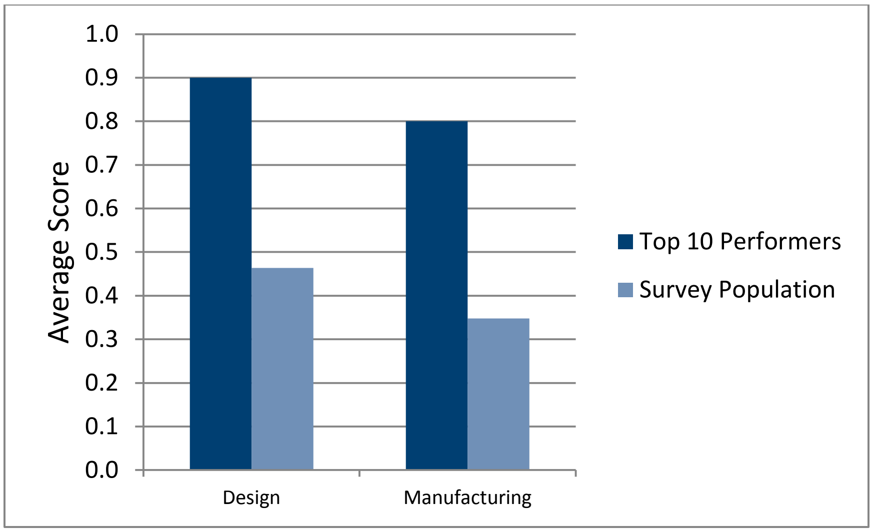


Figure 4-14. Measure Cost of Corrosion for Design and Manufacturing/ Construction Phases

- The top 10 performers identified in the survey were between 12 and 44% more likely to evaluate a given performance metric (Figure 4-15).
- The top 10 performers identified in the survey were nearly six times more likely to have their performance monitored and reported to all management levels and have instances of noncompliance resolved by organization-wide management (Figure 4-16).

  Given the impact of corrosion on assets, having noncompliance and performances monitored by the leadership of the organization allows for the leadership to address these issues and create the necessary change to have impact on the corrosion management practices.

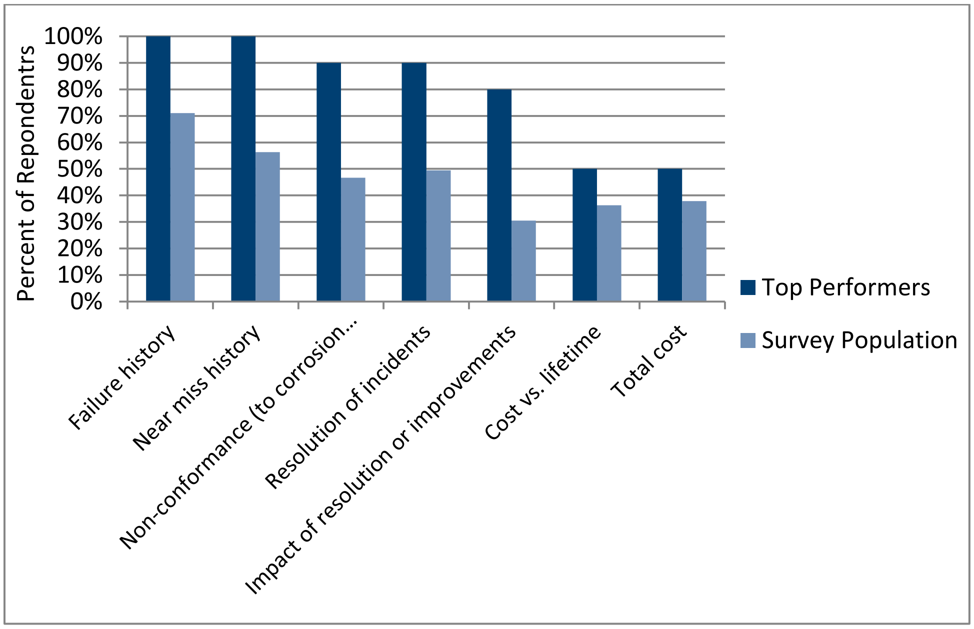


Figure 4-15. Corrosion Management Performance Metrics

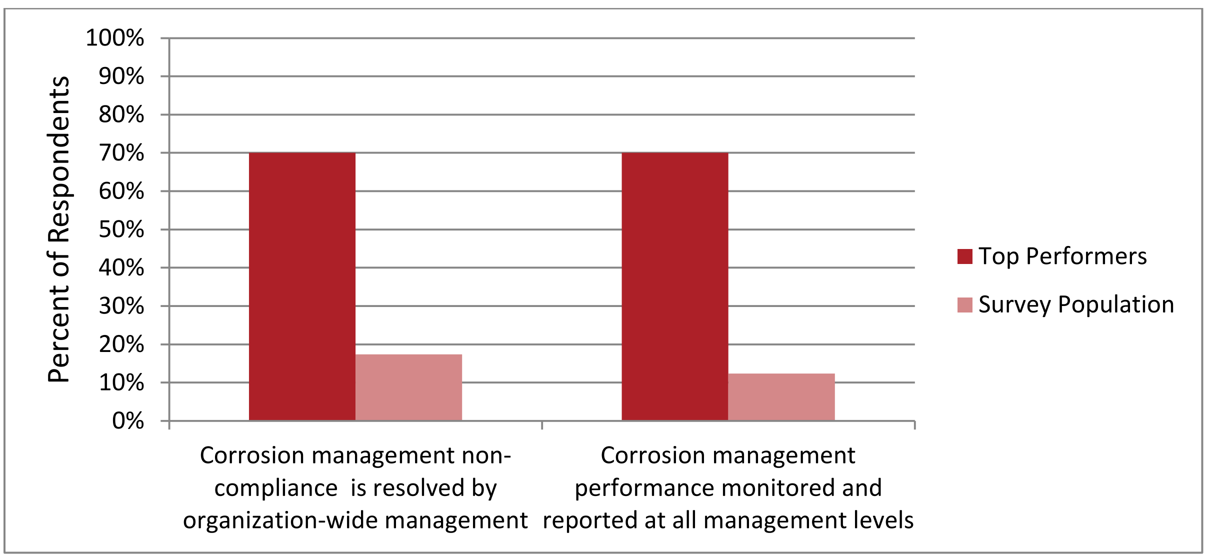


Figure 4-16. Noncompliance and Performance Monitoring

- The top 10 performers identified in the survey were between two and three times more likely to have corrosion management (i) as part of a formal MOC process, (ii) improvements identified, assessed, and prioritized, (iii) in compliance with their organizational MOC practices, and (iv) improvements funded, staffed, and measured for intended results (Figure 4-17).

  This observation clearly shows that the top-performing organizations evaluate and improve their corrosion management practices as an integral part of operations. This is important, as a change in the corrosion management practices could have a significant impact on how the organization designs, constructs, operates, or retires an asset impacted by corrosion.

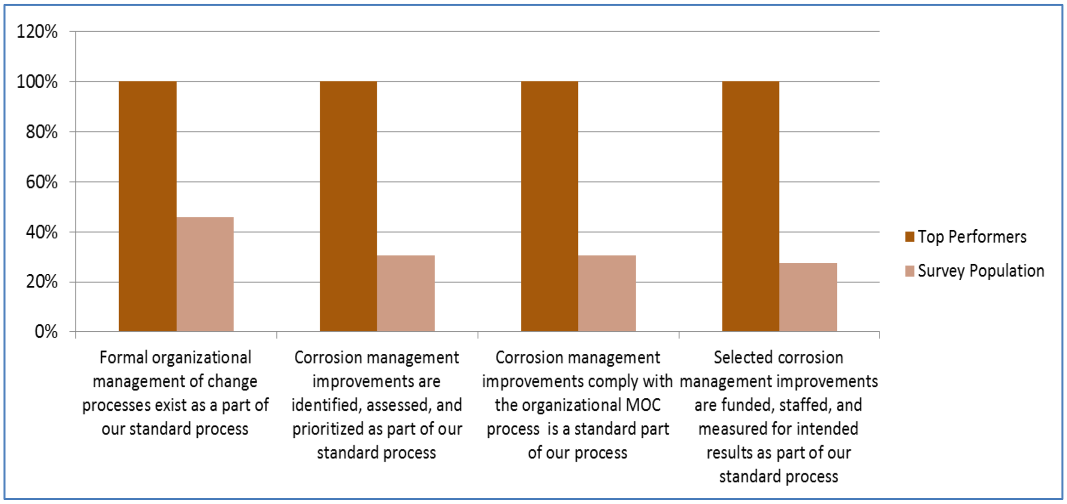


Figure 4-17. Corrosion Management Improvements and Change Management

- The top 10 performers identified in the survey were nearly six times more likely to have competencies defined as part of a career path for corrosion professionals (Figure 4-18). In addition, nine of the top 10 performers indicated that corrosion management and technical training is provided for both internal and external resources.

  In general, it is difficult to find corrosion professionals who are skilled in managing and implementing corrosion practices. There are very few university engineering programs that provide a corrosion engineering degree. Top performers have developed career paths with identified competencies that allow corrosion professionals to maximize the benefits of a robust CMS. Organizations should establish corrosion management career paths with clearly defined competencies.

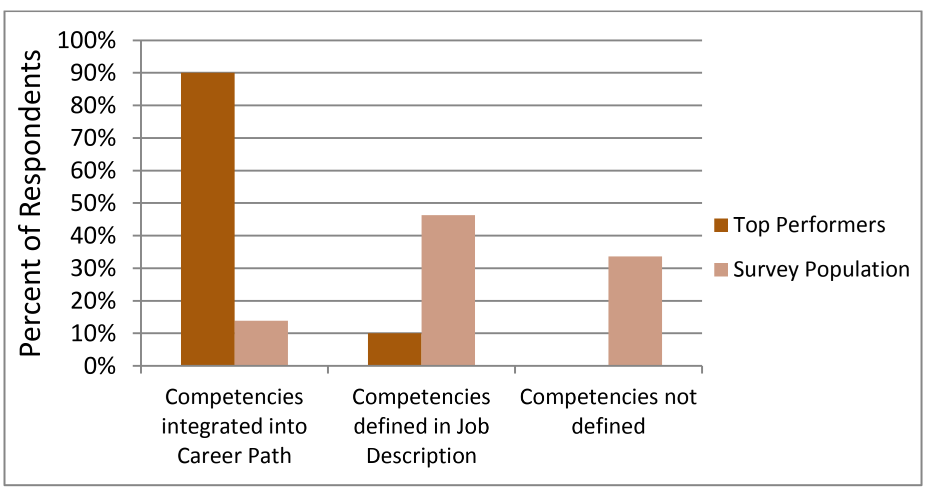


Figure 4-18. Corrosion Management Competencies

- The top 10 performers identified in the survey were more likely to use various forms of knowledge transfer mechanisms in order to allow corrosion management competencies to be disseminated. In addition, nine of the top 10 performers had a budget allocated to training, conference attendance, and certifications (Figure 4-19).

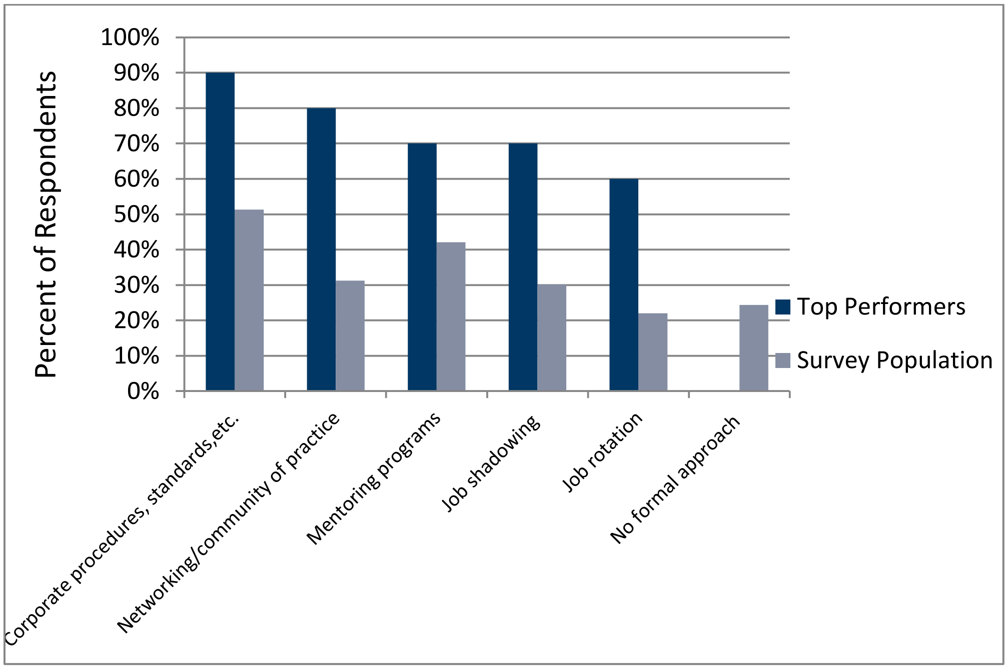


Figure 4-19. Corrosion Management Knowledge Transfer

4.3.3 Performance Gaps Determined by the Survey Results

Many of the common practices of the top performers become gaps for the majority of organizations. In addition, the surveys also indicated where consistently low scores were recorded. These areas establish the performance gaps in a CMS. The following are considered performance gaps based on the self-assessment surveys.

- Only 14% of participants believe that their CMS is robust. This leaves room for significant improvements in CMSs. Seventy five percent of survey participants do not have corrosion management performance integrated into organizational performance metrics.
- Only about half of total respondents state that their asset design strategy addresses the following with respect to corrosion: regulation, HSE, the intended life of the asset, and the functional requirements.
- Most CMPs do not address abandonment, decommissioning, or mothballing (ADM). The petroleum/oil/gas and pipelines industries provide the most consideration for this phase of the asset life cycle (see Figure 4-20). ADM poses a significant organizational risk (based on the asset involved) when taking into account environmental, safety, and financial considerations.

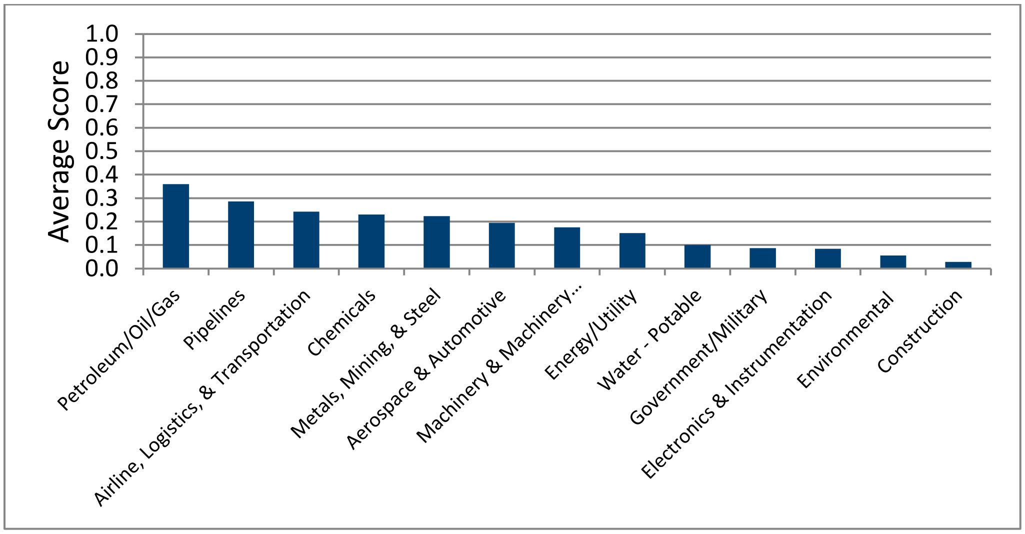


Figure 4-20. Average Scoring for Corrosion Management Addressing ADM

- Corrosion management resourcing exhibited relatively low scores across all regions indicating that resourcing was more ad-hoc than planned (see Figure 4-21). This claim is backed by a comment provided by a Chinese Survey participant:

  "[My organization] is missing the expertise to build corrosion SME teams. Non-experts cannot easily find hidden corrosion issues."

  Without adequate resources it would be difficult to implement a robust CMS.

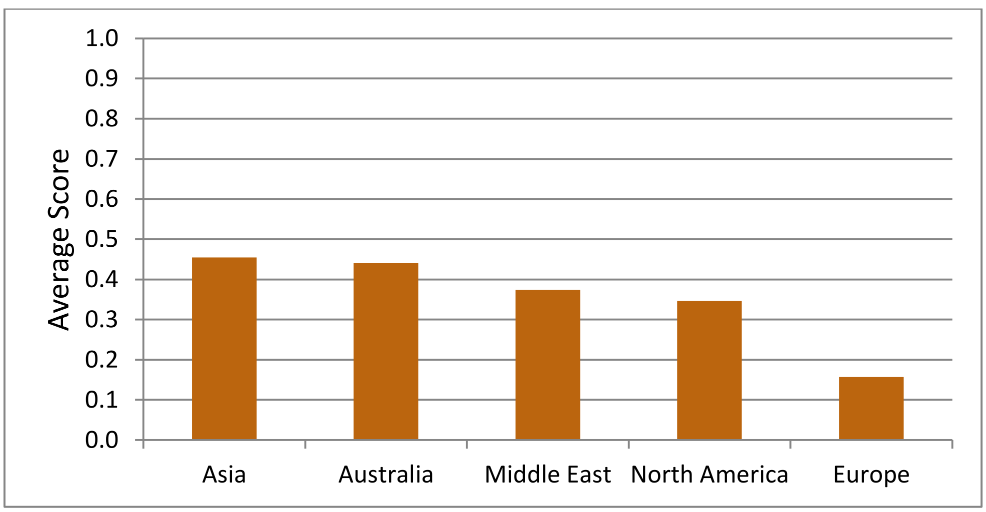


Figure 4-21. Average Score for Impact of Resources by Geography

5 ASSESSMENT OF CORROSION MANAGEMENT PRACTICES

In the following sections, corrosion management practices in various industries and organizations across the world are examined in order to assess corrosion management practices and to identify best practices as well as gaps in the approach to corrosion management.

5.1 Approach

The results of the survey as well as focus group meetings and discussions with industry SMEs have demonstrated that corrosion management practices vary significantly based on the type of industry, geography, and organizational culture. As discussed in Section 4, these practices range from absence of corrosion management to full incorporation of corrosion management into an organization's management system and practices. Even within the same organization, significant differences can exist, depending on local culture and practices.

In the following sections the corrosion management practices in various industries across the world are examined, and based on the results of the surveys, the individual and focus group meetings, and some case studies, standard and best practices are identified and discussed. Gaps in corrosion management practices are identified and mitigation measures for improvement are recommended.

The survey was sent to a broad range of industries and organizations. While the corrosion management practices could not be discussed for each industry and organization, a selection was made of industries where corrosion has a major impact on safety, environment, cost of operation, and reputation. These industry segments are:

- Oil and Gas
- Pipelines
- Drinking and Wastewater

In addition to these three industry segments, the corrosion management practices within the U.S. Department of Defense (DoD) were examined. While the U.S. DoD manages a wide range of weapon systems, it also operates an infrastructure that is very similar to that operated by other industries and organizations. As will be discussed in Section 5.1.4, the U.S. DoD has a mature CMP that serves as an example for others.

5.1.1 Oil and Gas

5.1.1.1 General

The oil and gas industry is a capital intensive industry with assets ranging from wells, risers, drilling rigs, and offshore platforms in the upstream segment, to pipelines, liquefied natural gas (LNG) terminals and refineries in the midstream and downstream segments. Corrosion has been a major cost in the operation of oil and gas facilities; hence, most oil and gas companies have some sort of corrosion control or management program, the level of which depends on size, geographic location and culture of the companies. In order to capture the differences across the oil and gas industry, corrosion management practices for international, national, intermediate, and unconventional oil and gas companies were examined.

Any oil and gas asset that is susceptible to corrosion should have a CMP to protect against the consequences of corrosion. However, in many cases the CMS is limited to corrosion engineering and corrosion control practices without the management system components. This lack of a true CMS can lead to increased risk of failure and reduced asset life due to corrosion, leading to:

- Decreased safety and increased environmental exposure.
- Higher chemical treatment, repair, and inspection.
- Increased number and duration of unplanned shutdowns.

Lack of corrosion management can also lead to an inefficient use of resources because corrosion control activities are not adequately prioritized on the basis of ROI (all costs including direct financial and safety and environmental risk). For example, a sound technical corrosion control solution might not be implemented because (i) a positive ROI does not exist or (ii) a positive ROI exists but is not communicated. When a technical solution has both a positive ROI and is justified by ROI, then the technical solution can be evaluated on equal terms to other proposed projects being considered for funding. In all cases, a robust CMS is the driver for realizing/maximizing ROI from corrosion mitigation activities.

In the oil and gas industry, the development and implementation of corrosion management varies greatly across the industry and across global regions as is demonstrated by the survey results shown in Section 4.

Benchmarking survey results shows that four groups exist across the oil and gas industry with practices ranging from no corrosion management in place to having a mature CMP that is an integral part of an organization's overall management system.

Whereas most surveyed oil and gas industry organizations claim to have a corrosion management policy, corrosion management policy and implementation differed significantly among organizations and even among a single organization's operating geographies. When there are significant policy differences within the same company, this would indicate that the corrosion management policy is not truly integrated into the organization's policy at the highest level, either deliberately or by omission.

Differences in corrosion management practices within the oil and gas industry could be caused by several factors, including the following:

- The scope of the organization, i.e. international oil companies versus NOCs, intermediate companies, and unconventional oil companies.
- Strategic national interests.
- The differences in corporate philosophy, culture, and risk tolerance.
- The effect of local regulation.
- Offshore versus onshore and geographic location; e.g., operation in the Gulf of Mexico versus the North Sea, Africa, and the Far East, etc.
- Financial position (cash flow/capital availability).

In the following sections, the corrosion management practices for international oil companies, NOCs, intermediate oil companies, and unconventional oil companies, respectively, are discussed. These discussions are based on document review, discussions with company SMEs, and industry focus groups with additional input from the survey results.

Appendix D includes a case study of a NOC that is in the process of implementing a CMS.

5.1.1.2 International Oil Companies

International oil companies (IOCs) can be defined as oil companies that are vertically integrated, operate outside of their home country, and are predominantly publicly owned. The IOCs characteristically operate in many countries, and are accordingly "international." The five or six largest companies that belong to this group of so-called "super majors" include Chevron, Exxon Mobil, Royal Dutch Shell, BP, Total, and ConocoPhillips. Ranked by volume of oil and gas reserves, only six of the top 20 upstream companies are IOCs; the remaining are NOCs. The IOCs are working in increasingly challenging environments where corrosion is one of the major threats to the integrity of their assets. With increasing water cut, increasingly high concentration of corrosive gases, and higher temperatures and pressures, internal corrosion has become a major threat to asset integrity. Hence all IOCs have a corrosion control program to mitigate the effects of both internal and external corrosion.

While the IOCs all practice corrosion control, the level of corrosion management greatly differs depending on management culture, risk tolerance, and project portfolio. The benchmarking of IOCs indeed suggests significant differences in management approach, and further in-depth examination of selected IOCs highlights some significant differences in corrosion management practices.

A comparison between two major IOCs and the aggregated oil and gas scores (all companies), shown in Figure 5-1, reveals different scoring, indicating different corrosion management approaches. Company A's survey results suggest that corrosion management is mostly regionalized. For example, in one region where regulation is strong, corrosion management has been developed and implemented, whereas in other regions with weak regulations, corrosion management is limited to the task of corrosion control, and only to the extent of meeting minimum local requirements. Company B, on the other hand, reports a strong centralized CMP that is intended to be equally implemented to all parts of the organization including all regions. However, even with a strong centralized CMP, it often turns out to be difficult to roll out and implement the program to different parts and regions of the company, often because of differences in operating practices and culture. Company B considers itself the closest to "best practices."

The conclusions from the surveys were confirmed by SMEs having experience with the surveyed companies.

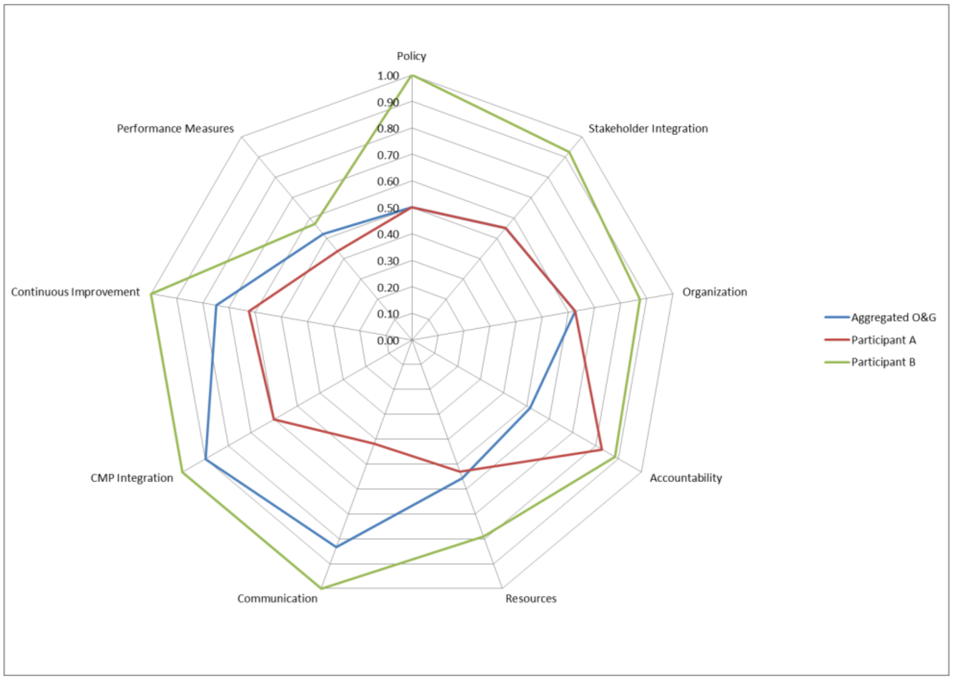


Figure 5-1. Benchmarking of Two IOCs against Aggregate Oil and Gas Scoring

5.1.1.3 National Oil Companies

Although there is confusion on how to define NOCs, a common definition is that they are predominantly owned and controlled by a single national government. Other aspects of NOCs are (i) the company has or does not have privileged access to resources in its home country and (ii) the company is or is not transparent and reports performance in accordance with regulatory requirements (e.g., U.S. Securities and Exchange Commission requirements). There can be a separation between state ownership and state control, where the government retains a minority "golden share" with substantial approval or veto rights.

Some NOCs have begun operating as multinationals, so the distinction between "national" and "international" companies has become less clear. Another way to think of the conventional NOC and IOC definitions is therefore "nation-owned oil companies" and "investor-owned oil companies," respectively. The NOCs are a hard group to define, in part because they appear in developed/centrally planned and developing countries alike. Some companies, such as Statoil, have shifted between the NOC and IOC definitions over time. They tend to have close relationships with the government of the country in which they are based, but they range from wholly controlled by the government to power centers in their own right independent of changes in a current government. For the purpose of this report, some regional oil companies that predominantly operate within a country are included in discussions with NOCs.

Finally, a number of auxiliary businesses are often associated with NOCs, including electric power generation, chemicals, minerals, and all manner of infrastructure, with some having far-flung interests in non-energy retail and commercial assets. For example, an NOC in Asia operates general grocery stores because such outlets happen to be the channel through which petroleum products are distributed in that country.

The results of the survey of three NOCs in the Middle East (A), Asia (B), and South America (C), along with the aggregate oil and gas results are shown in Figure 5-2.

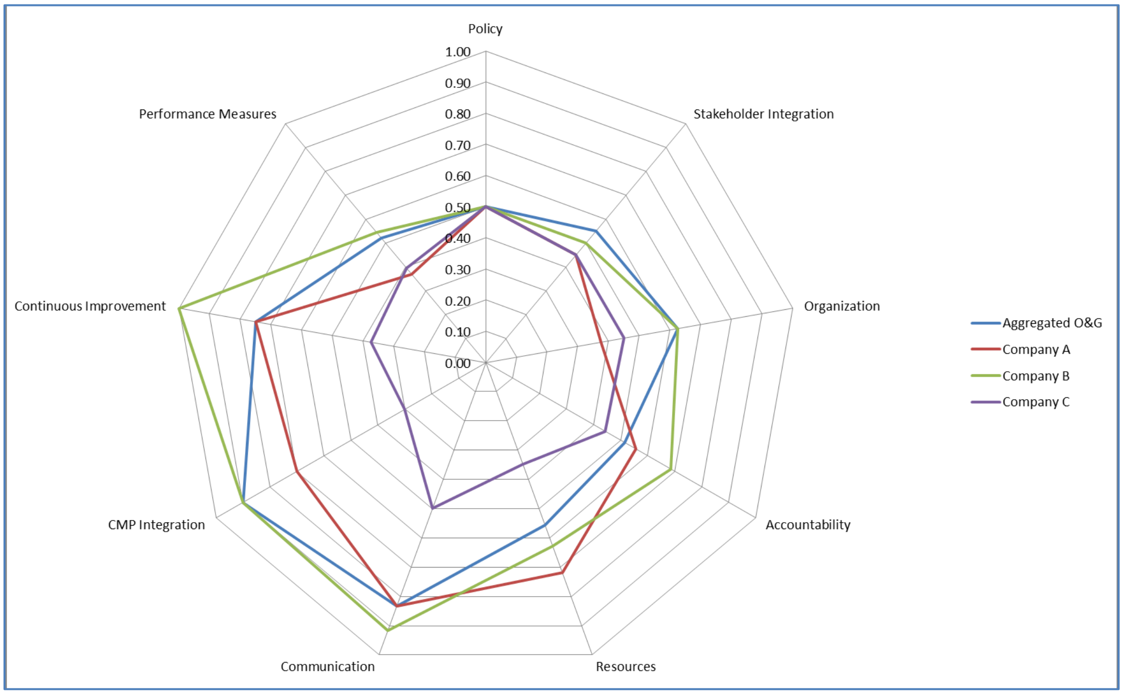


Figure 5-2. Benchmarking of Middle East (A), Asian (B) and South American (C) NOC against Aggregate Oil and Gas Scoring

Companies A and B show similar trends in the aggregated results, where the low scores are for the elements Performance Measures, Policy, Stakeholder Integration, Organization, and Accountability. Again, the low scores suggest little commitment from management to a CMP (i.e., low policy scores), and no follow-up practice as indicated by the low key performance scores.

Further examination of the companies' corrosion management practice explained some of the findings from the surveys. Without clear commitment by management to some form of corrosion management, other elements regardless of scoring are not optimized. Even with the full backing of management, effective corrosion management often does not materialize.

For example, a Middle East NOC has received the commitment of management to develop and implement a corrosion management framework. With this commitment, the company has developed a detailed and well thought-out corrosion management approach and implementation plan. However, implementation of the plan has many obstacles. The company intends to implement its CMP in two ways:

1. Corrosion management for existing facilities, where the stakeholders often do not understand the requirement or don't see the need to implement such a program.

2. Corrosion management for new construction, where the Company requires the engineering firms to include a CMP in their front end engineering design (FEED) reports. While the engineering firms try to comply with these requirements, they often don't have the right competency and hence don't know how to handle the requirements.

In this case, the link between having a CMP and implementing the plan is missing. Therefore before rolling out the plan, the company should invest time in educating its own staff in the field as well as contractors on the use of the plan and instill in them the importance of buying in to the plan.

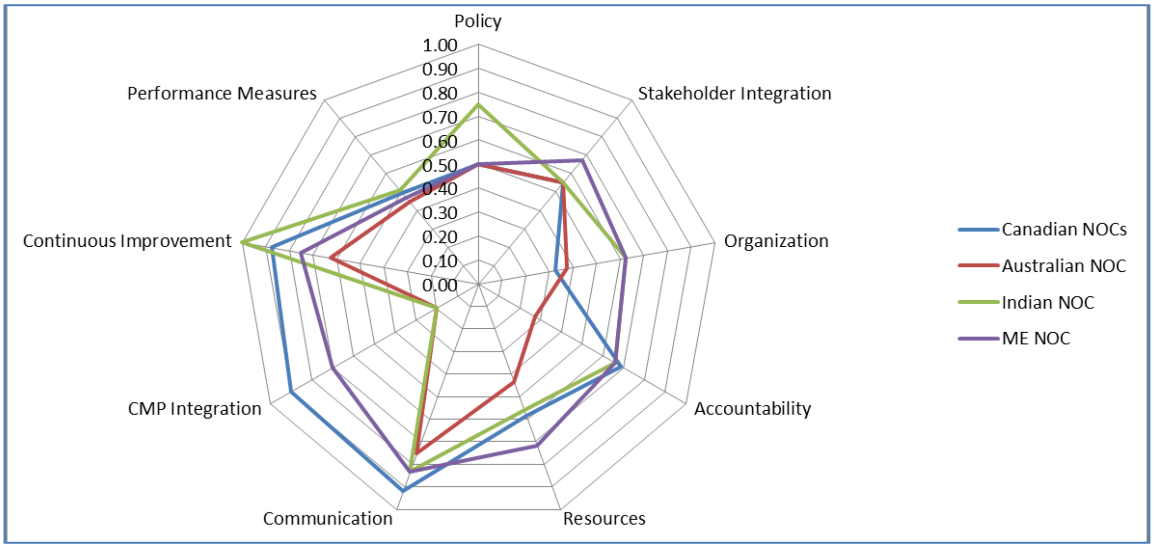


Figure 5-3. Benchmarking of NOCs and Regional Oil Companies from Four Different Geographic Regions

Figure 5-3 shows a different look of the survey results, where responses of NOCs and regional oil companies (Canada and Australia) from four different geographic regions are shown. These geographically diverse groups show similar trends for performance measures (although relatively low scores), stakeholder integration, and communication (relatively high scores). A wide scatter in results occurred for CMP integration and continuous improvement. Significant overall trends were not observed, although Middle East and Canadian oil companies trended closer than did any other combination of geographical regions.

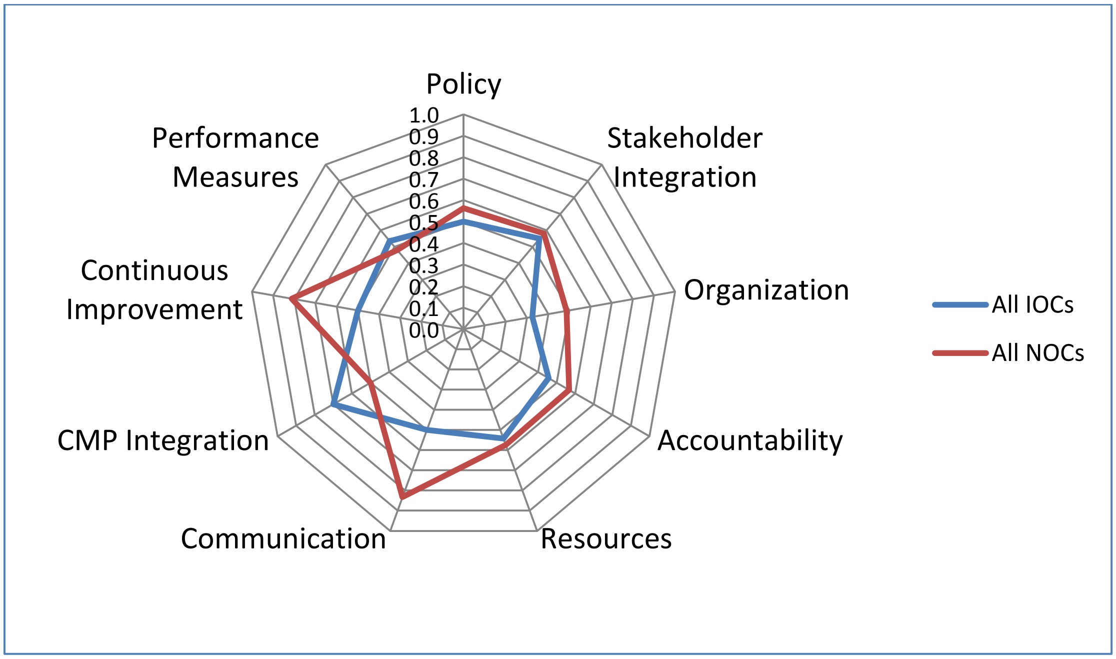


Figure 5-4. Benchmarking of all IOCs and NOCs that Responded to the Survey

When comparing all IOCs with all NOCs that responded to the survey, the resulting radar diagram in Figure 5-4 shows similar trends, with continuous improvement and communication having the most variation.

5.1.2 Pipelines

Within the pipeline industry it is well known that corrosion is a major contributing factor to pipeline failures. Pipelines carry products, including dry gas, wet gas, crude oil with entrained/emulsified water, and processed liquids.

Pipeline incidents in the U.S. and in Europe have been reported on in three major publications:

- 1995-2014 Pipeline and Hazardous Materials Safety Administration Pipeline (PHMSA) – *Pipeline Incident Data.*
- 1970-2013 European Gas pipeline Incident data Group (EGIG) – *Transmission Pipeline Incident Data.*
- 2004-2013 Transportation Safety Board (TSB) of Canada – *Pipeline Incident Data.*

The radar diagram in Figure 5-5 shows the response of selected pipeline operators in the US, Canada and India to the survey described in Section 4. The intent of creating this diagram was to observe differences in corrosion management for pipeline companies that operate under different regulatory environments. The diagram shows the scores of three groups of pipeline operators from India (three operators), Canada (four operators), and the U.S. (two operators). While the U.S. and Canadian pipeline companies operate under strict national regulations (set by PHMSA and the National Energy Board (NEB), respectively), where the majority of corrosion control activities are driven by regulations, the Indian pipeline company follows company standards and regulations, which are largely based on internal/local standards and recommended practices.

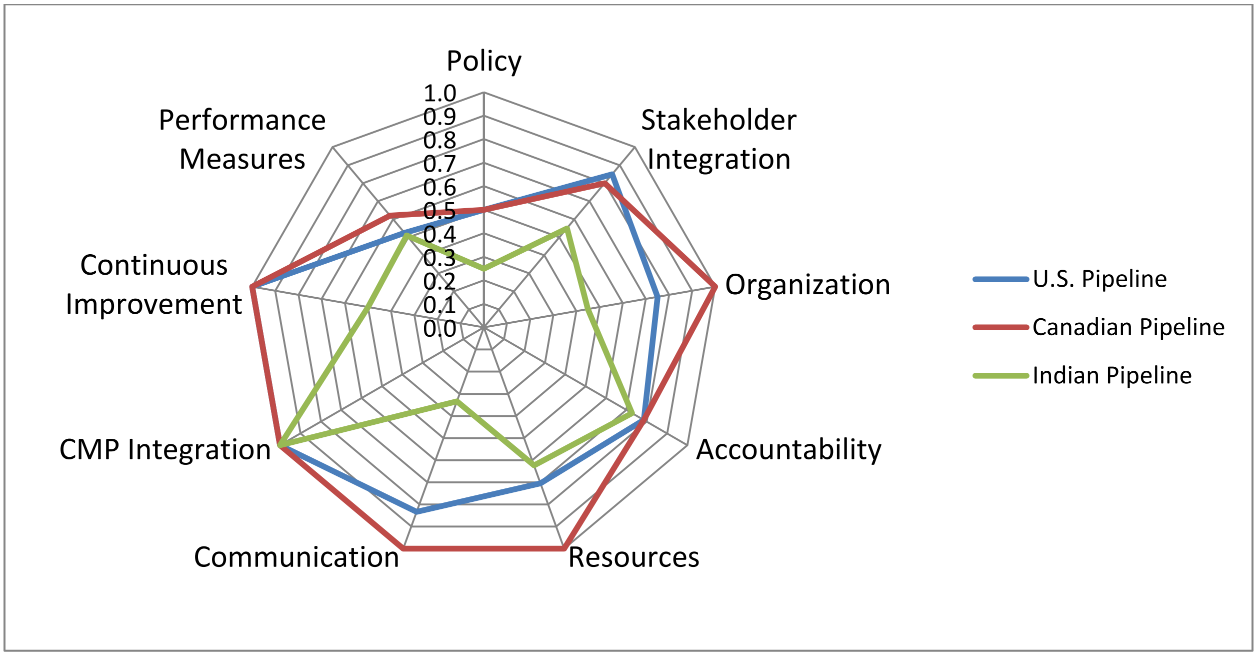


Figure 5-5. Benchmarking of U.S., Canadian, and Indian Onshore Pipeline Companies

Despite these different regulatory environments, all three pipeline groups show similar scores for the elements of performance measures, CMP integration, and accountability. All three pipeline companies show a low score for policy and performance measures, which might indicate an opportunity for improvement by better engaging senior management. Moreover, the relatively low score for performance Measures indicates that there is an inadequate feedback system or related KPIs that measure the status and quality of corrosion management. In general, the Canadian and U.S. pipeline companies exhibit similar trends and the Indian pipeline company is generally lower in scoring on many areas except as noted above.

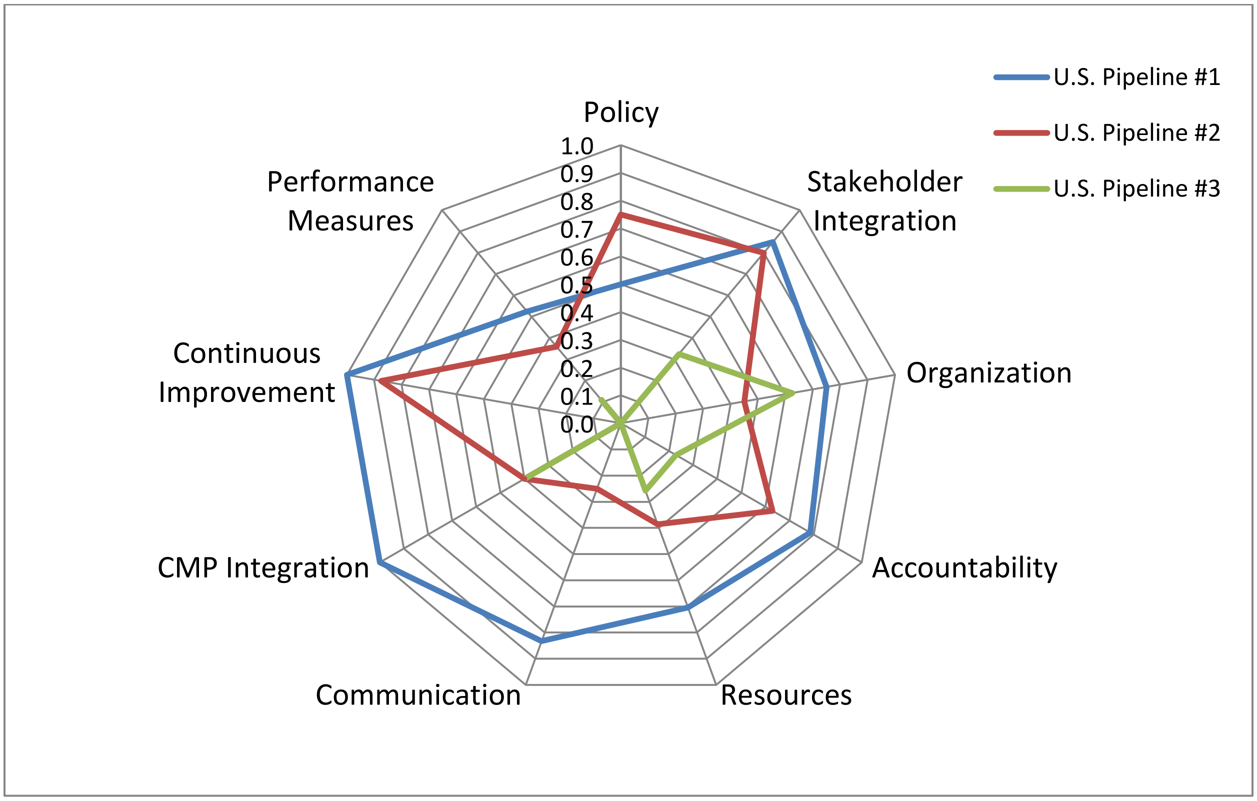


Figure 5-6. Benchmarking of Three U.S. Onshore Pipeline Companies

When the survey responses are examined at the more detailed level of individual U.S. pipeline companies (see Figure 5-6), significant differences between the companies become apparent. While Company #1 shows an overall better-than-average scoring, Company #3 scores poorly in most categories.

There is a significant varied approach to corrosion management within the U.S. pipeline companies responding to this survey. Some U.S. companies meet but do not exceed regulatory requirements; they often want to exceed the minimum but do not find an economic or other incentive with respect to corrosion management. With a fully integrated CMS, decisions on the ROI, cost benefit, or reduction in risk (whichever measure is used by an organization) would be better understood by all stakeholders, including senior management. These decisions would result in a lower risk picture for the organization, and consequently lead to (i) increased financial performance, (ii) safer pipeline operation, and (iii) fewer environmental issues.

Figure 5-6 shows a significant gap between communications from one company to another. This is the result of some companies drawing lines between responsibilities, which can create silos. As shown in the diagram, one company that scored high on communication also scored high on continuous improvement and CMP integration. The company scoring high on these three elements also has a lessons learned program.

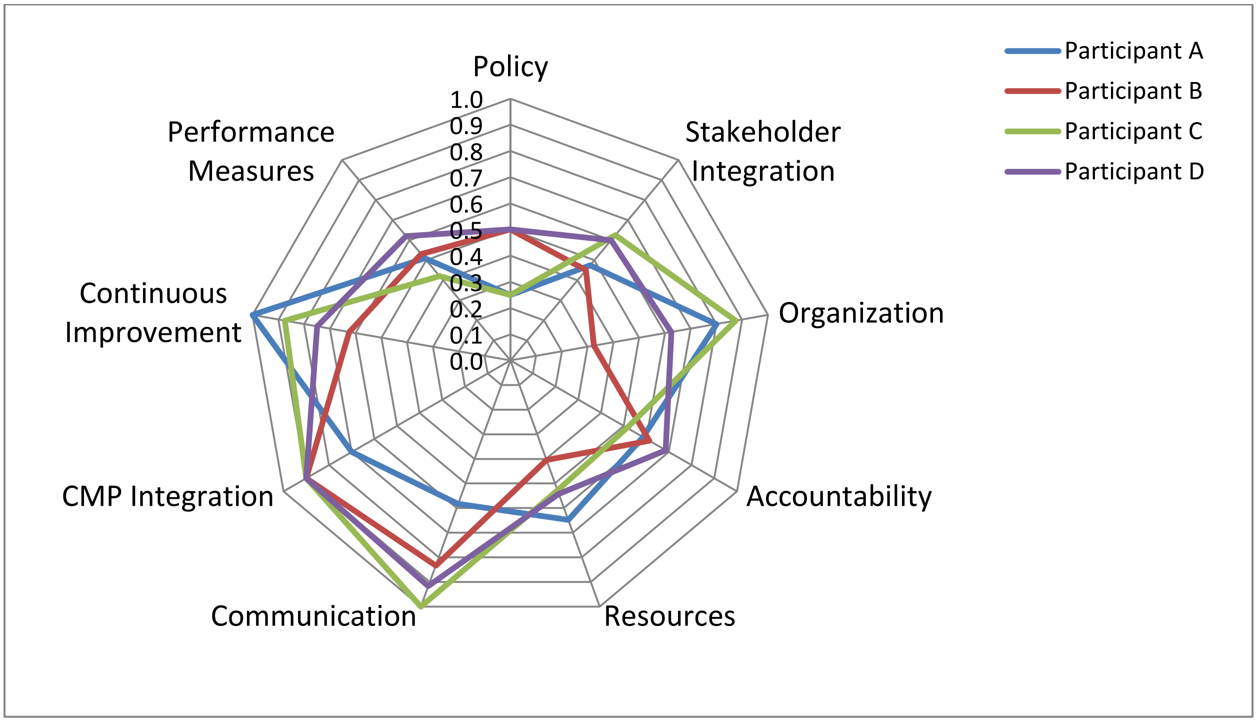


Figure 5-7. Benchmarking of Canadian-Based Onshore Pipeline Companies

Figure 5-7 shows the radar diagrams for responses from four Canadian-based pipeline companies showing trends similar to the U.S. pipeline industry. Unlike U.S. companies, Canadian pipeline companies show similar scoring with average to best scoring in the lower left quarter of the diagram; i.e., continuous improvement, CMP integration, and communication. As with the global and U.S.-specific companies, the policy, performance measures, and stakeholder integration elements scored medium to low. In addition, the accountability, and resources scores are in the mid-range of performance.

The relatively uniform response scores may be an indication that Canadian pipeline companies are all following the regulations that encourage continuous improvement, integration, and communication. However, as with the U.S. pipeline companies, the low scores for policy and performance measures indicate opportunity for improvement by better engagement of senior management.

As discussed in Section 4.3.1, a key observation from the survey was a correlation between survey respondents who indicated that their corrosion management approach (i) could use improvement to better understand the total cost of corrosion and (ii) have strong continuous improvement practices (Figure 4-8). While the pipeline industry was among the top performers in continuous improvement practices, the recognition that more could be done shows that corrosion management in these industries is still developing. Moreover, in order to truly understand the costs, these industries understand that there is still opportunity for improvement.

5.1.3 Drinking Water and Sewer Industry

Much of the world's drinking water infrastructure, with millions of miles of pipe, is nearing the end of its useful life. For example, nearly 170,000 public drinking water systems are located across the United States, and there are an estimated 240,000 water main breaks per year, most of which are caused by corrosion.

Failures in drinking water infrastructure result in water disruptions, impediments to emergency response, and damage to other types of infrastructure, such as roadways. Unscheduled repair work to address emergency pipe failures may cause additional disruptions to transportation and commerce. In cases where the water does not return to an aquifer, a valuable resource is lost. In addition, the availability of fresh water in the United States is a growing concern, especially on the West Coast where drought has significantly decreased water availability in many areas. This is only expected to grow as a major concern, making water loss from aging pipe infrastructure more critical. This has been a concern globally for a long time.

Despite these breaks, the quality of drinking water in the United States remains generally high. Although pipes and mains are often more than 100 years old and in need of replacement, disease attributable to drinking water is rare. Among other factors, this can be attributed to maintaining water pressure and the practice of boiling water after a pipe break. However, in countries such as India, uniform access to clean drinking water remains a challenge. Water line failure due to corrosion is a primary reason for water loss and the resulting threat of contamination. Many parts of India have drinking water unfit for consumption, which leads to jaundice and other waterborne diseases. Not maintaining positive water pressure in the pipelines and the failure to boil water after a pipe rupture are contributing factors.

Other pressures on a nation's drinking water systems impact infrastructure costs. Financial impacts of meeting regulatory requirements are a continuing issue for many communities. In the case of drinking water systems, the most pressing rules are new, either recently issued or pending, as the result of standard setting by the U.S. Environmental Protection Agency (EPA) to implement the Safe Drinking Water Act Amendments of 1996. These rules impose new or stricter drinking water limits on numerous contaminants, including arsenic, radioactive contaminants, microbiological organisms, and disinfection byproducts. Funding has increased, so localities sometimes find the funds through reduced maintenance.

In 2012, the American Water Works Association (AWWA) concluded that the aggregate replacement value for more than one million miles (1.6 million km) of pipes was approximately US$2.1 trillion if all pipes were to be replaced at once. Since not all pipes need to be replaced immediately, it is estimated that the most urgent investments could be spread over 25 years at a cost of approximately US$1 trillion.

Capital investment needs for the U.S. wastewater and storm water systems are estimated to total US$298 billion over the next 20 years. Pipes represent the largest capital need, comprising three quarters of total needs. Fixing and expanding the pipes will address sanitary sewer overflows, combined sewer overflows, and other pipe-related issues. In recent years, capital needs for the treatment plants comprised about 15 to 20% of total needs, but will likely increase due to new regulatory requirements. Storm water needs, while growing, are still small compared with sanitary pipes and treatment plants. Since 2007, the U.S. federal government has required cities to invest more than US$15 billion in new pipes, plants, and equipment to eliminate combined sewer overflows.

The Water Services Association of Australia (WSAA) provides an annual report that records and measures up to 117 indicators from 73 water utilities across Australia serving approximately 75% of its population.[5] A number of these indicators were used and examined along with other information to determine costs associated with corrosion. The costs were determined according to the following groupings:

- Water loss from pipeline failures.
- Intangible costs associated with water and sewer pipe failures and replacement.
- Water pipeline corrosion repairs.
- Sewer pipeline corrosion repairs.
- Sewage treatment costs due to infiltration.
- Capital cost for water and sewer pipeline replacements.
- Maintenance and repair water treatment plants.
- Maintenance and repair of other assets (tank, pump stations, etc.).
- Maintenance and repair of sewage treatment plants.

Based on the study, the total annual (2010) cost was estimated to be US$690 million ± 30%. This translates to US$42 per person per year in Australia, compared to the cost per person per year in the U.S. of about US$85.[6]

Following the Australian study, recommendations were made (i) to raise the awareness in the water industry of the impact of corrosion on the infrastructure and the associated direct costs that result and (ii) to provide additional training in conjunction with key stakeholders.

When comparing corrosion management practices in North America and Australia, some significant differences in the responses from the water industry in the two different countries are evident. The radar plot in Figure 5-8 shows distinct differences in Continuous Improvement, CMP Integration, and Communication; where the Australian water companies scored significantly higher than the North American water industry. This is somewhat surprising considering the fact that the Australian water industry scored very low on policy, suggesting that on average the industry has limited corrosion management policy, which is considered critical to good corrosion management practices. The American water industry appears to have policies, but implementation can be improved.

Discussions with management and engineers of two U.S. municipal water companies are in agreement with the finding of the survey that the overall corrosion management is inadequate. Neither of the companies has a corrosion management policy, and discussions merely focused on near-term objectives such as the various corrosion control methods and limited budget to control corrosion. One company in a region in the U.S. that currently suffers a drought quoted:

5 Greg Moore, "Corrosion Urban Water Industry."

6 G. Koch et al. "Corrosion Cost and Preventive Strategies in the United States" FHWA-RD-01-156, March 2002.

> *"The drought leads to a call for water conservation, leading to lower water sales, leading to smaller budgets."*

The radar plot in Figure 5-8 shows that both the U.S. and Australian water companies struggle with resources, which was confirmed by discussions with U.S. water companies. Engineers have a general responsibility for their organization's infrastructure, of which corrosion control is a small part. There was a consensus that corrosion is limited as a career path, and often civil engineers with inadequate training and competency development in corrosion are charged with overseeing corrosion issues.

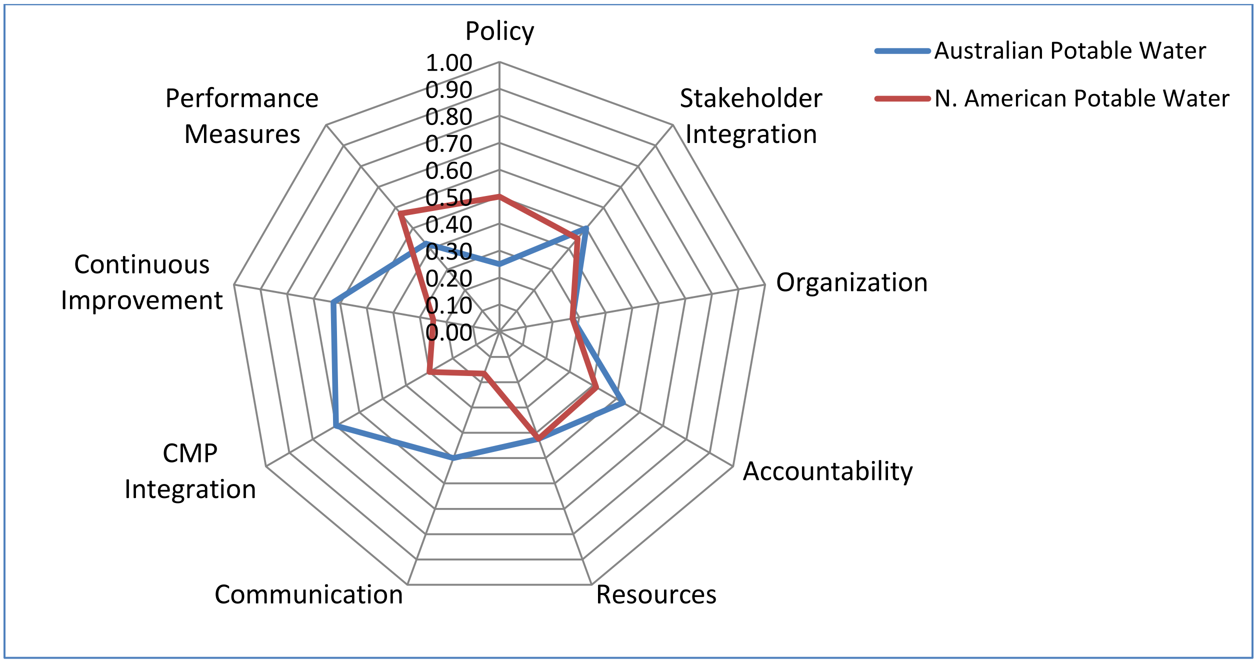


Figure 5-8. Radar Plot Comparing Corrosion Management Practices in Australia and North America

5.1.4 U.S. Department of Defense

Following the 2002 FHWA study, "Corrosion Costs and Preventive Strategies in the United States," the U.S. - DoD has been in the process of developing and implementing a comprehensive CMP. The 2002 study estimated the cost of corrosion to DoD at approximately US$20 billion and this value has been validated through DoD's cost of corrosion analyses. The question asked was: with a bureaucracy the size of DoD, what can be done? As with any new, groundbreaking initiative, it is important to have top down support; the Under Secretary of Defense for Acquisition, Technology and Logistics was a supporter from the start. This program is integrated into the DoD's management systems ranging from setting policy to calculating the cost of corrosion of projects, assets, and components. The program is run by the Corrosion Policy and Oversight (CPO) Office and includes all critical components of a CMS.

The DoD mirrors other industries by having vehicles, airplanes, plants, and physical infrastructure. This section of the report discusses DoD's corrosion management practices and its corrosion cost assessment model.

5.1.4.1 Background

The U.S. DoD submitted the first version of its long-term corrosion strategy to Congress in December 2003. The DoD developed this long-term strategy in response to direction in the Bob Stump National Defense Authorization Act for Fiscal Years 2003 to 2013. In November 2004, the DoD revised its long-term corrosion strategy and issued the *DoD Corrosion Prevention and Mitigation Strategic Plan*. The purpose of this strategic plan was to articulate policies, strategies, objectives, and plans that will ensure an effective, standardized, affordable DoD-wide approach to prevent, detect, and treat corrosion and its effects on military equipment and infrastructure. The DoD strives to update its strategic plan periodically.

Specific objectives of this strategic plan included the following:

- Establishment of a fully functioning DoD CPO organization reporting directly to the Undersecretary of Defense (Acquisition).
- Initiation and communication of the DoD corrosion policy.
- Formation of a multiple-service Corrosion Prevention and Control Integrated Product Team (CPCIPT).
- Institutionalization of corrosion prevention and mitigation as a key component of the DoD's transformation process through the planning, programming, budgeting, and execution process.
- Development of a project plan template that will be completed for each new DoD corrosion-related project. (Key elements include technology, schedule, budget, benefits, ROI, operational readiness, and management support.)
- Creation of a DoD corrosion web site that enables the near-real-time exchange of corrosion-related information and collaboration on corrosion projects, products, specifications, training, and prototype testing.
- Establishment of communication links with various private-sector corrosion activities (such as NACE International) in order to strengthen data-sharing.
- Development of a corrosion project "road map" that identifies specific projects that, if funded, would prevent or mitigate corrosion based upon mission requirements.

Within the DoD, corrosion has been recognized to have three major negative impacts – financial cost, asset/equipment availability, and safety. For example, corrosion has been found to have the following negative impacts on military aircraft:

- Corrosion affects financial cost mainly in terms of labor hours for maintenance and materials needed to mitigate corrosion.
- Corrosion can cause aircraft to be deemed unavailable to perform their mission or to have a degraded capability. DoD uses the term 'readiness' to measure weapon system nonavailability and/or degraded capability.
- Corrosion has also been the cause of aircraft failures in flight that have resulted in injury and death.

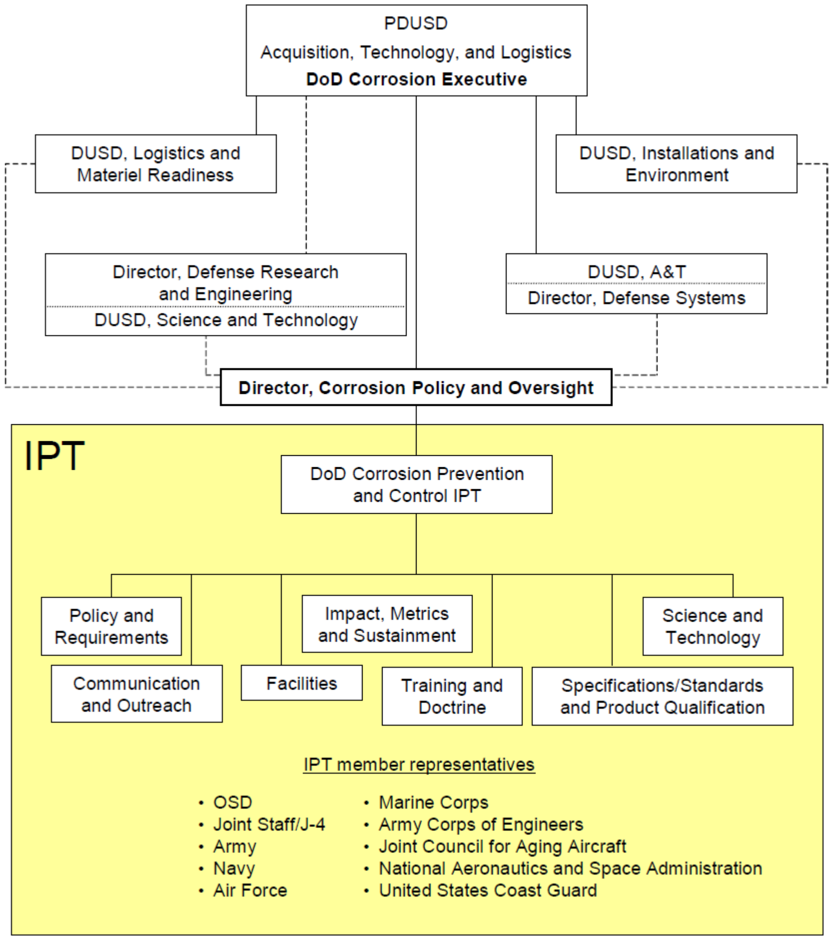
5.1.4.2 DoD Corrosion Management Structure

In order to manage corrosion across the services and meet the objectives of the 2003 Corrosion Strategic Plan, the DoD adopted the Integrated Product and Process Development (IPPD) approach. The IPPD approach is a management technique, widely used in industry, that simultaneously integrates all essential activities through the use of multidisciplinary teams in order to optimize the design, manufacturing, and support processes. The IPPD approach facilitates meeting both cost and performance objectives from product concept through production, including field support. One of the key IPPD advantages is multidisciplinary teamwork through IPTs.

IPTs are composed of representatives from all appropriate functional disciplines working together with a team leader to build successful and balanced programs, identify and resolve issues, and make sound and timely decisions. Team members do not necessarily commit 100% of their time to an IPT, and a person may be a member of more than one IPT.

The purpose of IPTs is to make team decisions based on timely input from the entire team (e.g., program management, engineering, manufacturing, test, logistics, financial management, procurement, and contract administration) including customers and suppliers. IPTs are generally formed at the program manager level and may include members from both government and contractors. A typical IPT at the DoD program level may be composed of the following functional disciplines: design engineering, manufacturing, systems engineering, test and evaluation, subcontracting, safety and HAZMAT, quality assurance, training, finance, reliability, maintainability and supportability, procurement, and contract administration, suppliers, and customers.

Figure 5-9 shows the structure of the DoD corrosion management organization, including the CPCIPT.



Note: A&T = Acquisition and Technology; DUSD = Deputy Undersecretary of Defense; PDUSD = Principal Deputy Undersecretary of Defense; OSD = Office of the Secretary of Defense

Figure 5-9. DoD Corrosion Organization

The CPCIPT is responsible for providing strategic direction, policy, and guidance to prevent and mitigate corrosion of the military equipment and infrastructure of the department. The specific goals of the CPCIPT are:

- Provide a strategic review and advice to deal with:
  - ♦ An expanded emphasis on corrosion prevention and mitigation.
  - ♦ A uniform application of requirements and criteria for testing and certification of new corrosion prevention technologies.
  - ♦ A coordinated approach to collect, review, validate, and distribute information on proven corrosion prevention methods and products.
  - ♦ A coordinated science and technology program that includes demonstration, validation, and transition of new corrosion technologies into operational systems.

- Develop and recommend policy guidance on the prevention and mitigation of corrosion.
- Provide overviews and summaries of the corrosion programs and funding levels proposed and executed by the military departments and defense agencies.
- Develop a roadmap and monitor the progress of corrosion-related activities.
- Develop strategies to investigate the feasibility of developing methodologies that efficiently track corrosion costs and the effects of corrosion on readiness and safety.
- Provide guidance for improving maintenance and training plans.
- Ensure that the use of corrosion control technologies and the application of corrosion treatments are considered throughout the life cycle of equipment and infrastructure.

The CPCIPTs have been established to focus on the following topics (see Figure 5-9):

- Policy and Requirements.
- Facilities and Infrastructure.
  - ♦ An example of corrosion management facilities is given in Appendix B.
- Outreach and Communication.
  - ♦ Web site (http://www.corrdefense.org) and newsletters dedicated to corrosion management and corrosion control.
- Science and Technology.
  - ♦ Academia, basic research, applied research, and implementation (see Section 6).
- Standards, Specifications, and Qualifications.
  - ♦ MIL specs, NACE, etc.
- Metrics, Impact, and Sustainability.
  - ♦ Corrosion costing models – Appendix E presents DoD's corrosion costing methodology.
- Training and Certification.
  - ♦ NACE, SSPC, etc. (see Section 06).

The various aspects of the IPPD/IPT concept are continuously refined and adjusted through actual practice. This concept has the potential to help DoD shift corrosion management from an environment of regulation and enforcement to one of incentivized performance, and to create a climate of risk-informed approaches. In 2003 the Under Secretary of Defense (Acquisition and Technology) identified critical changes that had to take place in DoD in order to form successful IPTs:

> *"...move away from a pattern of hierarchical decision making to a process where decisions are made across organizational structures by integrated product teams. It means we are breaking down institutional barriers. It also means that our senior acquisition staffs are in a receive mode - not just a transmit mode. The objective is to be receptive to ideas from the field to obtain buy-in and lasting change."*

These changes in corrosion management approach highlight the two most important characteristics of IPTs:

Cooperation

Teams must have full and open discussions without secrets, where all facts need to be available to each team member to understand and assess. Each member brings a unique expertise to the team that needs to be recognized by all. Because of that expertise, each person's views are important in developing a successful program, and these views need to be heard. Full and open discussion does not mean that each view must be acted on by the team. The team is not searching for lowest common denominator consensus. There can be disagreement on how to approach a particular issue, but that disagreement must be reasoned disagreement based on an alternative plan of action rather than unyielding opposition. Issues that cannot be resolved by the team must be identified early so that resolution can be achieved as quickly as possible at the appropriate level.

Empowerment

The functional representatives assigned to the IPTs at all levels must be empowered by their leadership to give good advice and counsel to the program manager. They must be able to speak for their superiors, the principals, in the decision-making process. IPT members cannot be expected to have the breadth of knowledge and experience of their leadership in all cases. However, they are expected to be in frequent communication with their leadership, and thus ensure that their advice to the program manager is sound and will not be overturned later, barring unforeseen circumstances or new information. One of the key responsibilities of leadership is to train and educate their people so they will have the required knowledge and skills to represent their organizations leaders. IPT members are an extension of their organizations and their leadership; they must be able to speak for those organizations and leaders.

5.1.4.3 Government Accountability Office (GAO) Recommendations

In the United States, the GAO's work includes oversight of federal programs and providing insight into ways to make government more efficient, effective, ethical and equitable. It is known as the "investigative arm" of the United States Congress.

The GAO has audited the workings of the DoD corrosion program twice since its inception in order to encourage continuous improvement in the program. One of their earlier recommendations was for the Office of the Secretary of Defense (OSD) to develop an action plan to exploit the data from the cost of corrosion studies (internal DoD) based on above discussed costing methodology. The GAO concluded that the data provides the military services an opportunity to achieve long-term cost savings were it to be properly exploited. It is realized that corrosion is an issue with significant cost, readiness, and safety impacts, and DoD has developed the cost of corrosion assessment methodology that has been widely accepted among the DoD community, as well as within the GAO (see Appendix D).

In September 2013 the GAO published an audit of military departments, with the following major findings:

- The GAO noted that the DoD has invested more than $63 million in 88 projects in fiscal years 2005 through 2010 to demonstrate new technology or methods addressing equipment-related corrosion.

- DoD requires the military departments to collect and report to the Corrosion Office key information from equipment-related corrosion projects about new technologies or methods. However, the GAO reported that the DoD did not have complete information about the benefits of all projects. It was found that the military departments inconsistently reported measures of achievement other than the ROI, such as when outcomes prompted changes to military equipment specifications.
- Further, the military departments did not always collect required information needed to recalculate the estimated ROI, and were unable to determine whether projects had achieved their estimated ROI. Following these findings, the Corrosion Office officials plan to revise guidance on how project managers should be reassessing the ROI.
- The GAO noted that the DoD has taken steps to improve oversight of its equipment-related corrosion projects, such as revising its *DoD Corrosion Prevention and Mitigation Strategic Plan* to provide additional guidance on reporting requirements. However, it was found that the DoD does not have a comprehensive overview of the status of all equipment-related corrosion projects.
- While the reports provide the status for each project, the GAO found that the Corrosion Office does not consolidate information to monitor the status of all these projects, such as if a project has not transitioned to service use or has been discontinued.
- The DoD has identified and incorporated lessons learned from equipment-related corrosion projects and shared some lessons with the corrosion community; however, the GAO noted that the DoD has no centralized and secure database or other source to share lessons from all project reports, including those with sensitive information.
- While the DoD has begun to develop a database that would contain lessons learned on all projects, development is in the early stages. The GAO noted that until a comprehensive, centralized, and secure database is developed that includes lessons learned from all completed projects, officials from DOD's corrosion community will not have full and complete information on lessons learned, including proven methods or products to prevent or mitigate corrosion of military equipment.

6 CORROSION MANAGEMENT FINANCIAL TOOLS

Corrosion management includes all activities, through the lifetime of the structure, that are performed to prevent corrosion, repair its damage, and replace the structure, such as maintenance, inspection, repair, and removal. These activities are performed at different times during the lifetime of the structure. Some maintenance is a regular activity, characterized by annual cost. Inspections are scheduled as periodic activities, and repair is done as warranted. Rehabilitation may be done once or twice during the lifetime of the structure, and the cost is usually high. Applying different corrosion management methods may positively affect the lifetime of a structure of a particular design without increasing the cost.

In order to meet the corrosion management objectives, tools or methodologies are available to calculate the cost of corrosion over part of an equipment's or asset's lifetime or over the entire life cycle. These methods, which range from cost-adding to life-cycle costing (LCC) and constraint optimization are summarized below and discussed in detail in Appendix E.

ROI is a primary performance measure used to evaluate the efficiency of an investment (or project) or to compare the efficiency of a number of different investments. ROI measures the amount of return (profit or cost savings) on an investment relative to the investment's cost. An ROI calculation is used along with other approaches to develop a business case for a given proposal. ROI is calculated by simply dividing the return or cost savings (projected or achieved) on an investment divided by the cost of the investment. The complex part of ROI is determining the cost savings and investment costs. To compare investment proposals, ROI must either be annualized or the time over which the ROI is achieved is stated.

For example, it has been suggested (Section 2) that as much as 30% of the corrosion costs can be saved by implementing state-of-the-art corrosion control technology. If the cost of this implementation is 10% of the savings, the following ROI is realized over the applicable time frame. If your annual corrosion costs are US$10,000, and state-of-the-art corrosion control is implemented; projected annual savings would be US$3,000 at an annual cost of US$300. The cost of a given project may be:

- An annual cost (chemical treatment).
- A one-time cost with a specified life expectancy (coatings).
- A one-time capital investment with an annual cost to maintain (cathodic protection [CP]).

Each of these can be converted to an annual cost or a cost over a lifetime based on the corrosion control method. ROI can be calculated over a defined life or on an annual basis. In our example, the savings (avoided cost) is $3,000 and the investment is $300, giving an ROI of 10. This is sometimes expressed as a ratio; e.g., 10:1. An ROI of less than 1.0 is often expressed as a percentage. The key is to include all costs in the calculation of investment:

- Capital cost.
- Installation cost.

- Maintenance cost.
- Abandonment/decommissioning costs (if applicable).

Include all savings in the avoided costs:

- Capital savings (extended life of an asset).
- Maintenance savings (fewer shutdowns or longer time between outages).
- Decreased inspections if applicable.
- Increase in reliability (lower risk of failure).
- Decreased risk of environmental accidents.
- Decreased risk of personal injury.
- Decreased shareholder or public confidence.

Some of the savings may be difficult to monetize, such as decreased risk of environmental accidents, decreased risk of personal injury, lower risk of failure (possibly related to environmental risk and safety), and a cost associated with poor public relations. The details of how to handle these can be different for different industries and applications. One way to deal with these is a risk-based approach and to analyze the risk benefit of a specific project (how much will the performance of a project decrease the risk picture for the organization).

The following approaches use some form of ROI or cost benefit to evaluate and differentiate between different proposals or between doing a project versus not doing the project.

6.1 Cost-Adding Methodology

This method, developed by the U.S. DoD, calculates the cost of corrosion of an asset or a project by looking from the top down. Programs, projects, and assets are analyzed to determine cost components that are related to corrosion. The top-down corrosion cost assessment removed all cost components that have no corrosion. However, usually significant gaps remain that are filled by looking from the bottom. All corrosion-related expenditures are added and compared with the top-down cost assessment. By comparing the top-down and bottom-up corrosion cost assessment, the U.S. DoD has been able to accurately determine direct corrosion costs of a project or asset and to calculate ROI.

The U.S. DoD has used the direct financial approach to track the effectiveness of corrosion control equipment and techniques by determining ROI for specific projects. That is, the DoD only considers those costs that can be tracked by their financial system. A few relevant case studies are presented in Appendix D. The calculated ROI for these projects range from 3 to 56 and are summarized below. Although these cases have a U.S. DoD basis, they are broadly applicable and can easily be applied to the general industry.

- ROI = 9.4 Green Water Treatment. Goals: improving the reliability and reducing the cost of operating and maintaining boilers and cooling towers by using nonhazardous corrosion inhibitors and a smart control system.

- ROI = 8.8 Coating System for CP and Fire Resistance for Metal Structures. Goals: reducing the corrosion rate of the structural steel and increasing fire safety for the structures, as well as validating the technology for other uses.
- ROI = 33 Development of Corrosion Indices and Life-Cycle Protection. Goal: develop a life cycle predictive tool to optimize preventive maintenance cycles based on region and material; the predictive tool will be a location-based corrosivity software model.
- ROI = 13 CP of Rebar in Critical Facilities. Goal: corrosion prevention of rebar in concrete in critical facilities located in coastal environments.
- ROI = 15 Ceramic Anode Upgrades. Goal: demonstrate the efficacy of the CP technology in conjunction with remote monitoring.
- ROI = 11 CP Utilizing IR Drop Free Sensors. Goal: Improve corrosion CP monitoring systems and bring cross country pipeline in compliance with industry standards for critical pipelines.
- ROI = 56 Wire Rope Corrosion for Guyed Antenna Towers. Goal: develop a reliable corrosion inspection tool that will ride remotely along each guy wire and measure the corrosive state along the full length of each and every guy wire.
- ROI = 3.0 Solar-Powered CP. Goal: demonstrate a solar powered CP system using recently developed high efficiency (96 to 98%) controls that have flexibility to match the anode groundbed (and its fluctuating conditions).
- ROI = 56 Magnesium Rich Primer for Chrome Free Aircraft Coating Systems. Goal: facilitate the refinement of Mg-rich primer prototype formulations, evaluate the performance, and obtain field-level performance evaluation of Mg-rich based chrome-free coating systems.
- ROI = 16 Corrosion Detection Algorithm for Ship's Topside Coatings. Goal: deliver a modified corrosion detection algorithm (CDA) that could be used to conduct damage assessments.

6.2 Life-Cycle Costing

LCC is a well-known approach to determine the cost of corrosion of certain assets by examining:

- Capital cost (CAPEX).
- Operating and maintenance cost (OPEX).
- Indirect cost caused by equipment failure.
- Material residual value.
- Lost use of asset (i.e., opportunity cost).
- Any other indirect cost, such as damage to people, environment, and structures as a result of failure.

The LCC approach makes it possible to compare alternatives by quantifying a long-term outlook and determining the ROI. LCC can be performed by using several costing methods. One method is the Cost Adding method discussed above. Other methods include the Bayesian Network (BN) approach.

A detailed example of the BN approach to determine the cost of corrosion due to the mechanism of corrosion under insulation (CUI) is given Appendix D. A brief overview is provided here. CUI is a problem in refineries[7, 8] and other chemical and petrochemical plants. The management of CUI requires a systems perspective because a number of design, construction, and operational factors interact to cause CUI. BN models are highly suited to assess the performance of complex interactive systems because they try to represent the whole system in terms of its interacting parts through cause-consequence relationships. Furthermore, BN models are probabilistic and observational in nature, so they can represent the uncertainties of the system and can be modified based on inspection and sensor data. Finally, BN is a great tool to capture the diverse knowledge of personnel who work with a system.

The predicted business impact could be a valuable KPI for operational leaders to make risk-informed decisions, based on their risk appetite and internal decision criteria. The business impact criteria are defined as follows:

- Direct costs: Revenue lost due to down time and clean-up costs from product leaks.
- People: Injury or fatality leading to legal fees, escalating insurance costs, and fines.
- Repair/ Replace: Cost of parts and labor for repair/replacement.
- Major Accident Potential: defined by the Seveso Directive in Europe (Seveso, 2012), covering any fire or explosion or accidental discharge of a dangerous substance in defined quantities, a fatality of more than six persons injured with hospitalization, massive evacuation, immediate and severe damage to the environment (permanent/long-term), damage to own property (> 2 million euro), or eventual cross-border damage.
- Loss of reputation: Reputational damage can lead to loss of clients, additional government oversight, increased borrowing costs, and loss of high-value staff.

A number of scenarios can be constructed on the basis of inputs to BN and the corresponding business impacts can be estimated (detailed costs are shown in Appendix D). For example, in one scenario, the surface temperature is low and therefore the corrosion rate is likely to be low leading to a low probability of failure and injury/fatality. Therefore, most business costs (other than maintenance costs) are low. On the other hand, if the surface temperature is 60º C, there is no coating under the insulation, and the product is flammable, there is a higher probability of high corrosion and failure leading to significant business costs. The example provided in Appendix D is to examine the cost of an existing system based on multiple scenarios; scenarios that included mitigation measures could also be included, thereby providing a cost benefit analysis of proposed mitigation methods.

7 M. M. Chauviere, J.W. Krynicki, and J.P. Richert, "Managing CUI In Aging Refinery Pressure Vessels," NACE International, Corrosion-2007, Paper No. 07566.

8 W. Geary, "Analysis of a corrosion under insulation failure in a carbon steel refinery hydrocarbon line," Elsevier, Case Studies in Engineering Failure Analysis 1 (2013) 249–256.

An example using this approach was developed by the aeronautical industry. Although this example does not deal with corrosion, it has general applicability and can readily be applied to corrosion management. Prognostics and Health Management (PHM) is described by Feldman et al.[9] PHM provides opportunities to lower sustainment costs, improve maintenance decision making, and provide product usage feedback into the design and validation process. In the case of PHM, the investment includes all the costs necessary to develop, install, and support a PHM approach, where the avoided cost is a quantification of the benefit realized through the use of this approach. The paper[4] offers a case study of a multifunctional display in a Boeing 737 comparing the LCC of a display system using unscheduled maintenance to the same system using a precursor or anticipation of failure. Analysis of the uncertainties in the ROI calculations was addressed using a probabilistic approach that was deemed necessary to develop realistic business cases.

This case study addresses a specific aircraft avionics failure; however, it can be easily applied to other types of failure such as corrosion. Feldman et al. concluded that in order to determine the ROI of a system, an analysis of all cost-contributing activities is needed such that PHM can be implemented, and a comparison of the costs of maintenance actions with and without PHM can be made. The inclusion of variability in the operational profile, false alarm, random failure rates, and system complexity in PHM ROI models using probabilistic methods (Monte Carlo) enables a more comprehensive treatment of PHM to support decision making.

LCC can be approached in a deterministic and probabilistic manner. Both of these approaches are discussed in detail in Appendix D.

6.3 Constraint Optimization

A constraint optimization framework is used to determine the optimal corrosion management practice for a specific structure or facility. This method allows application of optimal practices with a fixed or limited available budget.

Development of the constrained optimization framework requires three major steps:

1 Optimizing expenditures of the structure.

2 Maximizing service level subject to budget constraint.

3 Building a constrained optimization model.

The constrained optimization model is presented in Appendix E.

6.4 Maintenance Optimization

Maintenance optimization calculates the financial benefit of a maintenance action. It allows inspect/repair/replace projects to be justified by financial benefit. When expressed in terms of net present value (NPV), scheduling of maintenance projects can also be optimized. One way to monetize corrosion maintenance decisions is through risk, which combines probability of failure and its consequence (which can be expressed as cost). An example case study is presented in Appendix D.

[9] Kiri Feldman, Taouft Jozouli, and Peter Sandborn, "A Methodology for Determining the Return on Investment Associated with Prognostic and Health management", IEEE Trans. On Reliability, Vol 58, No. 2, pp 305 – 316, June 2009.

7 Education and Training Related to the Corrosion Management System Pyramid

In the next decade a significant transition and turnover in knowledge will occur in the corrosion community. An age distribution of NACE International membership (2007) indicated that only approximately 20% of the membership is 40 years of age or younger and almost 50% are 51 or older.[10] In comparison, other aging workforce studies have estimated that approximately 25% of the total workforce in the U.S. is over 50 years old.[11]

Assuming that the NACE International membership is representative of the overall corrosion workforce, knowledge transfer and education and training (E&T) of our younger workforce is critical. Based on the CMS survey (Section 4), the top performers define corrosion management competencies as part of a career path for corrosion professionals and provide training for both internal and external resources. This core competency E&T internal to an organization is one way to address the aging workforce issues. A few organizations have gone to the establishment of internal "universities" with specific curriculum addressing corrosion core competencies. Two examples of best practices are a Middle East NOC and the U.S. DoD, both of which have formalized internal "universities" for E&T. A few quotes from the NOC emphasize its commitment to education and training:

> "The company also has a professional engineering department – an internal training organization that can even develop its own advanced courses. This department has KPIs within the company."
>
> "New graduates work with mentors for 10 to 15 years and have goals (career mapping)."
>
> "The company offers and underwrites advanced degrees, courses, certifications, and internships."

The aging workforce and the retirement of SMEs will cause institutional knowledge of operations and historical lessons learned to be lost unless efficient programs are developed to transfer this organizational knowledge. This concern is clearly stated by a U.S. water company senior engineer:

> *"I have very specialized knowledge (water quality, chemistry, and corrosion) and have been in the business for 30 years. There's no one being trained to replace me, and I am concerned about that."*

CMSs must focus attention on effectively transferring this institutional knowledge. These SME knowledge transfer programs will be different from the core competency development programs discussed above. Specific on-the-job training and mentoring programs are being used to transfer SME knowledge.

The following discussion of E&T is related to the availability of offerings at the various levels of the CMS Pyramid, and the relevant preventive strategies for the Management Systems Elements (see Figure 7-1).

---

[10] Aziz Asphahani and Helena Seelinger, NACE Foundation, "The Need for Corrosion Education," Presentation at the Materials Forum 2007: Corrosion Education for the 21st Century.

[11] SHRM Foundation's Effective Practice Guidelines Series, EPG, Underwritten by a grant from the Alfred P. Sloan Foundation "The Aging Workforce: Leveraging the Talents of Mature Employees" (2014).

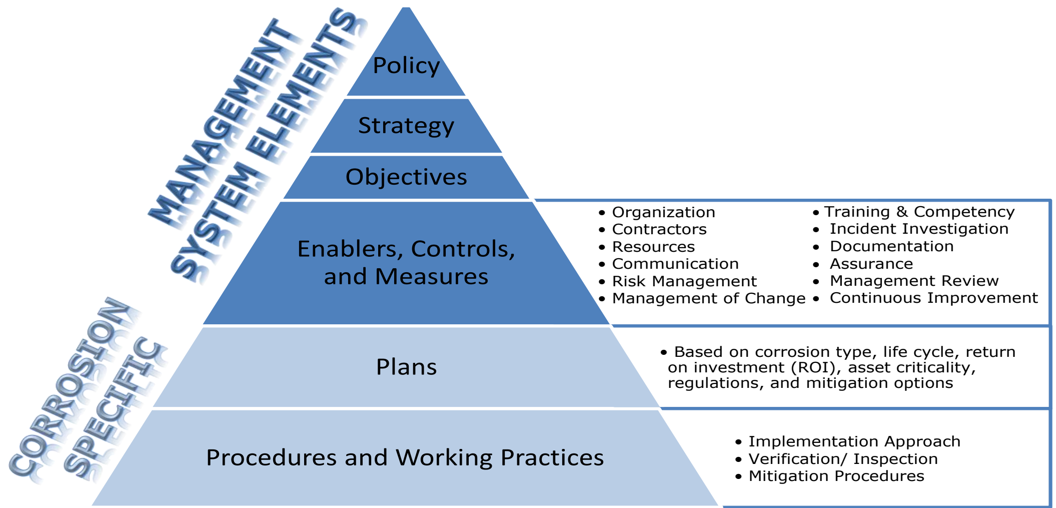


Figure 7-1. The Corrosion Management System Pyramid

In the university setting, corrosion is multi-disciplinary with contributions from materials science, chemistry, and electrochemistry. All deal with the corroding material, the corrosive environment, and the electrochemical reactions at the corroding interface. University faculty teaching corrosion resides in Materials Science and Engineering, Chemical Engineering, Mechanical Engineering, Chemistry, and others. Akron University provides the only bachelor's degree in Corrosion Engineering in the United States and its first graduating class was in 2015. This program had significant support within the corrosion community and by the U.S. DoD; all realizing that a lack of corrosion professionals was going to become a critical barrier to furthering corrosion engineering and corrosion management in the future. Even with this corrosion engineering program, curricula primarily focus on science and technology of corrosion processes and mitigation and corrosion control, rather than corrosion management. This pertains to the foundational levels (1 and 2) of the CMS Pyramid, and there is little or none related to the mid and upper levels of the pyramid (Levels 3 to 6).

The majority of professional development and vocational training for corrosion professionals is offered by NACE International. Over 16,000 students were trained in 2014 through 829 courses in 36 countries.

Figure 7-2 indicates the level at which the various course materials provide education and training. The qualitative rankings in the figure are based on review of course descriptions, and the three sizes of solid circles indicate "significant," "moderate," or "modest" rankings. The open circles indicate that the courses do not address the upper three level of the corrosion management pyramid.

It is apparent that the E&T course content is heavily focused on the lower levels of the CMS Pyramid (Procedures and Working Practices), and that there is essentially no content at the upper levels of the pyramid (Policy, Strategy, and Objectives). Moreover, there is little or no content to inform those working in the foundation levels (Procedures and Working Practices, and Plans) on how to effectively communicate sound corrosion management to the Policy and Strategy levels.

E&T will play an important role in the integration of corrosion management into an organization's management system. E&T programs must prepare corrosion professionals to better communicate with those outside of the profession. Corrosion professionals should not expect outsiders to learn their technical language. In addition, corrosion professional societies must emphasize business strategy and/or public policy when advocating positions to those outside of the corrosion profession. Using the principles of CMS will make these arguments more persuasive.

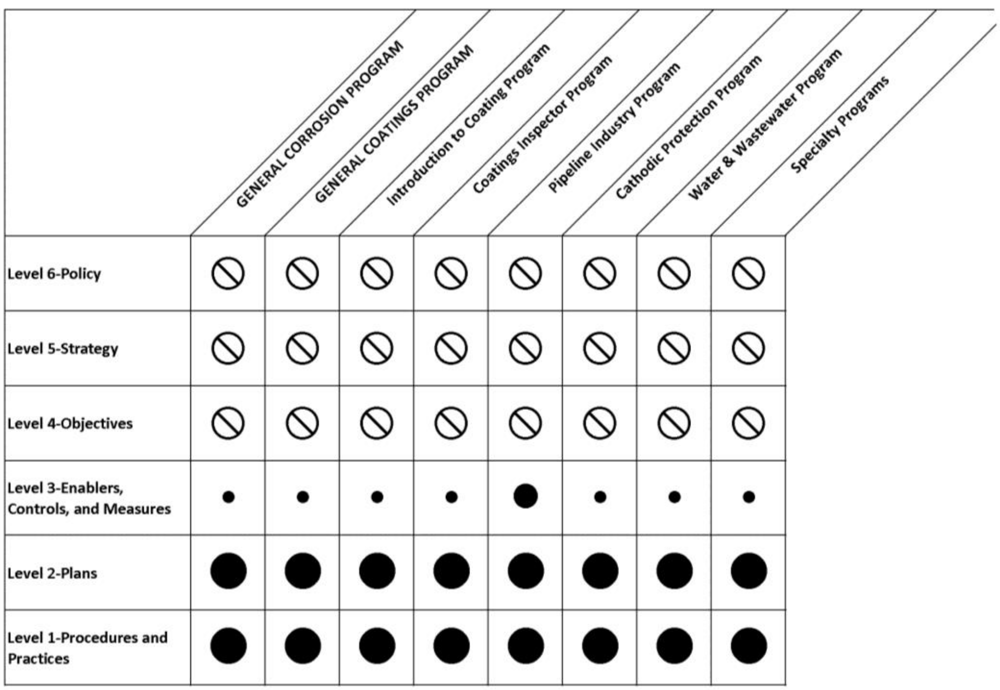


Figure 7-2. Relationship of NACE Corrosion Education and Training Programs to Levels of Corrosion Management Pyramid

Level 3 (Enablers, Controls, and Measures) can be viewed as a transition/communication level bridging between corrosion management practices and policies, where corrosion management can be linked to an organization's established management systems, such as HSE, asset integrity, performance, and profitability. Corrosion E&T programs at their most advanced levels touches on some Level 3 corrosion management issues; e.g., design, materials selection, performance, life-cycle costing, condition assessment, risk assessment, safety/reliability, and repair/replace/abandon.

An observation that can be drawn from an analysis of the current E&T efforts is that the corrosion community spends a significant amount of these efforts talking among itself, i.e. on the important task of passing the knowledge of corrosion experts in practices and procedures on to the next generation of corrosion practitioners and experts, while it spends little time on E&T of corrosion professionals on speaking and presenting to upper management in a way that upper management understands (cost benefit, ROI, risk reduction, etc.). E&T plays an important role in the integration of corrosion management into an organization's management system. E&T programs must prepare corrosion professionals to better communicate to those outside of the corrosion profession. Corrosion professionals should not expect those outside the profession to learn their specific technical language. In addition, corrosion professional societies must address business strategy and/or public policy where corrosion management may have an impact. Using the principles of CMS will make these arguments more persuasive.

Business communication can be defined as how to interact with other business entities in a way that is diplomatic but drives business and commerce forward. Training on business communication is lacking for the engineer. Another way to phrase this is that engineers need to learn to sell their projects (which may be technically sound and often innovative and promote state-of-the-art technology) based on "moving business forward," not on the merits of technology only. The technology may be great, but eventually it will be a business decision that is made on whether to move it forward or to implement it. The American Society Of Mechanical Engineers (ASME) promotes the art, science, and practice of multidisciplinary engineering and allied sciences around the globe. ASME says "….. modern business communication has been shaped by the information age. However, skills must be strong in nonverbal communication, as studies have revealed that posture and gesticulation can communicate more of an individual's thinking than words."[12] Business communication E&T is a significant gap that must be filled to achieve the goals of integrating CMSs into organizations on a broader scale.

Moreover, the existing course content is heavily biased toward a limited number of industries, where corrosion is perceived to be a major threat. These include the oil and gas and pipeline industries, and to a lesser extent the chemical/petrochemical, power, and water industries. This trend is not unexpected, since corrosion E&T is a market-driven endeavor. More detailed discussion of the status of educational programs can be found in Appendix E.

[12] https://www.asme.org/engineering-topics/business-communication (December 17, 2015)

8 STRATEGIES FOR SUCCESSFUL CORROSION MANAGEMENT

Realizing the maximum benefit in reducing corrosion costs (both direct and consequential) requires more than technology; it requires integrating corrosion decisions and practices within an organizational management system. This is enabled by integrating a CMS within system elements that range from corrosion-specific procedures and practices up through organizational policy and strategy; i.e., all levels of the management system pyramid (Figure 8-1). This figure is central to the IMPACT study goal and has been shown throughout this report. It is essential that traditional corrosion management procedures and practices (lower levels of the pyramid) be expressed to policy setters and decision makers (higher levels of the pyramid) in the form and terminologies of organizational policies. Simply, the corrosion practices need to be translated into the language of the broader organization. The organization as a whole must commit to ownership of the CMS and its processes. This means buy-in at all levels within an organization.

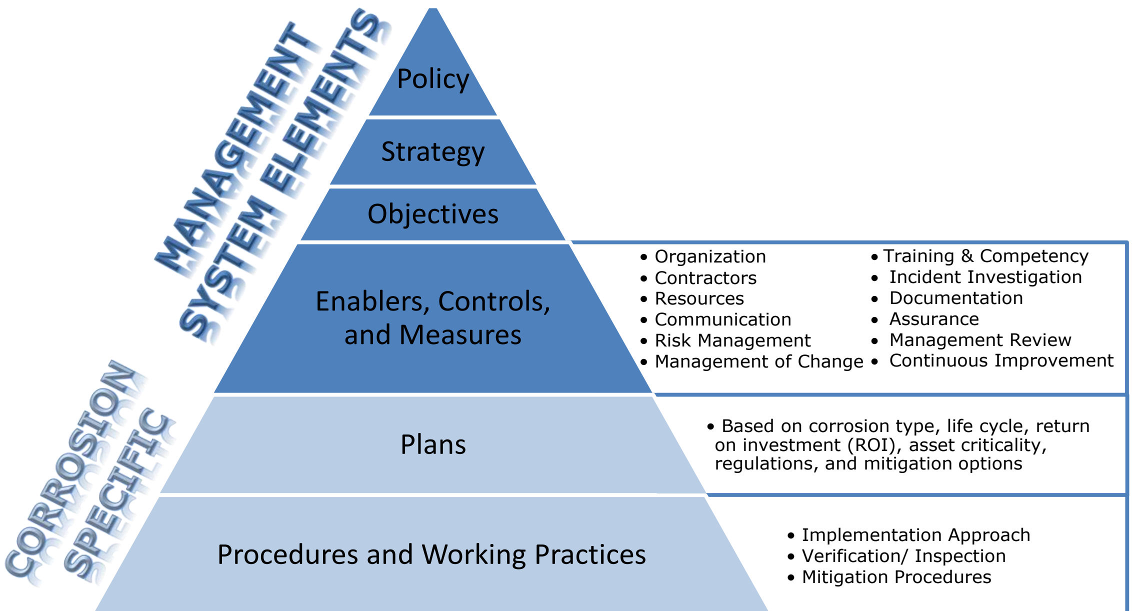


Figure 8-1. The Corrosion Management System Pyramid

Buy-in can be defined as the acceptance of and commitment to a specific concept or course of action. When asked what buy-in meant, a group of participants in an APQC study came up with a series of definitions that ranged from approval to espousal of a change and included acceptance, support, compliance, commitment, endorsement, and adoption.[13] The general consensus was that all of the definitions were valid yet their applicability depended on the situation and at what level in the organization the buy-in is targeted. For example, the ultimate goal of buy-in may be different for the CEO than for the operation's staff (see Table 8-1).

[13] APQC paper.

Table 8-1. Different purposes for buy-in

Target Audience	Purposes
Senior Management	Gain approval to make the change
	Garner sponsorship and resources
Middle Management	Speed up adoption
	Identify change agents to lead by example
Front-Line Employees	Develop a common understanding of the change
	Ensure widespread adoption and compliance

The adoption of a CMS into an organization's management system requires buy-in at both the top and bottom. The technical manager (corrosion/integrity/risk/maintenance manager, part of middle management), is the likely promoter of the need for a CMS.

Without buy-in at the top, initiatives have little chance of getting off the ground. Buy-in with senior management is necessary to get approval to move forward and garner resources. To ensure the message is effective, organizations require a business case that includes a clear statement of the problem, outlines its impact on the organization, lists the required resources, and includes the outcome in terms of cost reductions, increased productivity, improved quality, and/or decrease in risk (environmental, safety, business interruption, public relations, etc.).

Initiatives have also failed because concerns and issues were not addressed at lower levels in the organization. Buy-in with front-line employees is to create a shared understanding around the change and ensure compliance. Individuals may understand the change but take a wait and see stance until they see how it will negatively affect them personally.

To facilitate business case communication between corrosion professionals and senior management leading to integration of a CMS throughout an organization's management system, the following steps are necessary.

1. The corrosion professional should broaden his competence with respect to business tools, to include financial decision making, risk assessment, and management systems. Use of financial and risk assessment tools should be a normal and expected activity for evaluating corrosion control expenditures. Whenever relevant and possible, LCC should be considered.
    - Universities and professional societies should incorporate management system elements and supporting tools into corrosion E&T curricula.
    - Corrosion professional societies should promote management system elements and supporting tools within symposia, seminars, workshops, and technical exchange groups.

2. Communication between those inside and outside of the corrosion profession should be in the language of the external decision maker (e.g., operations or business manager) or stakeholder (e.g., regulatory, policy, or public) with the goal of business improvement.
   - Corrosion professional societies, such as NACE International, should develop training similar to ASME's business communication program described in Section 7, with a specific focus on corrosion professionals to educate and train corrosion professionals to better communicate to those outside of the profession. Corrosion professionals should not expect an organization's business leaders and policy makers to learn their technical language. These communications range from justifying a single corrosion control activity to recommending policy changes. This has the added benefit of moving the corrosion professional away from what is often perceived as alarmist language towards enabling sound business practice.
   - Industry spokespersons must emphasize business strategy and/or public policy when advocating positions to those outside of the corrosion profession. Corrosion professional societies, including NACE International, have worked hard to make organizational leaders and policy makers aware of the cost of corrosion and the cost-saving opportunities that can be realized by sound corrosion control. This was a primary goal of the 2002 cost of corrosion report. Using the principles of CMS will make these arguments more persuasive.
3. Organizations should develop, integrate, and implement corrosion management elements into an organization's overall management system.
   - NACE International should take the lead in educating asset owners on how to (and the value of) integrating a CMS into their organization's management system.
   - Industry should develop a consensus standard on corrosion management to define expectations of standard practice for corrosion management. This is a first step in the process of institutionalizing CMS into standard industry practice.
   - Organizations should adopt a framework and guidelines for integrating corrosion control into an organizational management system such as discussed in Section 3. Appendix B provides a how-to approach on building a best practice CMS.
   - Regulators should incorporate corrosion management effectiveness into regulatory and other oversight practices.
   - Organizations should align long-term, applied, and basic corrosion R&D with the strategic goals of the organization consistent with the principles of CMS.

APPENDIX A
Assessment of Global Cost of Corrosion

A.1 INTRODUCTION

The purpose of the "cost of corrosion" portion of the IMPACT Study is to establish a cost of corrosion at a global level utilizing past studies. The current study did not attempt to collect new raw data and perform any new cost of corrosion analysis. Therefore, the cost of corrosion performed within the IMPACT Study is limited by the completeness and number of available studies.

A.2 HISTORIC PERSPECTIVE

Since the 1950's several countries considered the economic consequences of corrosion. Studies conducted during this time indicated that the cost of corrosion to society was significant. The different approaches used to arrive at the Cost of Corrosion included:

- The Uhlig method, which defines corrosion cost as the total expenditure by manufacturing industries and corrosion-protection measures. [See Section A.2.1 for more details.]
- The Hoar method, which estimates corrosion costs for individual industrial sectors, taking account of both direct corrosion cost and spending on countermeasures. In addition to operational costs, cost of capital can also be included. [See Section A.2.3 for more details.]
- The input/output economic model, used in the 1970's Battelle study [14, 15], which uses domestic commercial interactions among industries. In this model, the gross domestic product (GDP) is calculated under the assumption of three universes:
    - ♦ (Universe I) Actual world with corrosion.
    - ♦ (Universe II) Imaginary world with no corrosion.
    - ♦ (Universe III) Ideal world with inhibited corrosion.

  The GDP for each universe is calculated, and then the corrosion cost and avoidable corrosion cost are calculated by:

    - ♦ Corrosion cost = GDP (Universe II) – GDP (Universe I).
    - ♦ Avoidable corrosion cost = GDP (Universe III) – GDP (Universe I).

NBS estimated that the uncertainty of this method is 30%.

A.2.1 United States (1949): The Uhlig Report

The 1949 study, "The Cost of Corrosion in the United States" led by H.H. Uhlig[16] was the earliest effort to estimate the costs of corrosion. The annual cost of corrosion to the United States was estimated to be $5,500,000,000 (US$5.5 billion) or equivalent to 2.1% of the 1949 gross national product (GNP).[17] Assuming a GDP of US$220 billion for 1949,[18] the cost of corrosion is equivalent to 2.5% of the GDP.

[14] Economic Effects of Metallic Corrosion in the United States, NBS Special Publication 511-1, SD Stock No. SN-003-003-01926, 1978.
[15] Economics Effects of Metallic Corrosion in the United States, Appendix B, NBS Special Publications 511-2, SD Stock No. SD-003-003-01926-5, 1978.
[16] H.H. Uhlig, "The Cost of Corrosion to the United States," Chemical Engineering News, Vol. 27, p 2764, 1949; or Corrosion, Vol. 6, p 29, 1950.
[17] GNP was used in original study.
[18] U.S. Bureau of Economic Analysis.

This study measured the total costs by summing up the cost for (i) the owner/operator and (ii) the users of corroding components. The cost for the owners/ operators was estimated by summing up cost estimates for corrosion prevention products and services used in the entire U.S. economy (for example, coatings, inhibitors, corrosion-resistant metals and cathodic protection). The cost for private consumers/users was evaluated as costs due to select services (domestic water heater replacement, automobile internal combustion engine repairs, and replacement of automobile mufflers). An advantage of the method is that the cost data are more readily available for well-defined products and services. The disadvantage is that several costs can be left out including other operational costs and costs of capital due to corrosion of assets.

A.2.2 West Germany (1969)

West Germany conducted a study of corrosion costs at the end of the 1960s.[19] The total cost of corrosion was estimated to be 19 billion Deutschmarks (DM) (US$6 billion) for the period of 1968 to 1969. Of this cost, 4.3 billion DM (US$1.5 billion) was estimated to be avoidable. This gave a total cost of corrosion equivalent to approximately 3% of the West German GNP for 1969 (equivalent to 2.8% of estimated GDP (US$215 billion) in 1970)[20] and avoidable costs were estimated to be 25% of total corrosion costs. There was no detailed information separating the corrosion cost into economic sectors.

A.2.3 United Kingdom (1970): The Hoar Report

In March 1966, the U.K. Committee on Corrosion Protection was established by the U.K. Minister of Technology under the chairmanship of T.P. Hoar. In 1970, the committee issued its report entitled "Report of the Committee on Corrosion and Protection".[21] The committee summarized its findings as follows: "*We conservatively estimate the cost of corrosion as £1,365 million per annum, which represents 3.5% of the gross national product of 1970. We believe that a saving of approximately £310 million per annum could be achieved with better use of current knowledge and techniques*." This represents savings of approximately 23% of the total national corrosion costs.

The Hoar report determined the cost of corrosion for industry sectors of the economy. The cost of corrosion for each industry sector was subsequently added together to arrive at an estimate of total cost of corrosion for the whole U.K. economy. The Industry Sectors included: Building and Construction, Food, General Engineering, Government Departments and Agencies, Marine, Metal Refining and Semi-Fabrication, Oil and Chemical, Power, Transport, and Water. Information was gathered by interviewing corrosion experts who worked in companies and agencies and by surveys on expenditures for corrosion protection practices. Corrosion experts estimated corrosion costs and the potential savings based on their experiences with major economic sectors.

---

[19] D. Behrens, Br. Corrosion Journal, Vol. 10, Issue 3, p. 122, 1967.

[20] http://macroeconomics.kushnirs.org/index.php?area=germany&indicator=gdp&lang=en.

[21] Report of the Committee on Corrosion and Protection – A Survey of Corrosion Protection in the United Kingdom, Chairman T.P. Hoar, 1971.

A.2.4 Japan (1974)

Japan conducted a survey of the cost of corrosion to its economy in 1977 through the Committee on Corrosion and Protection.[22] The committee was chaired by G. Okamoto and was organized by the Japan Society of Corrosion Engineering and the Japan Association of Corrosion Control. Support for the study came from the Ministry of International Trade and Industry. The survey determined that the annual cost of corrosion to Japan was approximately 2.5 trillion yen (US$9.2 billion) in 1974. Estimating Japan's GDP at US$472 billion for 1974, the cost of corrosion was the equivalent of 2.0% of Japan's 1974 GDP.

A.2.5 United States (1975): The Battelle – NBS Report

In response to a Congressional Directive, the National Bureau of Standards [NBS, now the National Institute of Standards and Technology (NIST)] studied the cost of metallic corrosion in the United States using Battelle Columbus Laboratories (Battelle) to perform the analysis. The results of this work were presented in two reports and a series of publications in Materials Performance.[14,15, 23] The Battelle-NBS study was the first to combine the knowledge of corrosion and economics experts to determine the economic impact of corrosion on the U.S. economy. The study used a version of the Battelle National Input/Output Model to estimate the total corrosion cost. This model quantitatively identified corrosion-related changes in the resources (i.e., materials, labor, and energy), changes in capital equipment and facilities, and changes in the replacement lives of capital items for entire sectors of the economy. The input/output model is able to account for both the direct effects of corrosion on individual sectors and the interactions among various sectors.

The final results of the Battelle-NBS study, after adjustments by NBS to the Battelle report, for the base year of 1975 were: (i) the total U.S. cost of metallic corrosion per year was estimated to be US$70 billion, which is equivalent to 4.5% of the GDP in 1975 (US$1,549 billion), and (ii) 14% or US$10 billion was estimated to be avoidable by the use of the most economically effective, presently available corrosion technology.

A.2.6 Australia (1982)

In 1982, the Commonwealth Department of Science and Technology commissioned a study to determine the feasibility of the establishment in Australia of a National Center for Corrosion Prevention and Control. The feasibility study included a determination of the annual cost of corrosion to Australia. The results were presented in a 1983 report entitled "Corrosion in Australia – The Report of the Australian National Centre for Corrosion Prevention and Control Feasibility Study".[24]

---

[22] Report of the Committee on Corrosion and Protection – A Survey of the Cost of Corrosion to Japan, Japan Society of Corrosion Engineering and Japan Association of Corrosion Control, Chairman G. Okamoto, 1977.

[23] J.H. Payer, W.K. Boyd, D.G. Lippold, and W.H. Fisher, "NBS-Battelle Cost of Corrosion Study ($70 Billion!)," Part 1-7, Materials Performance, May-November 1980.

[24] B.W. Cherry and B.S. Skerry, Corrosion in Australia – The Report of the Australian National Centre for Corrosion Prevention and Control Feasibility Study, 1983.

The study concluded that the annual cost of corrosion to the Australian economy was AUD2 billion at 1982 prices, approximately 1.5% of Australia's GNP in 1982 (equivalent to 1.0% of the GDP (estimated at AUD196 billion)).[25] The report indicated that improved technology transfer and implementation could potentially recover a large portion of the corrosion costs. Furthermore, it was noted that the value of the savings to the Australian community from improved corrosion control would make a worthwhile contribution to the nation's economy.

A.2.7 Kuwait (1987/1992)

In 1992, Kuwait conducted an economic assessment of the total cost of corrosion to its economy using a modified version of the Battelle-NBS IO model.[26] The base year study (1987) gave a total cost of corrosion estimated at US$1 billion (1987 dollars), equivalent to 5.2% of Kuwait's 1987 GDP. Avoidable corrosion costs were estimated at US$180 million or 18% of the total cost.

On the sector level, the estimates for total cost of corrosion in the oil sectors (crude petroleum and petroleum refining) were US$60 million in 1987. The avoidable cost in these sectors was estimated to be US$10 million. The commercial services sector, the government, and the social and household services sectors were responsible for the largest share (70%) of the total cost of corrosion.

A.2.8 Japan (1997)

In 1999, 25 years had passed since the prior 1974 study, and the industrial structure in Japan had changed. Correspondingly, the Committee on the Cost of Corrosion in Japan was organized in 1999 jointly by the Japan Society of Corrosion Engineering (JSCE) and the Japan Association of Corrosion Control (JACC) to update the cost of corrosion.[27] The project was funded by the National Research Institute for Metals (NRIM) as part of the Ultra-Steels (STX-21) Project.

Cost of corrosion in 1997 was estimated by the Uhlig method and the Hoar method. In addition to the above estimation, a preliminary analysis by the Input/Output method was performed to estimate the total cost of corrosion including the direct and indirect costs. The overall corrosion-related cost estimated by the Uhlig and Hoar methods were 3,938 billion yen and 5,258 billion yen, respectively, which were equivalent to 0.77 percent and 1.02 percent of the 1997 GNP (converting to GDP (560,993 billion yen in 1997)[28], the cost of corrosion is equivalent to 0.70 and 0.94 respectively). The total cost including the direct and indirect costs, which were estimated by the Input/Output analysis, was equivalent to 1.88% of the 1997 GNP (1.73% of GDP). The value for the Input/Output economic model for 1997 is similar to the 1974 cost of corrosion, i.e. equivalent to 1.8% of the GDP.

The GNP and GDP analyses gave similar values for the percent cost of corrosion (especially when considering the conversions used to estimate the GDP) and since the Hoar method provided a division by Sectors, the Hoar method values were used in the global cost of corrosion analysis.

25 http://macroeconomics.kushnirs.org/index.php?area=australia&indicator=gdp&lang=en.

26 F. Al-Kharafi, A. Al-Hashem, and F. Martrouk, Economic Effects of Metallic Corrosion in the State of Kuwait, Final Report No. 4761, KISR Publications, December 1995.

27 "Survey of Corrosion Cost in Japan", Committee on Cost of Corrosion in Japan, 1997.

28 http://macroeconomics.kushnirs.org/index.php?indicator=gdp&area=japan&lang=en.

A.2.9 United States (1998): The FHWA Report

In 1998, the U.S. Congress approved an amendment to the Transportation Equity Act for the 21st Century to conduct a Cost of Corrosion study.[29] This study was funded through the Federal Highway Administration (FHWA) and performed by CC Technologies, Inc. (now part of DNV GL) partnering with NACE International, and Professor Joe Payer. This project used a combination of the Uhlig and Hoar methods with inclusion of significant expert knowledge input.

The total direct cost of corrosion was estimated at $276 billion per year, which is 3.1% of the 1998 U.S. GDP. This cost was determined by analyzing 26 industrial sectors in which corrosion is known to exist and extrapolating the results for a nationwide estimate. The sectors were divided among five major categories: infrastructure, utilities, transportation, production and manufacturing, and government. The indirect cost of corrosion was conservatively estimated to be equal to the direct cost (i.e., total direct cost plus indirect cost is 6% of the GDP). Social cost (lost time and productivity of the general public due to delays and business interruption caused by corrosion and corrosion control activities) was the primary indirect cost considered. It was found that the sectors of drinking water and sewer systems (US$36 billion), motor vehicles (US$23.4 billion), and defense (US$20 billion) had the largest direct corrosion impact. A total of US$121 billion per year was spent on corrosion control methods and services.

A.2.10 Australia (2010)

The Australasian Corrosion Association (ACA) in conjunction with industry experts performed a project to (i) examine, identify and estimate corrosion failure costs attributable to industry practices, industry skilling and regulatory frameworks, and (ii) estimate potential corrosion failure cost reductions by implementing avoidable/preventable strategies within the water transportation, processing and sewage industry in Australia.[30]

The study included: water loss from pipeline leakage, water loss from pipeline failures, intangible costs associated with water and sewer pipe failures and replacements, water pipeline corrosion repairs, sewer pipeline corrosion repairs, sewage treatment costs due to infiltration, capital cost for water and sewer pipeline replacements, maintenance and repair water treatment plants, maintenance and repair of other assets (tanks, pump stations etc.), and maintenance and repair sewage treatment plants. This approach gave a total cost of corrosion of water and sewer industry of AUD981.67 million. Although this study provided a detail cost of one industry sector, this could not be used in the IMPACT cost of corrosion study, which requires a more detailed national cost of corrosion.

[29] "Corrosion Cost and Preventive Strategies in the United States", FHWA-RD-01-156, G. Koch, M. Brongers, N. Thompson, P. Virmani, and J. Payer, March 2002.

[30] "The Australian Corrosion Association Inc. Corrosion Challenge Project", November 2010.

A.2.11 India (2011-2012)

In a study led by R. Bhaskaran at Lovely Professional University, Phagwara, Punjab, India and N.S. Rengaswamy at Central Electrochemical Research Institute, Karaikudi, India, the cost of corrosion was estimated using the NBS input/output economic model for 2011 to 2012.[31]

The India study gave one of the most detailed sector breakdowns of any of the national costs of corrosion. The direct cost of corrosion for India was US$26.1 billion or 2.4% of India GDP. The avoidable cost of corrosion was US$9.3 billion or 35% of the direct cost of corrosion. The indirect cost of corrosion was US$39.8 billion or 3.6% of India GDP. Several of the indirect cost of corrosion for the India study (input/output model) were classified as direct costs in the 1998 United States study (Hoar method). These include: loss of product, loss of efficiency, and production loss; only social costs were classified as indirect costs in the United States study. If only the social costs are classified as indirect costs, the direct cost of corrosion in India is 4.5%.

A.3 IMPACT COST OF CORROSION ANALYSIS

Since various geographic regions differ in the proportion of different economic sectors in their economy, to relate the above cost of corrosion studies to a global cost of corrosion, a relationship between economic sectors and corrosion costs is needed. Furthermore, the GDP of the economic sectors by country must be known to permit the use of the "percent cost of corrosion by economic sector" within the extrapolation to global corrosion costs. For instance, those studies that provide only a total input/output model cost of corrosion for the whole country do not permit a global cost of corrosion based on an economic sector analysis.

Considering the data in the available studies, the economic sectors used in this analysis were (1) Agriculture, (2) Industry, and (3) Services. For each of these Sectors, (1) the cost of corrosion was estimated by summing the costs of the appropriate sub-sectors for a given study and (2) the GDP for every nation globally divided into these Sectors was available from the World Bank data[32].

The studies that were included in the IMPACT cost of corrosion Study were: India 2011-2012, United States 1998, Japan 1997, Kuwait 1987, and United Kingdom 1970. Each of these studies provided data that could be divided into the three economic sectors discussed above.

As previously mentioned, several other studies produced a cost of corrosion associated with the total annual GDP; the GDP and cost of corrosion was not divided into sectors. These studies included Saudi Arabia, United Arab Emirates, Oman, Qatar, Bahrain, Australia and Columbia. Therefore, these studies could not be included in the Sector analysis of cost of corrosion.

---

[31] "An Analysis of the Updated Cost of Corrosion in India", Materials Performance, Vol. 53, No. 8, pp. 56-65.

[32] The World Fact Book, GDP – Composition, by Sector of Origin (%), https://www.cia.gov/library/publications/the-world-factbook/fields/2012.html.

A.4 DEFINITION OF 'GROSS DOMESTIC PRODUCT – GDP'

The GDP was used for the IMPACT cost of corrosion global analysis, because it permits the summing of GDPs of multiple countries to provide an aggregate GDP for a given analysis. In addition, the GDPs for all countries were available along with the division of GDP into economic sectors.

The GDP of the three economic Sectors (Agriculture, Industry, and Services) is the basis for extrapolating the cost of corrosion from six countries (those with detailed cost of corrosion analyses) to a global cost of corrosion. GDP is the monetary value of all the finished goods and services produced within a country's borders in a specific time period, although GDP is usually calculated on an annual basis.[33] It includes all private and public consumption, government outlays, investments and exports less imports that occur within a defined territory.

GDP = C + G + I + NX

where:

"**C**" is equal to all private consumption, or consumer spending, in a nation's economy; "**G**" is the sum of government spending; "**I**" is the sum of all the country's businesses spending on capital; and "**NX**" is the nation's total net exports, calculated as total exports minus total imports (NX = Exports - Imports).

A.5 SECTOR BREAKDOWN

Economic breakdown by sector can be performed in multiple ways: (1) sectors of primary importance to a given technology (e.g. NACE International has technical committees broken down by industries), (2) sectors consistent with prior studies (e.g. Sectors from the 2002 FHWA report "Corrosion Cost and Preventive Strategies in the United States"), (3) sectors determined by a committee of subject matter experts, or (4) sectors based on the World Bank data. To facilitate comparison of studies, it was decided to utilize the World Bank international categorization of the GDP[15] with some modification to permit mapping and provide as much detail as possible. Each study used was mapped into the Sector list given in Table A-1.

The World Bank measures a countries' GDP by breaking the GDP into three primary sectors referred to as Level 1 in Table A-1: Agriculture, Industry, and Services. Each Level 1 Sector was subdivided into subcategories (Levels 2 and 3). Green shade indicates the three primary Sectors of the GDP, pink represents the Level 2 subcategories and no shading represents the Level 3 subcategories. World Bank sub-sectors are denoted by letters A to S in front of the category name (the majority of these were Level 2 with N, O, P, and Q placed under a Level 2 heading of "Community, Social and Personal Services".

33 http://www.investopedia.com/terms/g/gdp.asp#ixzz3dEila2AG.

Table A-1. Breakdown of Sectors

Level 1	**Level 2**	Level 3
Agriculture & Allied Activities	**A. Agriculture, Forestry & Fishing**	
Industry	**B. Mining & Quarrying**	Petroleum & Natural Gas
		Other Mining
	C. Manufacturing	Non-metallic products
		Metal products & Basic Metal Industries
		Electrical machinery
		Transport equipment
		Chemicals, etc.
		Petroleum Refining and other related products
		Paper & Printing, etc.
		Food products, Beverages & Tobacco
		Other manufacturing (General)
	F. Construction	New Construction
		Repair & Maintenance
	D. Electricity, Gas, Steam, & AC Supply	Gas (icl. distribution pipelines)
		Electricity, Power Generation, Transmission
	E. Water Supply, Sewage, Waste Management & Remediation	
Services	**I. Accommodation & Food Service Activities**	
	H. Transportation & Storage	Rail transport, Trains
		Road transport, Automobiles
		Water transport, Ships, Marine
		Air transport
		Transmission Pipelines
		Power Transmission
		Waterways & Ports
		Hazardous Material Transport
		Transportation Services
		Highway Bridges
		Storage
	J. Information & Communication	
	K. Financial & Insurance Activities	Real Estate
		Legal Services
	G. Wholesale and retail trade	
	R. Arts, Entertainment & Recreation	
	M. Professional, Scientific & Technical Activities	
	S. Other Service Activities	
	Community, Social & Personal Services	N. Administrative & Support Services Activities
		O. Public Administration & Defense; Social Security
		P. Education
		Q. Human Health & Social Work Activities

A.6 RESULTS

A.6.1 Summary Cost of Corrosion Studies

Table A-2 presents the cost of corrosion as an equivalent percentage of the GDP for the countries that have performed studies. Several of the countries noted performed the input/output model and reported only a total cost of corrosion with no sector breakdown.

Table A-2. Cost of Corrosion Summary for Countries (percentage of the GDP)

Study	Agriculture %CoC	Industry %CoC	Services %CoC	Total %CoC
Saudi Arabia 2011* [34]				2.7
Kuwait 2011*[18]				1.7
United Arab Emirates 2011*[18]				1.3
Oman 2011*[18]				1.8
Qatar 2011*[18]				0.7
Bahrain 2011*[18]				2.1
Columbia 1993[35]				2.4
Australia 1982*[24]				1.5
United States 1998 [29]	1.1	9.3	1.3	3.1
India 2011** [31]	6.1	4.7	3.4	4.5
Japan 1974*** [22]				1.8
Japan 1997 [27]		3.6	0.1	1.0
United Kingdom 1970 [21]		8.6	2.2	3.5
Kuwait 1987 [26]	9.5	2.2	8.3	5.2

Note: * Input output model with only the total cost of corrosion provided.
** Based on indirect cost of corrosion other than social costs included in "cost of corrosion".
*** The Hoar method was used instead of the Input/Output method because Sector information was available from the Hoar method. In addition the GNP and estimate for GDP were similar.

A.6.2 Sector Cost of Corrosion

For national cost of corrosion studies to be used in an economic sector analysis, the study itself had to include sector details. For the purpose of this study, the individual study sector detail was mapped to the Sectors given in Table A-2. The following studies had the necessary sector detail (although the level of detail varied) and were used in the IMPACT cost of corrosion Global analysis:

- India 2011-2012.
- United States 1998.
- Japan 1997.

[34] "Corrosion in the Gulf Cooperation Council (GCC) States: Statistics and Figures", A. Al-Hashem.

[35] "A System Approach for Estimating Corrosion Incidence to the Economy of a Nation", 1994 International System Dynamics Conference, R. Sotaquira, et al., 1994.

- Kuwait 1987.
- United Kingdom 1970.

Table A-3 through Table A-7 provide the Sector detail for the individual studies.

Table A-3. Cost of Corrosion by Sector for India 2011-2012 study

Sector	*CoC [USD million]*	*GDP [USD million]*	*%CoC [of GDP]*
Agriculture & Allied Activities	***12,496.0***	***203,934.0***	***6.1%***
A. Agriculture, Forestry & Fishing			
Industry	***22,805.0***	***488,110.0***	***4.7%***
B. Mining & Quarrying	1,619.0	26,388.0	6.1%
Petroleum & Natural Gas	172.0	11,677.0	1.5%
Other Mining	417.0	14,711.0	2.8%
C. Manufacturing	10,277.0	178,757.0	5.7%
Non-metallic products	50.0	10,310.0	0.5%
Metal products & Basic Metal Industries	1,472.0	41,200.0	3.6%
Electrical machinery	135.0	9,254.0	1.5%
Transport equipment	374.0	17,313.0	2.2%
Chemicals, etc.	486.0	22,489.0	2.2%
Petroleum Refining and other related products	304.0	18,425.0	1.6%
Paper & Printing, etc.	112.0	6,209.0	1.8%
Food products, Beverages & Tobacco	69.0	18,788.0	0.4%
Other manufacturing (General)	7,275.0	34,769.0	20.9%
F. Construction	8,015.0	251,266.0	3.2%
New Construction	6,472.0	201,635.0	3.2%
Repair & Maintenance	1,543.0	49,631.0	3.1%
D. Electricity, Gas, Steam, & AC Supply	2,102.0	18,445.0	11.4%
Gas (icl. distribution pipelines)	11.00	1,367.0	0.8%
Electricity, Power Generation, Transmission	1,721.0	17,078.0	10.1%
E. Water Supply, Sewage, Waste Management & Remediation	792.0	13,254.0	6.0%
Services	***13,471.0***	***396,093.0***	***3.4%***
I. Accommodation & Food Service Activities	3,655.0	15,823.0	23.1%
H. Transportation & Storage	2,392.0	80,267.0	3.0%
Rail transport, Trains	496.0	17,608.0	2.8%
Road transport, Automobiles	1,614.0	52,073.0	3.1%
Water transport, Ships, Marine	83.0	2,347.0	3.5%
Air transport	104.0	2,945.0	3.5%
Transmission Pipelines			
Power Transmission			
Waterways & Ports			
Hazardous Material Transport			
Transportation Services	72.00	4,532.00	1.6%
Highway Bridges			
Storage	23.00	762.0	3.0%
J. Information & Communication	799.0	21,125.0	3.8%
K. Financial & Insurance Activities	1,194.0	53,061.0	2.3%
Real Estate	1,153.00	49,707.0	2.3%
Legal Services	41.00	3,354.0	1.2%
G. Wholesale and retail trade	3,660.0	173,464.0	2.1%
R. Arts, Entertainment & Recreation	16.00	4,872.0	0.3%
M. Professional, Scientific & Technical Activities			
S. Other Service Activities	1,590.0		
Community, Social & Personal Services	165.0	47,481.0	0.3%
N. Administrative & Support Services Activities			
O. Public Administration & Defense; Social Security			
P. Education	98.0	32,578.0	0.3%
Q. Human Health & Social Work Activities	67.0	14,903.0	0.4%

Table A-4. Cost of Corrosion by Sector for United States 1998 study

Sector	CoC [USD billion]	GDP [USD billion]	%CoC [of GDP]
Agriculture & Allied Activities	***1.1***	***96.6***	***1.1%***
A. Agriculture, Forestry & Fishing			
Industry	***159.7***	***1,712.4***	***9.3%***
B. Mining & Quarrying	1.5	100.2	1.5%
Petroleum & Natural Gas	1.4	72.8	1.9%
Other Mining	0.1	27.4	0.4%
C. Manufacturing	60.3	2,092.4	2.9%
Non-metallic products			
Metal products & Basic Metal Industries			
Electrical machinery			
Transport equipment			
Chemicals, etc.	1.35	164.8	0.8%
Petroleum Refining and other related products	3.7	89.7	4.1%
Paper & Printing, etc.	6.0	151.3	4.0%
Food products, Beverages & Tobacco	2.1	139.1	1.5%
Other manufacturing (General)	47.15	1,547.5	3.0%
F. Construction	50.0	380.8	13.1%
New Construction			
Repair & Maintenance			
D. Electricity, Gas, Steam, & AC Supply	11.9	204.8	5.8%
Gas (icl. distribution pipelines)	5.0		
Electricity, Power Generation, Transmission	6.9		
E. Water Supply, Sewage, Waste Management & Remediation	36.0		
Services	**93.5**	**6,972.5**	**1.3%**
I. Accommodation & Food Service Activities			
H. Transportation & Storage	56.5	539.6	10.5%
Rail transport, Trains	0.5	24.3	2.1%
Road transport, Automobiles	23.4	323.4	7.2%
Water transport, Ships, Marine	2.7	13.6	19.9%
Air transport	2.2	85.8	2.6%
Transmission Pipelines	7.0	6.1	114.8%
Power Transmission	0.6		
Waterways & Ports	0.3		
Hazardous Material Transport	0.9		
Transportation Services	3.47	86.40	4.0%
Highway Bridges	8.30		
Storage	7.1		
J. Information & Communication	31.2	238.5	13.1%
K. Financial & Insurance Activities			
Real Estate			
Legal Services			
G. Wholesale and retail trade			
R. Arts, Entertainment & Recreation	5.8	99.2	5.8%
M. Professional, Scientific & Technical Activities			
S. Other Service Activities			
Community, Social & Personal Services	5.8	2,933.2	0.2%
N. Administrative & Support Services Activities			
O. Public Administration & Defense; Social Security			
P. Education			
Q. Human Health & Social Work Activities			

Table A-5. Cost of Corrosion by Sector for Japan 1997 study

Sector	CoC [Yen billion]	GDP [Yen billion]	%CoC [of GDP]
Agriculture & Allied Activities		**6,172**	
A. Agriculture, Forestry & Fishing			
Industry	***4713.5***	***131,672***	***3.58%***
B. Mining & Quarrying			
Petroleum & Natural Gas			
Other Mining			
C. Manufacturing	2659.1		
Non-metallic products			
Metal products & Basic Metal Industries	27.6		
Electrical machinery			
Transport equipment			
Chemicals, etc.	1070		
Petroleum Refining and other related products			
Paper & Printing, etc.			
Food products, Beverages & Tobacco			
Other manufacturing (General)	1561.5		
F. Construction	1597.6		
New Construction			
Repair & Maintenance			
D. Electricity, Gas, Steam, & AC Supply	456.8		
Gas (icl. distribution pipelines)			
Electricity, Power Generation, Transmission			
E. Water Supply, Sewage, Waste Management & Remediation			
Services	**544.7**	**376,499**	**0.14%**
I. Accommodation & Food Service Activities			
H. Transportation & Storage	544.7		
Rail transport, Trains	18.4		
Road transport, Automobiles	445.7		
Water transport, Ships, Marine	80.6		
Air transport			
Transmission Pipelines			
Power Transmission			
Waterways & Ports			
Hazardous Material Transport			
Transportation Services			
Highway Bridges			
Storage			
J. Information & Communication			
K. Financial & Insurance Activities			
Real Estate			
Legal Services			
G. Wholesale and retail trade			
R. Arts, Entertainment & Recreation			
M. Professional, Scientific & Technical Activities			
S. Other Service Activities			
Community, Social & Personal Services			
N. Administrative & Support Services Activities			
O. Public Administration & Defense; Social Security			
P. Education			
Q. Human Health & Social Work Activities			

Table A-6. Cost of Corrosion by Sector for Kuwait 1987 study

Sector	CoC [KD thousand]	GDP [KD thousand]	%CoC [of GDP]
Agriculture & Allied Activities	**1,761**	**18,517**	***9.5%***
A. Agriculture, Forestry & Fishing	1,761		
Industry	***69,789***	**3,123,194**	***2.23%***
B. Mining & Quarrying	8,786		
Petroleum & Natural Gas			
Other Mining			
C. Manufacturing	32,734		
Non-metallic products	8,292		
Metal products & Basic Metal Industries	673		
Electrical machinery			
Transport equipment			
Chemicals, etc.	3,252		
Petroleum Refining and other related products	10,480		
Paper & Printing, etc.			
Food products, Beverages & Tobacco	3,585		
Other manufacturing (General)	6,452		
F. Construction	34,394		
New Construction			
Repair & Maintenance			
D. Electricity, Gas, Steam, & AC Supply	-6,125		
Gas (icl. distribution pipelines)			
Electricity, Power Generation, Transmission			
E. Water Supply, Sewage, Waste Management & Remediation			
Services	**250,028**	**3,030,610**	**8.3%**
I. Accommodation & Food Service Activities	7,258		
H. Transportation & Storage	17,627		
Rail transport, Trains			
Road transport, Automobiles			
Water transport, Ships, Marine			
Air transport			
Transmission Pipelines			
Power Transmission			
Waterways & Ports			
Hazardous Material Transport			
Transportation Services			
Highway Bridges			
Storage			
J. Information & Communication			
K. Financial & Insurance Activities			
Real Estate			
Legal Services			
G. Wholesale and retail trade			
R. Arts, Entertainment & Recreation			
M. Professional, Scientific & Technical Activities			
S. Other Service Activities	118,203		
Community, Social & Personal Services	106,940		
N. Administrative & Support Services Activities			
O. Public Administration & Defense; Social Security			
P. Education			
Q. Human Health & Social Work Activities			

Table A-7. Cost of Corrosion by Sector for United Kingdom 1970 study

Sector	CoC [£ million]	GDP [£ million]	%CoC [of GDP]
Agriculture & Allied Activities		*273.0*	
A. Agriculture, Forestry & Fishing			
Industry	*680*	*7950.0*	*8.55%*
B. Mining & Quarrying			
Petroleum & Natural Gas			
Other Mining			
C. Manufacturing	*345*		
Non-metallic products			
Metal products & Basic Metal Industries	15		
Electrical machinery			
Transport equipment			
Chemicals, etc.			
Petroleum Refining and other related products	180		
Paper & Printing, etc.			
Food products, Beverages & Tobacco	40		
Other manufacturing (General)	110		
F. Construction	250		
New Construction	250		
Repair & Maintenance			
D. Electricity, Gas, Steam, & AC Supply	60		
Gas (icl. distribution pipelines)			
Electricity, Power Generation, Transmission	60		
E. Water Supply, Sewage, Waste Management & Remediation	25		
Services	630	30771.0	2.05%
I. Accommodation & Food Service Activities			
H. Transportation & Storage	630		
Rail transport, Trains			
Road transport, Automobiles	350		
Water transport, Ships, Marine	280		
Air transport			
Transmission Pipelines			
Power Transmission			
Waterways & Ports			
Hazardous Material Transport			
Transportation Services			
Highway Bridges			
Storage			
J. Information & Communication			
K. Financial & Insurance Activities			
Real Estate			
Legal Services			
G. Wholesale and retail trade			
R. Arts, Entertainment & Recreation			
M. Professional, Scientific & Technical Activities			
S. Other Service Activities			
Community, Social & Personal Services			
N. Administrative & Support Services Activities			
O. Public Administration & Defense; Social Security	55		
P. Education			
Q. Human Health & Social Work Activities			

India 2011-2012 and United States 1998 studies provided the most significant Sector detail. There are two main points pertinent to the IMPACT cost of corrosion analysis: (i) the degree of Sector detail varies significantly from study to study and (ii) there are only five studies with Sector data that can be applied to a global CoC analysis that uses Sector detail as a basis.

A.6.3 Economic Sector Analysis

The economic sector analysis divides each economy by GDP in Agriculture, Industry and Services based on 2013 data (primarily 2013 but varies slightly by country).[36] The economic breakdown for the five countries used in this analysis is shown in Figure A-1. The United States, United Kingdom and Japan are very similar, with India and Kuwait more unique.

In order to address the economic sectors for different parts of the world, the global economy was divided into economic regions with similar economies. Figure A-2 shows a division of the world economy into regions, in accordance with the 2013 GDP. Figure A-3 shows the Sector division for each economic Region.

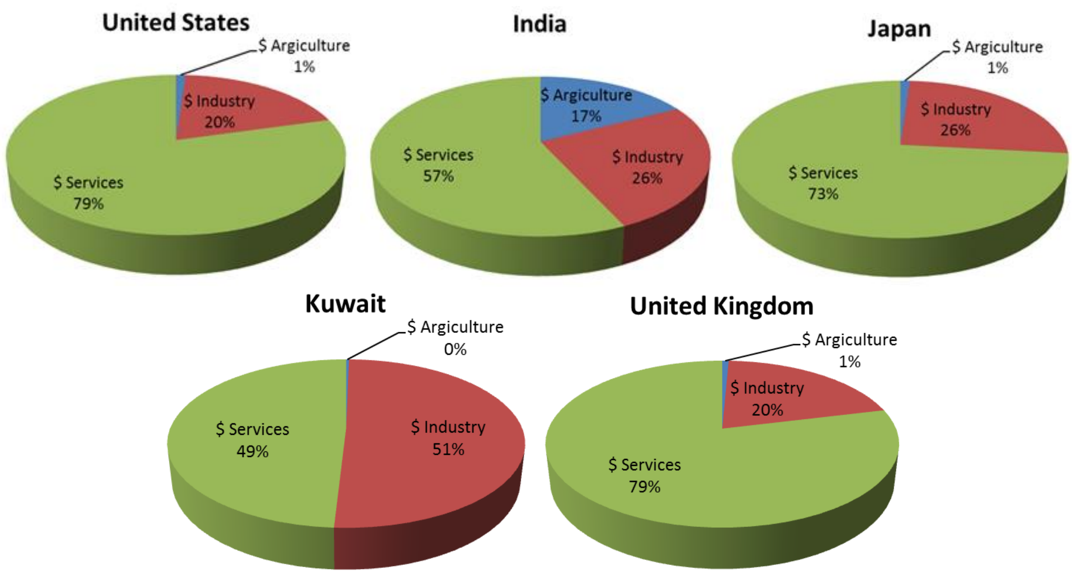


Figure A-1. Economic Sectors for the five countries used in the Global Cost of Corrosion Study

[36] The World Fact book.

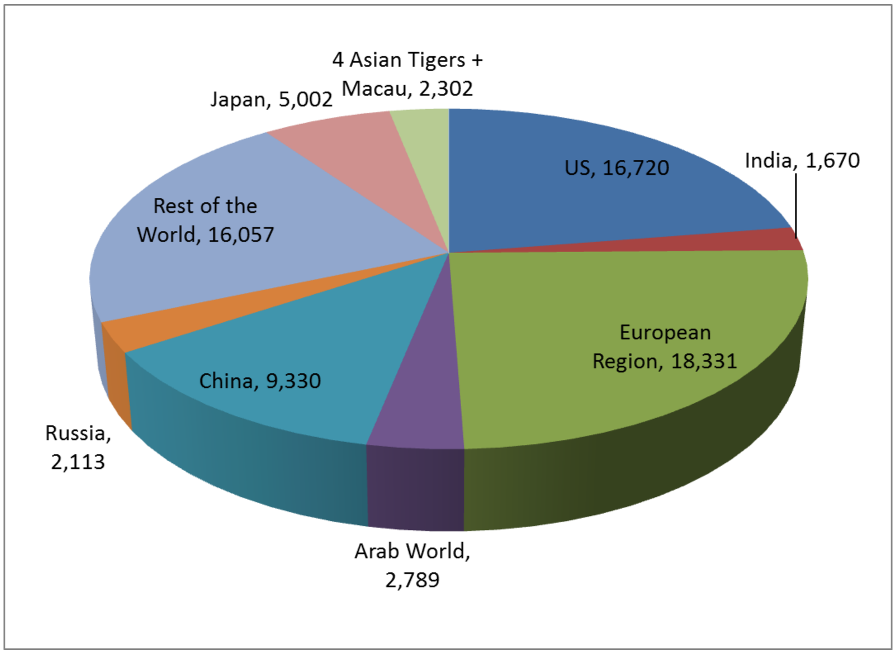


Figure A-2. Global GDP by Economic Region (BUSD)

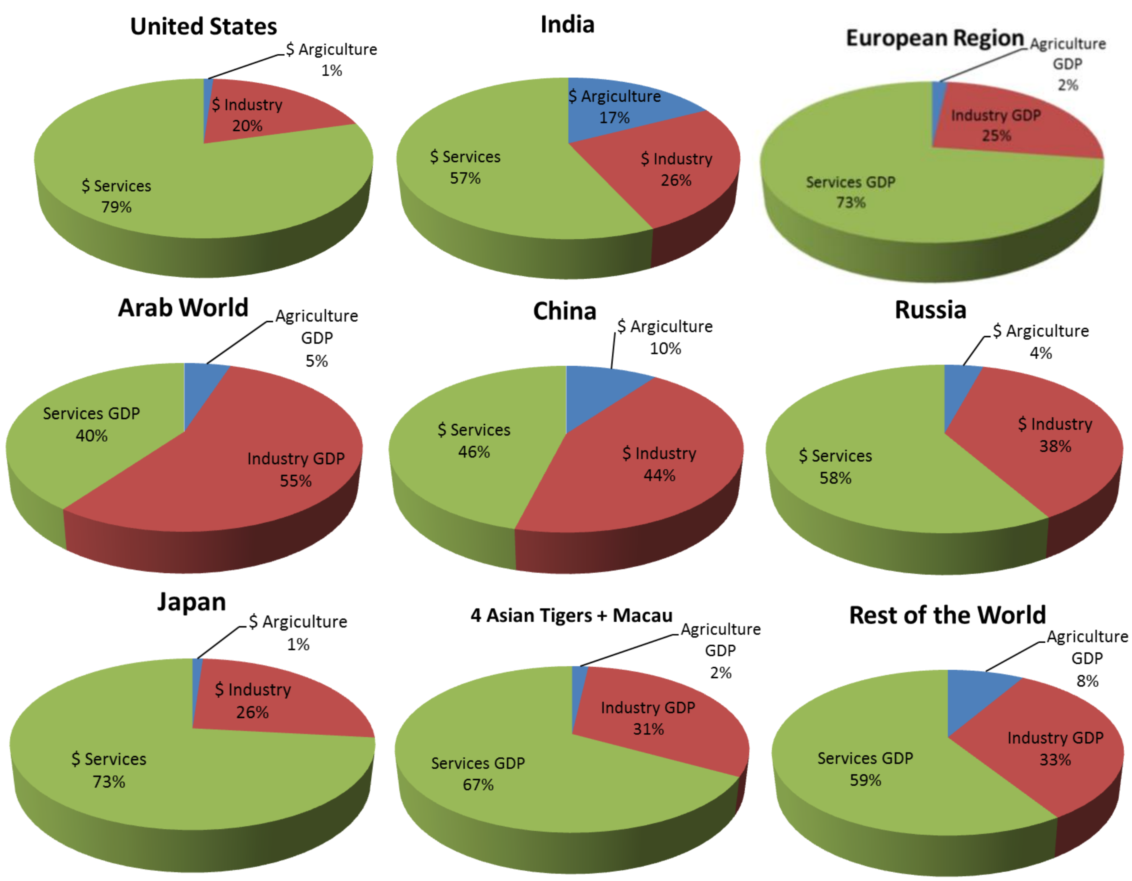


Figure A-3. Economic sectors for the nine economic Regions in Figure A-2

A.6.4 Global Cost of Corrosion Analysis

The global Cost of Corrosion was assessed by mapping the Cost of Corrosion studies to the nine economic Regions using Table A-8. The European Region, Arab World, Four Asian Tigers + Macau include the following countries:

- European Region
  - Austria
  - Belgium
  - Bulgaria
  - Croatia
  - Cyprus
  - Czech Republic
  - Denmark
  - Estonia
  - Finland
  - France
  - Germany
  - Greece
  - Hungary
  - Ireland
  - Italy
  - Latvia
  - Lithuania
  - Luxembourg
  - Malta
  - Netherlands
  - Norway
  - Poland
  - Portugal
  - Romania
  - Slovakia
  - Slovenia
  - Spain
  - Sweden
  - Switzerland
  - United Kingdom

- Arab World
  - Algeria
  - Bahrain
  - Comoros
  - Djibouti
  - Egypt
  - Iraq
  - Jordan
  - Kuwait
  - Lebanon
  - Libya
  - Mauritania
  - Morocco
  - Oman
  - Qatar
  - Saudi Arabia
  - Somalia
  - Sudan
  - Syria
  - Tunisia
  - UAE
  - West Bank
  - Yemen

- Four Asian Tigers + Macau
  - Hong Kong
  - Korea, South
  - Macau
  - Singapore
  - Taiwan

Table A-8. Map of Cost of Corrosion studies to economic Regions

Economic Regions	CoC Study used for Region CoC	Agriculture %CoC	Industry %CoC	Services %CoC
United States	United States 1998	1.1	9.3	1.3
India	India 2011	6.1	4.7	3.4
European Region	United Kingdom 1970	1.1*	8.6	2.2
Arab World	Kuwait 1987	9.5	2.2	8.3
China	India 2011	6.1	4.7	3.4
Russia	India 2011	6.1	4.7	3.4
Japan	Japan 1997	1.1*	3.6	0.1
Four Asian Tigers + Macau	Average of India and Japan studies	1.1*	3.6	0.1
Rest of the World	Average of all studies	3.8	7.4	1.2

Note: * CoC was not reported in primary study but value for the United States 1998 Study was used.

The World Factbook provides a breakdown of each country's GDP into the economic sectors; Agriculture, Industry and Services. The data by country is provided in Table A-10 at the end of this Appendix. Using Table A-8 and Table A-9, the Cost of Corrosion for each country by Sector and the total Cost of Corrosion for each country was determined. The Global Cost of Corrosion is then determined for each economic Region by Sector and is given in Table A-9. The global cost of corrosion is estimated to be US$2,505 billion or 3.4% of the global GDP (2013).

Table A-9. Global Cost of Corrosion by Region by Sector (Billion USD)

Economic Regions	Agriculture CoC USD billion	Industry CoC USD billion	Services CoC USD billion	Total CoC USD billion	Total GDP USD billion	CoC % GDP
United States	2.0	303.2	146.0	451.3	16,720	2.7%
India	17.7	20.3	32.3	70.3	1,670	4.2%
European Region	3.5	401	297	701.5	18,331	3.8%
Arab World	13.3	34.2	92.6	140.1	2,789	5.0%
China	56.2	192.5	146.2	394.9	9,330	4.2%
Russia	5.4	37.2	41.9	84.5	2,113	4.0%
Japan	0.6	45.9	5.1	51.6	5,002	1.0%
Four Asian Tigers + Macau	1.5	29.9	27.3	58.6	2,302	2.5%
Rest of the World	52.4	382.5	117.6	552.5	16,057	3.4%
Global	**152.7**	**1446.7**	**906.0**	**2505.4**	**74,314**	**3.4%**

This estimate of US$2,505 billion is based on available studies that had sufficient sector detail for a global sector analysis to be performed. As additional studies become available, the global cost of corrosion could be updated and improved. Previous cost of corrosion studies indicated that between 15 and 35% of the cost of corrosion could be saved by using current available corrosion control practices, which is between US$375 and US$875 billion globally.

Table A-10. GDP Sector Breakdown by Country

Country	GDP (Official Exchange Rate) (USD billion)	% Agriculture	$ Agriculture	% Industry	$ Industry	% Services	$ Services	Year Est.
Afghanistan	$20.65	20.0%	4.13	25.6%	5.29	54.4%	11.23	2011
Albania	$12.80	19.5%	2.50	12.0%	1.54	68.5%	8.77	2011
Algeria	$215.70	9.4%	20.28	62.6%	135.03	28.0%	60.40	2011
American Samoa	$0.46	N/A		N/A		N/A		
Andorra	$4.80	14.0%	0.67	79.0%	3.79	6.0%	0.29	2011
Angola	$124.00	10.2%	12.65	61.4%	76.14	28.4%	35.22	2011
Anguilla	$0.18	2.5%	0.00	23.6%	0.04	73.8%	0.13	2013
Antigua and Barbuda	$1.22	2.2%	0.03	16.4%	0.20	81.4%	0.99	2013
Argentina	$484.60	9.3%	45.07	29.7%	143.93	61.0%	295.61	2013
Armenia	$10.44	20.6%	2.15	37.3%	3.89	42.1%	4.40	2013
Aruba	$2.52	0.4%	0.01	33.3%	0.84	66.3%	1.67	2002
Australia	$1,488.00	3.8%	56.54	27.4%	407.71	68.7%	1,022.26	2013
Austria	$417.90	1.6%	6.69	28.6%	119.52	69.8%	291.69	2013
Azerbaijan	$76.01	6.2%	4.71	63.0%	47.89	69.8%	53.05	2013
Bahamas, The	$8.37	2.1%	0.18	7.1%	0.59	90.8%	7.60	2013
Bahrain	$28.36	0.3%	0.09	46.7%	13.24	53.0%	15.03	2013
Bangladesh	$140.20	17.2%	24.11	28.9%	40.52	53.9%	75.57	2013
Barbados	$4.26	3.1%	0.13	13.9%	0.59	83.0%	3.54	2013
Belarus	$69.24	9.2%	6.37	46.2%	31.99	44.7%	30.95	2013
Belgium	$507.40	0.8%	4.06	22.6%	114.67	76.6%	388.67	2013
Belize	$1.64	13.0%	0.21	23.0%	0.38	64.0%	1.05	2012
Benin	$8.36	31.6%	2.64	12.9%	1.08	55.6%	4.65	2013
Bermuda	$5.60	0.7%	0.04	5.7%	0.32	93.5%	5.24	2013
Bhutan	$2.13	13.8%	0.29	41.2%	0.88	45.0%	0.96	2013
Bolivia	$30.79	9.2%	2.83	38.5%	11.85	52.3%	16.10	2013
Bosnia and Herzegovina	$18.87	8.1%	1.53	26.4%	4.98	65.5%	12.36	2013
Botswana	$15.53	1.9%	0.30	35.7%	5.54	62.4%	9.69	2013
Brazil	$2,190	5.5%	120.45	26.4%	578.16	68.1%	1,491.39	2013
British Virgin Islands	$1.10	1.1%	0.01	11.7%	0.13	87.2%	0.95	2013
Brunei	$16.56	0.7%	0.12	70.9%	11.74	28.4%	4.70	2013
Bulgaria	$53.70	6.7%	3.60	30.3%	16.27	63.0%	33.83	2013
Burkina Faso	$12.13	33.6%	4.08	23.6%	2.86	42.8%	5.19	2013
Burma	$59.43	38.0%	22.58	20.3%	12.06	41.7%	24.78	2013
Burundi	$2.68	34.4%	0.92	18.4%	0.49	47.2%	1.26	2013
Cabo Verde	$1.96	9.3%	0.18	18.8%	0.37	71.9%	1.41	2013
Cambodia	$15.64	34.8%	5.44	24.5%	3.83	40.7%	6.37	2013
Cameroon	$27.88	20.6%	5.74	27.3%	7.61	52.1%	14.53	2013
Canada	$1,825.00	1.7%	31.03	28.4%	518.30	69.9%	1,275.68	2013
Cayman Islands	$2.25	0.3%	0.01	27.4%	0.62	72.3%	1.63	2013
Central African Republic	$2.05	56.6%	1.16	14.5%	0.30	28.9%	0.59	2013
Chad	$13.59	46.3%	6.29	9.9%	1.35	43.8%	5.95	2013
Chile	$281.70	3.6%	10.14	35.4%	99.72	61.0%	171.84	2013
China	$9,330.00	10.0%	933.00	43.9%	4,095.87	46.1%	4,301.13	2013
Columbia	$369.20	6.6%	24.37	37.8%	139.56	55.6%	205.28	2013
Comoros	$0.66	51.0%	0.34	10.0%	0.07	39.0%	0.26	2012
Congo, Democratic Republic of the	$18.56	44.3%	8.22	21.7%	4.03	34.0%	6.31	2013
Congo, Republic of the	$14.25	3.3%	0.47	73.9%	10.53	22.9%	3.26	2013
Cook Islands	$0.18	5.1%	0.01	12.7%	0.02	82.1%	0.15	2010
Costa Rica	$48.51	6.2%	3.01	21.3%	10.33	72.5%	35.17	2013
Cote d'Ivoire	$28.28	26.3%	7.44	21.3%	6.02	52.4%	14.82	2013
Croatia	$59.14	5.0%	2.96	25.8%	15.26	69.2%	40.92	2013
Cuba	$72.30	3.8%	2.75	22.3%	16.12	73.9%	53.43	2013
Curacao	$5.60	0.7%	0.04	15.5%	0.87	83.8%	4.69	2012

Table A-10. GDP Sector Breakdown by Country

Country	GDP (Official Exchange Rate) (USD billion)	% Agriculture	$ Agriculture	% Industry	$ Industry	% Services	$ Services	Year Est.
Cyprus	$21.78	2.4%	0.52	15.9%	3.46	81.7%	17.79	2013
Czech Republic	$194.80	2.4%	4.68	37.3%	72.66	60.3%	117.46	2012
Denmark	$324.30	1.5%	4.86	21.7%	70.37	76.8%	249.06	2013
Djibouti	$1.46	3.0%	0.04	17.3%	0.25	79.7%	1.16	2013
Dominica	$0.50	15.7%	0.08	15.6%	0.08	68.7%	0.34	2013
Dominican Republic	$59.27	6.0%	3.56	29.1%	17.25	64.9%	38.47	2013
Ecuador	$91.41	5.9%	5.39	35.1%	32.08	59.0%	53.93	2013
Egypt	$262.00	14.5%	37.99	37.5%	98.25	48.0%	125.76	2013
El Salvador	$24.67	10.3%	2.54	29.5%	7.28	60.1%	14.83	2013
Equatorial Guinea	$17.08	4.6%	0.79	87.3%	14.91	8.1%	1.38	2013
Eritrea	$3.44	11.7%	0.40	26.9%	0.92	61.4%	2.11	2013
Estonia	$24.28	3.9%	0.95	30.0%	7.28	66.2%	16.07	2013
Ethiopia	$47.34	47.0%	22.25	10.8%	5.11	42.2%	19.98	2013
European Union	$16,950.00	1.8%	305.10	25.2%	4,271.40	72.8%	12,339.60	2013
Falkland Islands	$0.16	95.0%	0.16	N/A		N/A		1996
Faroe Islands	$2.32	16.0%	0.37	29.0%	0.67	55.0%	1.28	2007
Fiji	$4.22	11.7%	0.49	18.1%	0.76	70.2%	2.96	2013
Finland	$259.60	2.9%	7.53	25.1%	65.16	71.9%	186.65	2013
France	$2,739.00	1.9%	52.04	18.7%	512.19	79.4%	2,174.77	2013
French Polynesia	$5.65	3.1%	0.18	20.0%	1.13	76.9%	4.34	2006
Gabon	$19.97	3.6%	0.72	63.9%	12.76	32.5%	6.49	2013
Gambia, The	$0.90	19.7%	0.18	12.6%	0.11	67.7%	0.61	2013
Georgia	$15.95	8.5%	1.36	21.6%	3.45	69.9%	11.15	2013
Germany	$3,593.00	0.8%	28.74	30.1%	1,081.49	69.0%	2,479.17	2013
Ghana	$45.55	21.5%	9.79	28.7%	13.07	49.8%	22.68	2013
Gibraltar	$1.11	0.0%	0.00	0.0%	0.00	100.0%	1.11	2008
Greece	$243.30	3.5%	8.52	16.0%	38.93	80.5%	195.86	2013
Greenland	$2.16	4.0%	0.09	29.0%	0.63	67.0%	1.45	2009
Grenada	$0.81	5.6%	0.05	15.8%	0.13	78.5%	0.64	2013
Guam	$4.60	N/A		N/A		N/A		2010
Guatemala	$53.90	13.5%	7.28	23.8%	12.83	62.7%	33.80	2013
Guernsey	$2.74	3.0%	0.08	10.0%	0.27	87.0%	2.39	2000
Guinea	$6.54	22.9%	1.50	46.5%	3.04	30.5%	2.00	2013
Guinea-Bissau	$0.88	58.0%	0.51	13.5%	0.12	28.5%	0.25	2013
Guyana	$3.02	20.7%	0.63	38.5%	1.16	40.8%	1.23	2013
Haiti	$8.29	24.1%	2.00	19.9%	1.65	56.0%	4.64	2013
Honduras	$18.88	14.0%	2.64	28.2%	5.32	57.8%	10.91	2013
Hong Kong	$272.10	0.0%	0.00	6.9%	18.77	93.0%	253.05	2013
Hungary	$130.60	3.4%	4.44	28.0%	36.57	68.7%	89.72	2013
Iceland	$14.59	5.9%	0.86	22.9%	3.34	71.2%	10.39	2013
India	$1,670.00	17.4%	290.58	25.8%	430.86	56.9%	950.23	2013
Indonesia	$867.50	14.3%	124.05	46.6%	404.26	39.1%	339.19	2013
Iran	$411.90	10.6%	43.66	44.9%	184.94	44.5%	183.30	2013
Iraq	$221.80	3.3%	7.32	64.6%	143.28	32.1%	71.20	2013
Ireland	$220.90	1.6%	3.53	28.0%	61.85	70.4%	155.51	2013
Isle of Man	$4.08	1.0%	0.04	11.0%	0.45	88.0%	3.59	2009
Israel	$272.70	2.4%	6.54	31.2%	85.08	66.4%	181.07	2013
Italy	$2,068.00	2.0%	41.36	24.4%	504.59	73.5%	1,519.98	2013
Jamaica	$14.39	6.5%	0.94	29.4%	4.23	64.1%	9.22	2013
Japan	$5,007.00	1.1%	55.08	25.6%	1,281.79	73.2%	3,665.12	2013
Jersey	$5.10	2.0%	0.10	2.0%	0.10	96.0%	4.90	2010
Jordan	$34.08	3.2%	1.09	29.9%	10.19	67.0%	22.83	2013
Kazakhstan	$224.90	5.2%	11.69	37.9%	85.24	56.9%	127.97	2011
Kenya	$45.31	29.3%	13.28	17.4%	7.88	53.3%	24.15	2013

Table A-10. GDP Sector Breakdown by Country

Country	GDP (Official Exchange Rate) (USD billion)	% Agriculture	$ Agriculture	% Industry	$ Industry	% Services	$ Services	Year Est.
Kiribati	$0.17	24.3%	0.04	7.9%	0.01	67.8%	0.12	2010
Korea, North	$28.00	23.4%	6.55	47.2%	13.22	29.4%	8.23	2012
Korea, South	$1,198.00	2.6%	31.15	39.2%	469.62	58.2%	697.24	2013
Kosovo	$7.15	12.9%	0.92	22.6%	1.62	64.5%	4.61	2009
Kuwait	$179.50	0.3%	0.54	50.6%	90.83	49.1%	88.13	2013
Kyrgyzstan	$7.23	20.6%	1.49	34.4%	2.49	44.8%	3.24	2013
Laos	$10.10	24.8%	2.50	32.0%	3.23	37.5%	3.79	2013
Latvia	$30.38	4.9%	1.49	25.7%	7.81	69.4%	21.08	2013
Lebanon	$43.49	4.6%	2.00	20.0%	8.70	75.4%	32.79	2013
Lesotho	$2.46	7.4%	0.18	34.5%	0.85	58.2%	1.43	2013
Liberia	$1.98	76.9%	1.52	5.4%	0.11	17.7%	0.35	2002
Libya	$70.92	2.0%	1.42	58.3%	41.35	39.7%	28.16	2013
Liechtenstein	$5.11	8.0%	0.41	37.0%	1.89	55.0%	2.81	2009
Lithuania	$46.71	3.7%	1.73	28.3%	13.22	68.0%	31.76	2013
Luxembourg	$60.54	0.3%	0.18	13.3%	8.05	86.4%	52.31	2013
Macau	$51.68	0.0%	0.00	6.5%	3.36	93.5%	48.32	2013
Macedonia	$10.65	10.2%	1.09	27.5%	2.93	62.3%	6.63	2013
Madagascar	$10.53	27.3%	2.87	16.4%	1.73	56.3%	5.93	2013
Malawi	$3.68	29.4%	1.08	18.9%	0.70	51.7%	1.90	2013
Malaysia	$312.40	11.2%	34.99	40.6%	126.83	48.1%	150.26	2013
Maldives	$2.27	3.0%	0.07	17.0%	0.39	80.0%	1.82	2012
Mali	$11.37	38.5%	4.38	24.4%	2.77	37.0%	4.21	2013
Malta	$9.54	1.4%	0.13	25.3%	2.41	73.3%	6.99	2013
Marshall Islands	$0.19	14.3%	0.03	13.9%	0.03	71.8%	0.14	2011
Mauritania	$4.18	16.9%	0.71	54.6%	2.28	28.5%	1.19	2013
Mauritius	$11.90	4.5%	0.54	22.0%	2.62	73.4%	8.73	2013
Mexico	$1,327.00	3.6%	47.77	36.6%	485.68	59.8%	793.55	2013
Micronesia, Federated States of	$0.34	14.0%	0.05	12.0%	0.04	74.0%	0.25	2011
Moldova	$7.93	13.8%	1.09	19.9%	1.58	66.2%	5.25	2013
Monaco	$5.75	0.0%	0.00	10.0%	0.57	90.0%	5.17	2011
Mongolia	$11.14	16.5%	1.84	32.6%	3.63	50.9%	5.67	2013
Montenegro	$4.52	0.8%	0.04	11.3%	0.51	87.9%	3.97	2011
Montserrat		1.6%		23.2%		75.1%		2013
Morocco	$104.80	15.1%	15.82	31.7%	33.22	53.2%	55.75	2012
Mozambique	$14.67	28.7%	4.21	24.9%	3.65	46.4%	6.81	2013
Namibia	$12.30	7.7%	0.95	29.6%	3.64	62.6%	7.70	2013
Nauru		6.1%		33.0%		60.8%		2009
Nepal	$19.34	36.8%	7.12	14.5%	2.80	48.7%	9.42	2013
Netherlands	$722.30	2.6%	18.78	25.4%	183.46	72.1%	520.78	2013
New Caledonia	$9.28	2.1%	0.19	30.0%	2.78	67.9%	6.30	2013
New Zealand	$181.10	5.0%	9.06	25.5%	46.18	69.5%	125.86	2013
Nicaragua	$11.26	17.1%	1.93	25.5%	2.87	57.5%	6.47	2013
Niger	$7.30	35.2%	2.57	14.2%	1.04	50.6%	3.70	2013
Nigeria	$502.00	30.9%	155.12	43.0%	215.86	26.0%	130.52	2012
Niue	$0.01	23.5%	0.00	26.9%	0.00	49.5%	0.00	2009
Northern Mariana Islands	$0.73	1.7%	0.01	3.3%	0.02	95.0%	0.70	2010
Norway	$515.80	1.2%	6.19	42.3%	218.18	56.5%	291.43	2013
Oman	$81.95	1.0%	0.82	64.4%	52.78	34.6%	28.35	2013
Pakistan	$236.50	25.3%	59.83	21.6%	51.08	53.1%	125.58	2013
Palau	$0.22	3.2%	0.01	20.0%	0.04	76.8%	0.17	2012
Panama	$40.62	3.7%	1.50	17.9%	7.27	78.4%	31.85	2013
Papua New Guinea	$16.10	27.6%	4.44	39.1%	6.30	33.3%	5.36	2013

Table A-10. GDP Sector Breakdown by Country

Country	GDP (Official Exchange Rate) (USD billion)	% Agriculture	$ Agriculture	% Industry	$ Industry	% Services	$ Services	Year Est.
Paraguay	$30.56	20.4%	6.23	17.7%	5.41	61.9%	18.92	2013
Peru	$210.30	6.2%	13.04	37.5%	78.86	56.3%	118.40	2013
Philippines	$272.20	11.2%	30.49	31.6%	86.02	57.2%	155.70	2013
Poland	$513.90	4.0%	20.56	33.3%	171.13	62.7%	322.22	2013
Portugal	$219.30	2.6%	5.70	22.2%	48.68	75.2%	164.91	2013
Puerto Rico	$93.52	0.7%	0.65	48.8%	45.64	50.5%	47.23	2013
Qatar	$213.10	0.1%	0.21	72.2%	153.86	27.7%	59.03	2013
Romania	$188.90	6.4%	12.09	34.2%	64.60	59.4%	112.21	2013
Russia	$2,113.00	4.2%	88.75	37.5%	792.38	58.3%	1,231.88	2013
Rwanda	$7.70	31.9%	2.46	14.8%	1.14	53.3%	4.10	2013
Saint Helena, Ascension, and Tristan da Cunha	N/A							
Saint Kitts and Nevis	$0.77	1.8%	0.01	23.1%	0.18	75.1%	0.58	2013
Saint Lucia	$1.38	3.1%	0.04	17.4%	0.24	79.5%	1.09	2013
Saint Martin	$0.56	1.0%	0.01	15.0%	0.08	84.0%	0.47	2000
Saint Pierre and Miguelon	$0.22	2.0%	0.00	15.0%	0.03	83.0%	0.18	2006
Saint Vincent and the Grenadines	$0.74	5.4%	0.04	20.3%	0.15	74.4%	0.55	2013
Samoa	$0.71	10.2%	0.07	25.9%	0.18	64.0%	0.45	2013
San Marino	$1.87	0.1%	0.00	39.2%	0.73	60.7%	1.13	2009
Sao Tome and Principe	$0.31	13.7%	0.04	19.5%	0.06	66.8%	0.21	2013
Saudi Arabia	$718.50	2.0%	14.37	62.5%	449.06	35.5%	255.07	2013
Senegal	$15.36	14.9%	2.29	22.7%	3.49	62.4%	9.58	2013
Serbia	$43.68	7.9%	3.45	31.8%	13.89	60.3%	26.34	2013
Seychelles	$1.27	2.0%	0.03	18.7%	0.24	79.4%	1.01	2013
Sierra Leone	$4.61	47.9%	2.21	18.6%	0.86	33.5%	1.54	2013
Singapore	$295.70	0.0%	0.00	29.4%	86.94	70.6%	208.76	2013
Saint Maarten	$0.79	0.4%	0.00	18.3%	0.15	81.3%	0.65	2008
Slovakia	$96.96	3.1%	3.01	30.8%	29.86	47.0%	45.57	2013
Slovenia	$46.82	2.8%	1.31	28.9%	13.53	68.3%	31.98	2013
Solomon Islands	$1.10	50.0%	0.55	10.6%	0.12	39.4%	0.43	2013
Somalia	$2.37	59.3%	1.41	7.2%	0.17	33.5%	0.79	2012
South Africa	$353.90	2.6%	9.20	29.0%	102.63	68.4%	242.07	2013
South Sudan	$11.77	N/A		N/A		N/A		
Spain	$1,356.00	3.1%	42.04	26.0%	352.56	70.8%	960.05	2013
Sri Lanka	$65.12	10.6%	6.90	32.4%	21.10	57.0%	37.12	2013
Sudan	$52.50	27.4%	14.39	33.6%	17.64	39.0%	20.48	2013
Suriname	$5.01	8.9%	0.45	36.6%	1.83	54.5%	2.73	2013
Swaziland	$3.81	7.6%	0.29	47.8%	1.82	44.6%	1.70	2013
Sweden	$552.00	2.0%	11.04	31.3%	172.78	66.8%	368.74	2013
Switzerland	$646.20	0.7%	4.52	26.8%	173.18	72.5%	468.50	2013
Syria	$64.70	17.6%	11.39	22.2%	14.36	60.2%	38.95	2013
Taiwan	$484.70	2.0%	9.69	29.4%	142.50	68.6%	332.50	2013
Tajikistan	$8.51	21.1%	1.80	23.2%	1.98	55.7%	4.74	2013
Tanzania	$31.94	27.6%	8.82	25.0%	7.99	47.4%	15.14	2013
Thailand	$400.90	12.1%	48.51	46.6%	186.82	44.2%	177.20	2013
Timor-Leste	$6.13	2.6%	0.16	81.6%	5.00	15.8%	0.97	2013
Togo	$4.30	27.6%	1.19	33.7%	1.45	38.7%	1.66	2013
Tokelau	N/A							
Tonga	$0.48	20.9%	0.10	21.9%	0.10	57.2%	0.27	2013
Trinidad and Tobago	$27.13	0.3%	0.08	57.7%	15.65	42.0%	11.39	2013
Tunisia	$48.38	8.6%	4.16	30.4%	14.71	61.0%	29.51	2013
Turkey	$821.80	8.9%	73.14	27.3%	224.35	63.8%	524.31	2013

Table A-10. GDP Sector Breakdown by Country

Country	GDP (Official Exchange Rate) (USD billion)	% Agriculture	$ Agriculture	% Industry	$ Industry	% Services	$ Services	Year Est.
Turkmenistan	$40.56	7.2%	2.92	24.4%	9.90	68.4%	27.74	2013
Turks and Caicos Islands	N/A	1.0%		22.5%		76.5%		2013
Tuvalu	$0.04	16.6%	0.01	27.2%	0.01	56.2%	0.02	2002
Uganda	$22.60	23.1%	5.22	26.9%	6.08	50.0%	11.30	2013
Ukraine	$175.50	9.9%	17.37	29.6%	51.95	60.5%	106.18	2013
United Arab Emirates	$390.00	0.6%	2.34	61.1%	238.29	38.2%	148.98	2013
United Kingdom	$2,490.00	0.7%	17.43	20.5%	510.45	78.9%	1,964.61	2013
United States	$16,720.00	1.1%	183.92	19.5%	3,260.40	79.4%	13,275.68	2013
Uruguay	$57.11	7.5%	4.28	21.5%	12.28	71.0%	40.55	2013
Uzbekistan	$55.18	19.1%	10.54	32.2%	17.77	48.7%	26.87	2013
Vanuatu	$0.83	22.4%	0.19	9.7%	0.08	67.9%	0.56	2013
Venezuela	$367.50	3.7%	13.60	35.5%	130.46	60.8%	223.44	2013
Vietnam	$170.00	19.3%	32.81	38.5%	65.45	42.2%	71.74	2013
Virgin Islands	N/A	1.0%		19.0%		80.0%		2003
Wallis and Futuna	N/A							
West Bank	$6.64	4.2%	0.28	17.9%	1.19	77.9%	5.17	2012
Western Sahara	N/A	N/A		N/A		40.0%		2007
Yemen	$43.89	7.7%	3.38	30.9%	13.56	61.4%	26.95	2013
Zambia	$22.24	19.8%	4.40	33.8%	7.52	46.5%	10.34	2013
Zimbabwe	$10.48	20.1%	2.11	25.4%	2.66	54.5%	5.71	2013
World	$74,310.00	6.0%	4,458.60	30.7%	22,813.17	63.3%	47,038.23	2013

APPENDIX B
Corrosion Management System Framework and Guidance

B.1 INTRODUCTION

A framework for a Corrosion Management System (CMS) for assets is described in this Appendix. The CMS developed shall include and document the following, which are discussed in more details throughout this framework:

- Defined asset corrosion management objectives and personnel accountabilities.
- Processes to establish and maintain the appropriate asset organizational structure.
- Processes to establish and maintain the appropriate competency of internal and contracted personnel.
- Processes to facilitate and verify corrosion management throughout the asset life cycle.
- Processes to prevent, detect, mitigate, and eliminate near-misses and noncompliances with corrosion management procedures, specifications, regulations, and referenced standards.
- Assessment of the achievement of corrosion management objectives throughout the asset life cycle.
- Methods to measure each process's effectiveness and enact continual improvement of the CMS.

Guidance

This framework can be utilized to develop a stand-alone CMS or to integrate corrosion management into an organization's existing management system. Additionally, some processes covered in this framework may already be implemented by an organization, for example, MOC. Existing processes may be modified to address the corrosion concerns identified in this framework.

B.2 SCOPE

This framework is applicable to organizations that manage assets affected by the risk of corrosion. The framework should be used to aid in the development of an organization-specific CMS.

B.3 TERMS AND DEFINITIONS

The following terms and associated definitions are utilized throughout this framework document.

1. Audit - a systematic, independent and documented process for obtaining records or information and evaluating it objectively to determine the extent to which a set of policies, procedures, or requirements are fulfilled.
2. Corrective Measure – an action taken to respond to the corrosion situation thereby limiting adverse consequences (i.e., actions taken to rectify an existing situation).
3. Inspection - an evaluation for conformity by observation and judgment accompanied, as appropriate, by testing and/or measurement.
4. Monitoring - a continuous, albeit not necessarily constant and complete, observation of parameters of a process. The intent of monitoring is to allow personnel, such as an inspector, to observe the activity or request performance data as needed.

5. Preventive Measure – an action taken to eliminate the causes of a potential corrosion issue in order to prevent occurrence (i.e., actions taken to prevent a situation from occurring. For instance, actions arising from a risk assessment or near miss).
6. Qualification - an activity or process carried out to demonstrate that a procedure, material, or technology is able to fulfil specified requirements. This is typically associated with an extended volume and modified scope of testing, as compared to normal production.
7. Near Miss – an event where the asset was not affected, but had the potential to be affected. An example of a near miss is an inspector stopping an improper backfilling task as the machinery operator is about to commence. A near miss is often a situation or event that may not be known to others outside the activity or project. If not attended to at an early stage, near misses can develop into actual corrosion issues.
8. Nonconformance – failure to follow a standard, specification, procedure, plan, etc., or non-fulfillment of a requirement contained in such document.
9. Audit Finding - a nonconformance, observation, or improvement opportunity identified during either internal audits or external audits conducted by third parties or auditors.
10. Incident – an undesired event that adversely affects integrity. These could include damages or failures, failures to meet corrosion management standards in the absence of damage, complaints that were caused by conformance to substandard procedures or specifications, or failures to comply with appropriate procedures or specifications.
11. Improvement Proposal – an action identified by the organization or suggested by an employee or contractor that may lead to an improvement in the organization's corrosion management standards, performance, or effectiveness of the CMS.
12. Corrosion Management System – A systematic approach designed to manage an organization's objectives, policies, procedures, and processes with regards to corrosion.
13. Supervise - to observe and direct the execution of a process, activity, or task.
14. Verification - an examination to confirm that an activity, product, service, or document is in accordance with specified requirements.
15. Witnessing - the presence at and observation of a defined and specified event or test. Work shall not proceed until the inspector is available to witness the event. This is equivalent to a "hold point" in the production. The inspector may, however, in advance inform in writing or through a formal minute of meeting that his/her presence is not required.

B.4 ABBREVIATIONS

CMS	Corrosion management system
MOC	Management of change
NACE	NACE International, formerly National Association of Corrosion Engineers

B.5 GENERAL

B.5.1 Corrosion Management System

A CMS shall be developed, implemented, maintained, and continually improved by the company in accordance with this framework document. An organization's CMS shall include requirements for suppliers, contractors, and subcontractors to verify that corrosion management requirements are met over the life cycle of the asset, as applicable.

B.5.2 Approach

The development, implementation, maintenance, and continual improvement of a CMS shall be achieved using a "process approach" by performing and documenting the following:

1. Identification of the asset processes and activities that require management over the life cycle of the asset.
2. Identification of the interactions between various asset processes and activities.
3. Determination of the criteria and methods required for the effective execution and monitoring of these processes.
4. Determination of the resources required to execute and monitor the CMS processes, as well as the assurance of the availability of necessary resources.
5. Measurement, monitoring, inspection, and analysis of these processes and activities.
6. Implementation of the activities required to achieve continual improvement.
7. Additional information regarding CMS implementation is presented in Section B.8, below.

B.5.3 Documents and Records

Guidance

For the purpose of this framework, a "document" contains plans or instructions for what actions will be performed. Documents can be continually improved and examples include the CMS manual, specifications, procedures, and inspection forms. Alternately, a "record" shows proof of compliance with a document's requirements at a single point in time. Examples of records include meeting minutes, training records, and inspection reports.

B.5.3.1 General

The organization shall assemble, manage, and maintain the following major types of documentation and records:

1. Documented requirements for the ways in which the organization expects each element of the management system to be met. These requirements may be included in a document such as a CMS manual or written management system and should include the following:
    a. CMS policy and objectives.
    b. Roles and responsibilities.
    c. Requirements of each CMS element outlined in this framework.
    d. Any additional organization-specific requirements, as applicable.
2. Supporting documentation and records to demonstrate conformance with the CMS requirements, including:
    a. Procedures.
    b. Planning, operation, and process control documents.
    c. Records.

The organization should perform a needs analysis to determine which records and documents should be retained, both for regulatory or legislative reasons, as well as to conform to organization requirements. In addition to maintaining records and documents, the organization shall store the information in an appropriate manner, i.e., in a format that allows usability, reliability, authenticity, and preservation.

Guidance

Suggestions for the minimum required documentation and records are contained in Table B-1 for a selection of the CMS and asset-level processes. This table is not all-inclusive.

Table B-1. Minimum Considerations for Documentation and Records Requirements

Element	***Requirement***
CMS Scope	• *Document the applicability of the Corrosion Management System as it pertains to the organization and its assets. Include the types of assets that do fall under this scope as well as any exclusions that may not.* • *Identify links to other programs that connect to or incorporate pieces of the CMS.*
CMS Policy and Objectives	• *Document the organization's policy on managing corrosion risks during asset life cycle and the objectives the organization strives to achieve through the CMS.*
CMS Records and Documents	• *Document the methods used for managing CMS records and documents.* • *Maintain an index of the records and documents that contain information that is relevant to, or used in conjunction with, the CMS.* • *Identify the person or role responsible for maintaining and approving documents and records related to the CMS and its associated activities.* • *Establish and document the review process to confirm that the documentation/records meet those requirements and are complete and reliable.*
Management of Change	• *Develop and implement a management of change process for changes that have the potential to affect corrosion of assets or the ability of the organization to manage corrosion.* • *Verify the MOC process procedures are in place to address and document corrosion-related changes.* • *Define and implement performance indicators for management of change.* • *Document risks associated with changes that are managed through the MOC process and the ways in which they could potentially affect the organization.*
Management Responsibility	• *Document management's responsibilities and accountabilities related to maintaining and supporting the CMS as well as activities associated with verifying corrosion management.*
Contractor and Supplier Responsibility	• *Document the responsibilities of contractors and suppliers as they relate to producing and providing services, products and equipment.* • *Define the organization's expectations of contractors and suppliers as they relate to corrosion management activities. Verify a process is in place to communicate the expectations in a written agreement.*

Table B-1. Minimum Considerations for Documentation and Records Requirements (continued)

Continual Improvement	• *CMS Audits:* • *Document the requirements for how, where, and how long CMS audit reports should be kept.* • *Maintain CMS audit reports in a manner that allows for efficient retrieval and access by authorized personnel.* • *Verify there is a way to demonstrate that the results of audits are communicated to, and agreed with, those who were audited, communicated to management, included in the management review process, and followed-up through to completion.*
	• *Findings and Recommendations:* • *Document the method(s) for tracking findings and recommendations, their associated corrective actions, and the process for closure of the items.* • *Maintain records of recommendations and closure of recommendations* • *Document the process for consulting with and informing appropriate personnel about corrosion issues and findings from audits and management reviews.*
	Learning from Events: • *Establish procedures for investigating and reporting incidents as well as near misses.* • *Document the feedback loops and methods for communication to potentially affected organization and contractor personnel.* • *Document the requirements for what should be included in incident and near miss reports, such as, but not limited to, the following:* o *A description of what occurred* o *Initial actions taken* o *An evaluation of potential severity and probable frequency of recurrence* o *Identification of root cause(s)* o *Need to notify regulatory authorities* • *Recommended corrective and/or preventive actions to prevent recurrence*
	Monitoring and Measurement: • *Define, document, and track performance indicators for the written CMS and associated critical activities.*

B.5.3.2 Control of CMS Documents

The organization shall establish procedures for the control and dissemination of CMS documents, including:

- Identification of documents that are required for the effective implementation of the CMS.
- Identification and review of documents that require access control and/or distribution control.
- Approval of documents, including assurances of legibility and accessibility.

- Identification of the current revision of each document, including procedures for removal of obsolete/invalid documents from circulation and use.
- Maintenance of documents, including back-up and archival of critical or obsolete documents.

Guidance

The organization may already have a document control process/system in place for existing document or records which can be used to manage the CMS documents.

B.5.3.3 Control of Records

The organization shall establish procedures for the control of records that demonstrate compliance with and the effectiveness of their CMS. Such records are generated as part of the CMS process and a system should be created to identify, organize, and retain these records.

Guidance

Examples of applicable records include:

- *Management review records.*
- *Contracts and contract review records.*
- *Correspondence and meeting minutes.*
- *Design review, verification, and validation records for new and acquired assets.*
- *MOC records.*
- *Descriptions of approved suppliers and contractors.*
- *Engineering/technical inquiries and associated responses.*
- *Traceability records, including equipment tag numbers and lists.*
- *Qualified processes, equipment, and personnel.*
- *Training records.*
- *Inspection and test records.*
- *Asset drawings.*
- *Nonconformance reports and records of subsequent actions.*
- *Internal and external audit reports.*
- *Records for monitoring and measurement activities.*
- *Standard formats and templates.*

B.5.4 Management of Change

The CMS shall include a MOC process to control, evaluate, verify, and validate technical and administrative (non-technical) changes to the design, contracting, procurement, manufacturing, fabrication, construction, operation, maintenance, or upgrade of assets, as well as changes to the CMS itself. Each MOC request must be approved prior to implementation. The review of such changes shall include evaluation of the effect each change or suite of changes can potentially have on corrosion management.

Guidance

The MOC process should identify the types of changes to be managed, provide a means of verifying the process is consistently utilized, and include metrics to determine if changes are being evaluated as intended by the CMS. Each change should be evaluated based on the significance of the change, the need, technical basis, and expert evaluation of the risk associated with the change. Utilizing this information, authorization to proceed with the change should be determined.

It is critical that the MOC is effectively communicated to all impacted parties to facilitate effectiveness. Additionally, records of MOC reviews and any necessary actions should be maintained as part of the MOC process. Any action items should be addressed as outlined in Section B.9, below, and tracked to closure.

Management of technical changes associated with the asset should be conducted to verify engineering regulations, codes, and standards are being met and to take into account ways in which the change can affect the corrosion risks and management. Appropriate subject matter experts should evaluate whether the risks associated with the change have been identified and understood by parties who can affect the risk or be affected by it and whether the risks have been mitigated or addressed appropriately.

B.5.4.1 Managing Administrative Changes

Changes to the written CMS document, as well as other associated administrative processes, procedures, and requirements shall be managed to determine the effects they may have on asset integrity.

When managing changes to the written CMS, the requirements for Continual Improvement, discussed in Section B.9, below, shall be followed as outlined in the CMS document. In addition, the effect the change may have on the organization’s risk profile, risk tolerance, corrosion philosophy, and other corporate standards shall be evaluated with the change.

Guidance

The organization should verify the MOC process manages changes that can affect the following, at a minimum:

1. *Approved supplier, contractor, and vendor lists.*
2. *Supplier, contractor, and vendor agreements and contract terms.*
3. *Procurement practices and requirements.*

4. *Contractor management practices and contractor oversight requirements.*
5. *Engineering standards.*
6. *Material and design specifications.*
7. *Operational plans.*
8. *Supplier/contractor requirements.*
9. *Construction and installation practices and procedures.*
10. *Safe work practices.*
11. *Inspection, mitigation, and maintenance procedures.*
12. *Spare parts requirements.*
13. *Modifications to operating philosophy or procedures.*
14. *Changes in the designation of key personnel responsible for specific work scope items, decision making, or communication requirements.*

B.5.4.2 Managing Temporary Changes and Exceptions

The CMS shall include requirements for managing temporary changes to construction, inspection, mitigation, operation, or maintenance plans and procedures, temporary exceptions to the CMS requirements, and exceptions to specifications. Although temporary in nature, these changes shall be evaluated to determine if they present a risk to asset integrity, operation, personnel safety, or environmental safety.

Guidance

The following listing provides examples of temporary changes; however, it is not intended to be a complete listing:

1. *A temporary change to an operational plan due to maintenance activities.*
2. *An exception to a material specification resulting from a shortage of the material.*
3. *A local exception to the procurement requirements resulting from limited choices in vendors.*

B.5.4.3 Learning from Events

Following continuous improvement activities, such as external complaints, incident investigations, near misses, non-conformances, audits, improvement proposals, or planned assessments, the organization may suggest changes to improve the CMS or corrosion management processes. Prior to the implementation of suggested changes on currently on-going projects, the MOC process, as described in Section B.5.4, shall be utilized to minimize the likelihood that the change will adversely affect the asset integrity.

Guidance

Suggested changes may come from either internal or external events. For example, an organization may choose to improve their CMS following a public corrosion incident experienced by another organization.

B.6 MANAGEMENT RESPONSIBILITY

The organization is responsible for:

- Conformance to regulations.
- Conformance to standards of the industry.
- Conformance to organization specifications.
- The ability of the asset to perform the intended function on a sustained basis in a safe and environmentally sound manner.

When utilizing contractor services, the organization shall verify the CMS and associated project specifications/requirements are followed by the contractor.

Guidance

The corrosion management should be consistent with the espoused principles. Therefore the organization has the responsibility to put into place a CMS with sufficient definition to manage corrosion over the life cycle of assets. The organization must verify:

- *Employees and contractors have the ability to design, procure, build, commission, acquire, operate, maintain, update, and decommission assets safely within their scope.*
- *Suppliers provide materials and equipment that meet requirements.*
- *Construction, operation, and maintenance meets or exceeds commonly accepted industry standards as supplemented by organization or project specifications.*
- *Control of the asset is maintained through competent asset management.*
- *The installed asset meets the standards and specifications through inspection and testing.*

B.6.1 Management Commitment

Management shall commit to developing, implementing, and continually improving the effectiveness of the CMS. This is achieved by:

- Establishing the corrosion management policy and its objectives.
- Communicating to the entire organization the importance of meeting all statutory, regulatory, and organization requirements.
- Having a written statement describing the management’s approval and support of the CMS.
- Conducting management reviews.

- Confirming the availability of resources.
- Preventing conflicts between budget and asset integrity.
- Identifying and documenting organization requirements in applicable orders, contracts, and specifications.

Guidance

Implementing and utilizing a fully-functional CMS will require additional up-front costs and staffing. However, these additional costs will promote integrity and may reduce operational and repair costs over the life of the asset. Management should be committed to providing the required resources.

B.6.2 Policy

The organization shall establish a corrosion management policy. This policy describes the organization's intentions with regards to managing corrosion risks utilizing a CMS; it shall:

- Be appropriate for the purpose of the organization and aligned with the organization values.
- Provide for a framework for establishing and reviewing corrosion management objectives.
- Be managed through a management review process.
- Be communicated and understood within the organization.
- Be reviewed on a regular basis for continuing suitability.

B.6.3 Communication

Communication processes must be established which facilitate awareness, understanding, and acceptance of the CMS and associated processes and procedures throughout the organization, as well as by contractors and other external stakeholders. Critical communications that require action should be tracked through completion.

Guidance

Channels should exist to allow communication to flow from management to asset/field personnel and vice versa.

B.6.3.1 Internal Communication

Internal communication links management, employees, and other internal stakeholders. The attainment of the corrosion management goals depends on successful communication. The communication process should allow for employees to give feedback and provide possible solutions to issues. Key communication processes include:

- Establishment, communication of, and adherence to best practice.
- Learning opportunities from ongoing activities, near-misses, and incidents.
- Effective MOC communications.

- Clear communication of roles, authorities, and responsibilities.

B.6.3.2 External Communication

The external communication process shall include:

- Sharing of organization requirements and expectations.
- Sharing of best practice.
- Learning opportunities from ongoing activities, near-misses, and incidents.
- Key contacts and elevation plans for technical and non-technical inquiries.
- Approval processes for subcontracting or other contractual changes.

B.6.4 Organization

B.6.4.1 Responsibilities and Authorities

The responsibilities and authority of each role in the organization with respect to the CMS or construction project shall be defined and documented. The responsibilities and authorities for each role shall be communicated throughout the organization to promote awareness.

Guidance

In addition to the defining of responsibility and authorities, minimum training and competency requirements should be established for all roles and should include criteria that must be met in order to hold a given role. Competency and training requirements should include assessments that verify that individuals have the knowledge and experience needed to perform the required tasks and make informed decisions. Additional information on training and competency can be found in Section 1.1B.7.2.1, below.

B.6.4.2 CMS Management Representatives

A management representative shall be appointed within each appropriate organizational unit to:

- Promote the establishment, implementation, and maintenance of processes needed for the CMS.
- Apply lessons learned from similar activities or assets.
- Communicate to management regarding the performance of the CMS and need for improvement with regard to their organizational unit.
- Facilitate the promotion of awareness within the organization as a whole.

B.6.5 Management Review of CMS

B.6.5.1 General

A management review shall be defined and carried out at the frequency necessary to promote the continuing effectiveness of the CMS, examine current issues, and assess opportunities for improvement. Additionally, continual improvement activities, conducted by individual or cross-functional groups, should be reviewed. Management reviews shall be documented.

B.6.5.2 Review Input

The management review input shall include information relative to the performance of the CMS and detection, mitigation, and resolution of corrosion risks or issues. In addition, the review shall consider the potential effect of external influences on corrosion management requirements.

Guidance

The management review input information should include but may not be limited to the following:

- *Nonconformances.*
- *Status of preventive and corrective actions.*
- *Follow-up actions from previous management reviews.*
- *Changes in the organization's operational environment that could affect the CMS including the requirements for additional or revised resources.*
- *Audit results.*
- *Overall performance of the CMS and opportunities for improvement.*
- *Changes in applicable regulatory requirements or applicable industry consensus standards.*

B.6.5.3 Review Output

The output from the management review shall include any actions related to:

- Corrective and preventative measures taken or planned.
- Reallocation or supplementing of resources.
- Redefinition of responsibilities or changing organizational details.
- Changes to procedures and/or documentation practices to meet changes in organization specifications and/or regulatory requirements.
- Changes to policy.
- Setting new objectives and initiating actions to improve the CMS, processes, and procedures.

Guidance

The format of the review output should be determined by the organization. Additionally, a process should be implemented to track the completion of any required actions.

B.7 RESOURCE MANAGEMENT

B.7.1 Provision of Resources

The organization shall determine the resources required to develop, document, implement, manage, supervise the application of, and continually improve the CMS.

Guidance

Those resource requirements may be met by providing a combination of organization staff and contracted, supplemental staffing.

B.7.2 Human Resources

B.7.2.1 Training and Competency

The organization is responsible for developing, documenting, implementing, managing, supervising, and continuously improving a program that trains personnel to meet the requirements of the CMS and other applicable organization standards, specifications, and regulations in a safe and environmentally responsible manner. Applicable training and competency requirements shall be applied to both organization personnel and contractor/supplier personnel responsible for the CMS system and for all life-cycle stages with corrosion management activities, including design, procurement, manufacturing, fabrication, construction, operation, maintenance, or upgrade of assets. The training and results of competency testing shall be documented and retained according to organization or regulatory requirements.

Guidance

Competency may be measured by organization-administered testing and/or job demonstration, external certification programs, or a combination of both. Consideration should be given to periodic retesting or re-certification.

Training and competency verification programs should be defined for the personnel performing work, which may be employed by the organization, contractor, or supplier, and should include:

- *Determining the competency needs for critical job activities.*
- *Determining the best mechanism for developing the competency, for example a combination of classroom training, practice on mock-ups, and specified amount of on-the-job training under the supervision of a qualified individual.*
- *Determining the most effective method of evaluating the competency and an acceptable assessment metric.*
- *Determining a re-training and evaluation protocol for those who don't demonstrate adequate competence or who later demonstrate unacceptable work quality after having been judged to be competent.*

- *Setting appropriate levels of differentiation between training and evaluation requirements for experienced employees and contractors compared to the needs of new employees with developing skills or employees in new positions.*
- *Identifying mechanisms for supplemental or revised training and evaluation to address changes in existing procedures or addition of new procedures.*
- *Measuring the effectiveness of the training by comparing work performance to competency evaluation results.*
- *Determining the need for periodic evaluation or auditing of work performance.*
- *Setting training, evaluation, and auditing result documentation formats and requirements.*

Competence evaluations can take many forms; examples include written examinations, oral examinations, demonstrations of competence, previous job experience, on-the-job evaluations by an "expert" in the task, the results of previous evaluations, or a combination thereof.

B.7.2.2 Contractor Services

The organization shall develop, document, apply, and refine processes at specified intervals to verify that contractor services meet or exceed the requirements of the CMS. The same considerations should be applied to the qualification of any subcontractors used by the contractor. The contractor shall be responsible for verifying the subcontractor meets the requirements of the CMS.

The organization shall define and document performance standards and communicate those to the contractor. The contractor and organization shall jointly define a suitable method and frequency of audits and performance monitoring and the manner in which the contractor will support the monitoring and assessment of contractor performance.

B.7.3 Infrastructure

The organization shall identify, provide, and maintain the infrastructure required to support the effective implementation of the CMS.

Guidance

The infrastructure, which is either provided directly by the organization or a contractor, should include:

- *Access to required power and water resources.*
- *Project management, supervision, and supporting services workspaces including related office technology.*
- *Construction, testing, and inspection equipment and technology.*
- *Space or facilities for other supporting services, if applicable, including temporary housing, food services, employee parking, etc.*

B.7.4 Work Environment

The organization shall identify and manage the environmental, human, organizational, and security factors of the project working conditions that could inhibit the ability to meet the requirements of the CMS.

Guidance

Examples of pertinent factors include, but may not be limited to:

- *Work schedules, including consideration of likely commuting distances and availability of local food and housing resources.*
- *Weather conditions (temperature, wind, and precipitation).*
- *Naturally occurring environmental hazards (unstable slopes, susceptibility to flooding, poisonous vegetation, dangerous animals, etc.).*
- *Restrictive limitations on work activities a result of endangered species, contentious landowners, or other considerations.*
- *Labor/management and reporting relationships.*
- *Relationships between inspectors or auditors and the production supervision.*
- *Ease of access to additional resources, including subject matter experts or other technical support, additional or replacement equipment, or additional labor.*
- *Access to emergency response resources (medical, fire, hazardous material release, etc.).*
- *Security of asset, materials, and equipment against theft and damage.*

B.8 CMS ASSET IMPLEMENTATION

Section B.8 describes the activities that directly support effective implementation of the CMS for an organization's assets. The processes and procedures for the implementation of the CMPs and activities shall:

- Be consistent with the corrosion management policy, strategy, and asset objectives.
- Ensure that costs, risks and asset performance are controlled across the asset life-cycle phases.

B.8.1 Life-Cycle Considerations

The organization shall establish, implement, and maintain processes and procedures for the implementation of its CMPs and activities across the life cycle of the asset, including:

- Design, procurement, building, and commissioning.
- Acquisition of existing assets.
- Operation, maintenance, and update of assets.
- Decommissioning and/or disposal.

B.8.2 Legal and Regulatory Requirements

The organization shall establish, implement and maintain processes or procedures for identifying, complying with, and communicating the legal, regulatory, statutory and other applicable corrosion management requirements.

B.8.3 Corrosion Risk Management

The organization shall identify the corrosion risks, or probability of events and their consequence, over the life cycle of each asset. Risks should be managed through monitoring, controlling, or minimizing the probability and/or consequences. Effective corrosion risk management relies upon the ability to identify potential sources of deviations or deficiencies and then to develop strategies to prevent or mitigate each.

B.8.3.1 Implementation of Corrosion Management Activities

Formal processes and procedures applicable to corrosion management activities include consideration of the following topics:

- Description of the objective.
- Identification of the responsible and accountable organizational element.
- Identification of resource requirements including training, qualification, or certification requirements for organization staff, contractors, manufacturers, or suppliers, where applicable.
- Documentation and record keeping.
- Management of change.
- Review and validation practices to verify consistency with applicable regulations, standards, and organization policy and procedures.
- Objective performance measurement targets and measurement methods.
- Scope and frequency of inspections and audits to verify that the objectives are being met, with feedback to a continuous improvement process.

Guidance

The information provided below includes an example of a corrosion management activity: cathodic protection (CP) system installation for an onshore pipeline. This information should not be considered all-inclusive, however the table provided below may be used to assist the organization to develop a CMP for this activity. The table includes the following information:

- *Potential corrosion management risks that may be encountered during the activity.*
- *Recommendations for improved corrosion management.*
- *Training and competency requirements for personnel performing the activity.*
- *Inspection requirements.*
- *Training and competency requirements for the personnel performing the inspection.*
- *Applicable records.*

Additional plans should be in place for the other life-cycle stages of the CP system, including operation, maintenance, upgrading, and decommissioning.

Table B-2. Considerations for the Development of a Corrosion Management Plan for Cathodic Protection (CP) System Installation for an Onshore Pipeline

Potential Corrosion Management Risks	• *Creation of undesirable microstructures in the pipe at the site of local attachments* • *Burn-through of thin-wall pipe when using an exothermic welding process* • *Poor electrical and or mechanical attachment* • *Detachment of leads during backfilling* • *Failure to effectively coat the connection* • *Improper installation of impressed current anode groundbeds* • *Installation of CP cables with damaged electrical insulation* • *Creation of stray current interference due to improper anode groundbed site selection* • *Reversed electrical connections between the pipeline and rectifier* • *Condition changes between design and installation leading to insufficient CP*
Recommendations for Improved Corrosion Management	• *Establish and properly qualify a written joining procedure for leads, which documents the following:* o *Surface preparation requirements* o *Minimum wall thickness and maximum carbon equivalent of the pipe at attachment sites* o *Measurement of attachment site wall thickness* o *Minimum distances from other welds, adjacent lead attachment or unsuccessful attempts to attach lead* o *Specification of exothermic charge size range, as applicable* • *Provide slack and be aware of wire placement to minimize stress on the lead during backfilling* • *Use an approved coating and coating application procedure* • *Inspect compaction of carbonaceous backfill around anodes* • *Visually inspect and test the area where the anode bed will be installed to identify potential buried structures susceptible to stray current.* • *Perform a CP survey to identify potential stray current after installing the pipeline and the CP system* • *Verify that the rectifier is properly connected*

Table B-2. Considerations for the Development of a Corrosion Management Plan for Cathodic Protection (CP) System Installation for an Onshore Pipeline (continued)

Inspection Requirements	• *Confirmation of electrical continuity* • *Confirmation of mechanical security of attached lead wires* • *Confirmation of field coating at attachment sites*
Training/Competency of Personnel	• *Trained on organization attachment procedures for CP and corrosion monitoring systems, as well as protective coating procedures* • *Ability to take required measurements* • *Trained to perform Cathodic protection surveys to identify potential stray current interference* • *Operator Qualified to perform the task, as applicable*
Records Requirements	• *Pipe attachment report, which includes:* o *Precise location of each attachment for correlation with in-line inspection (ILI) reports* o *Total number of unsuccessful/successful attempts to attach the lead to the pipe* • *Coating inspection reports, including documentation of coating type, manufacturer, lot numbers, etc.*

B.9 CONTINUAL IMPROVEMENT

B.9.1 General

Organizations shall plan, manage and take appropriate measures to enable the continual improvement of the CMS as well as associated procedures and processes. Both the effectiveness of the CMS and its continued relevance to the company's organizational goals and objectives should be evaluated through this process. Improvements may take the form of changes to the overall policy, the organization objectives for corrosion management, as well as the individual elements of the CMS and their associated processes and procedures.

Guidance

The continual improvement process is an integral part of CMS, and should include management's commitment to monitor and evaluate performance measures.

The continual improvement process should follow the Plan-Do-Check-Act (PDCA) model. This continuous process of identifying and analyzing the CMS (Plan), developing ways to address issues (Do), measuring the effectiveness of actions (Check), and implementing solutions (Act) should be utilized to verify the CMS remains relevant to the business, is achieving its goal of promoting integrity, and is being improved and enhanced as needed.

The most effective way to continuously improve the CMS is to use a combination of both formal and informal processes to systematically review the existing CMS. This information can then be used to measure performance against the requirements of the management system.

The following types of processes and activities will have an impact on the ability to continually improve the CMS:

1. *Management Review and CMS Audits.*
2. *Control of Nonconformance.*
3. *Learning from Events.*
4. *Management of Change.*
5. *Monitoring and Measurement.*

B.9.2 Management Review and CMS Audits

The effectiveness of the CMS shall be continually reviewed and improved through systematic management reviews and audits of the CMS. The processes to be used for each of these activities shall be documented as part of the CMS, along with requirements for re-assessment intervals.

B.9.2.1 Management Review

Management Reviews sha*l*l be undertaken as set out in Section 0 of this document and should be carried out in a way that will verify the following:

1. The corrosion management policy still reflects the organization's position on maintaining integrity over the life cycle of assets.
2. The corrosion management objectives continue to support the overall organizational objectives.
3. The CMS reflects current regulatory requirements and recognized and generally accepted good industry practices.
4. Management supports the CMS.
5. Management reviews are conducted at a defined frequency, and actions are undertaken to address findings.
6. Data are analyzed in a way that will identify trends and facilitate an appropriate response to corrosion issues.
7. Previous CMS audit action items have been closed or are in the process of being addressed.
8. The organization is in conformance with the CMS.
9. The effectiveness of the CMS is being evaluated.
10. Management Review minutes are circulated to appropriate personnel.
11. The MOC process is used to facilitate the appropriate management of changes to the CMS.

B.9.2.2 CMS Audit

An audit process shall be in place to verify that the organization is evaluating the performance of the CMS. For each CMS audit, a written plan or document should include the scope of the audit, people or positions to be interviewed, checklists or listing of documents to be reviewed, and other relevant information that will enable the auditor/audit team and audit organizer to have a common understanding of the audit's purpose. This information may be stated in a "terms of reference" (TOR) document, proposal, audit protocol, or similar and should be fit for purpose, as determined by the scope and scale of the audit.

Guidance

Careful consideration should be given to the type of audit conducted and the intended outputs of each audit. Audits of the CMS can be conducted by an internal audit function (such as a self-assessment or corporate audit) or by a third party auditor or consultant.

The CMS can also be evaluated in its entirety or by element; however, during each audit cycle, the CMS audits should determine, at a minimum, if the following are occurring:

1. The corrosion management policy is understood throughout the organization.
2. Staff understand their role in achieving the corrosion management objectives.
3. The written CMS is comprehensive and relevant to the organization's business and assets.
4. The requirements of the CMS are being met as intended.
5. Inspections are conducted on a regular basis, and actions are undertaken to address findings.
6. Preventive actions are taken to minimize the likelihood of foreseeable corrosion issues.
7. Corrective actions are taken to minimize the likelihood of a similar corrosion issue being repeated.
8. Corrosion issues are being addressed in a timely manner.
9. Lessons learned and corrosion management concerns are circulated to appropriate personnel.
10. Appropriate training is being done to enable conformance to the CMS.
11. The MOC process is used to facilitate appropriate management of changes to the CMS.

B.9.2.3 Review and Audit Reports

The CMS shall require findings or results of audits and management reviews to be reported in an appropriate form and communicated to appropriate personnel. Requirements for document control and retention time are addressed in Section B.5.3, above.

B.9.3 Addressing Findings and Recommended Actions

Documented procedures shall be established and maintained as part of the CMS to address non-conformances in an appropriate manner. Organizations should verify that procedures address the following:

1. Identifying and investigating non-conformances.
2. Determining causes of non-conformances.
3. Determining which type(s) of action(s) should be implemented – corrective or preventive.
4. Preventing recurrence of non-conformances.
5. Documenting preventive and corrective actions to be taken.
6. Implementing actions.
7. Promoting appropriate communication.
8. Reviewing the effectiveness of actions following implementation.

Both corrective and preventive actions may be used, as appropriate.

Guidance

Corrective actions should be taken to address findings such as those resulting from incident investigations, audits and management review activities. Preventive actions should be taken in response to proactive activities, such as risk assessments and near misses. Both corrective and preventive actions may take the form of, for example, revisions to procedures, development of new procedures, additional oversight, etc., all of which should be implemented as appropriate following the MOC requirements.

B.9.4 Learning from Events

Learning from events is critical to the continual improvement of the CMS. Formal, consistent, standard processes, such as incident investigations, shall be used to verify that a continuous improvement loop is in place to learn from events. In addition to formal processes, informal opportunities, such as employee concerns and impromptu feedback, should be utilized in an appropriate manner to improve the CMS.

Guidance

The ultimate goal of learning from events should be to identify necessary improvements to the CMS and associated processes and procedures. Examples of documents or activities that may be impacted include:

- *The written CMS document(s).*
- *Materials specifications and requirements.*
- *Personnel qualifications, competence, and oversight.*
- *Organization procedures for construction, installation, testing, and inspection.*

- *Inspection and preventive maintenance schedules.*
- *Operating philosophy and operating procedures.*

In all cases, when changes are made to the CMS, those changes shall be managed in accordance with the MOC requirements.

B.9.4.1 Reactive Learnings

The CMS shall include a process for evaluating incidents and events related to corrosion in a manner that will promote determination of the root cause of the event, incorporation of the findings into the CMS, and communication of important information to employees to maximize the likelihood that corrosion issues are not repeated.

If the root cause of a failure of an asset is determined to be corrosion, actions should be taken to determine if a similar situation could occur given the existing CMS and its associated processes and procedures. All efforts should be taken to improve the CMS, as well as related procedures and processes.

B.9.4.2 Proactive Learnings

Proactive activities, such as near miss investigations, utilize information to predict possible corrosion problems and correct them in a proactive manner. Proactive activities can be utilized to identify potential corrosion management concerns before an event occurs.

B.9.4.3 Informal Opportunities for Learning

Informal activities should also be considered as a means for capturing improvements to the CMS. Such activities may include, but are not limited to:

- Personnel concerns and suggestions.
- On-the-job observations.
- Potential improvements identified by employees or contractors through the regular use of the CMS and related procedures or documents.

B.9.5 Management of Change

The MOC process shall be utilized when making changes to the CMS as a result of any continual improvement or other activity. Changes should be communicated appropriately to personnel who could potentially be affected by the change, and any necessary training should be conducted. See Section B.5.4 above for details regarding the requirements for MOC.

B.9.6 Monitoring and Measurement

Appropriate performance metrics shall be in place to provide information that will help the organization improve the CMS and communicate pertinent information. A combination of leading and lagging metrics should be considered in an effort to provide the most effective improvement.

Guidance

Lagging metrics are derived from events that have occurred in the past, such as corrosion-related incidents, nonconformances, citations, etc. Leading indicators are those which look forward and indicate potential problems that could occur if corrective action is not taken.

Metrics should allow the organization to determine the following, at a minimum:

1. *Are appropriate controls are in place to manage corrosion risks?*
2. *How well is the organization conforming to the CMS requirements?*
3. *Are procedures that affect corrosion being followed as intended?*
4. *Is training being carried out in an appropriate manner and at appropriate intervals?*
5. *Are action items from management reviews and audits being addressed, tracked, and closed as required by the CMS?*

In addition to defining performance metrics, the organization should develop and document plans or procedures for collecting, processing, and validating the metrics, which include:

- *Organizational responsibility for collection of metric data.*
- *Required qualifications of personnel gathering and processing the metric data.*
- *Acceptable data sources.*
- *Timing limits for the collection and processing of metric data.*
- *Review and validation process for the collected and processed data to identify potential errors, and uncertainties.*
- *Required formats/systems for raw metric data retention, retrieval, and analysis, as well findings from the metrics.*

APPENDIX C
NACE Corrosion Management Practices Survey 2015

NACE INTERNATIONAL

Make Best Practices Your Practices[SM]

NACE Corrosion Management Practices Survey 2015

Instructions:

This survey is being conducted by APQC and DNV GL on behalf of NACE International, the Worldwide Corrosion Management Authority. The purpose of this survey is to gather corrosion management practice data across industries and geographies to better understand the cost of corrosion. The survey is structured into sections. Demographics, followed by questions about the Entire Asset Lifecycle (the heaviest question set), Design, Manufacturing and Construction, Operations and Maintenance, and Retirement.

The survey may take some time to complete. Please take as much time as you need. You may save your responses should you need to exit the application and come back to it another time by clicking on the "SAVE" button.

You may print the questions in advance by using the mouse right click button. If you do not know the answer to a question, please leave it blank. For those respondents wishing to remain anonymous you will require a Partner alpha code (see the Glossary link below), plus a numeric code per respondent assigned by your Partner.

There is a "PRINT" icon at the end of the survey that will allow you to print a record of your survey answers prior to submitting the survey online. Do not forget to accept the survey terms at the bottom and press the "SUBMIT" button in order to submit your completed, online response to APQC. Thank you for your participation!

The confidentiality of information provided is protected by NACE & APQC's Benchmarking Code of Conduct

For questions about the survey content, please contact Elaine Bowman at Elaine.Bowman@nace.org. For questions about the online survey tool or submission, please contact APQC at NACEImpactStudy@apqc.org.

We have created a Glossary of Terms for this survey, here. It will open in a new window allowing you to reference these definitions while you complete the survey. It is recommended you open the Glossary now.

Demographics

Note: Fields marked with an asterisk (*) are required. All company and personal information will be held confidential. Please use your corporate or business e-mail address for this survey as confidential organization data cannot be sent to anonymous web-based e-mail services. If you wish for your responses to be blinded to the researchers, please enter your Partner code from the "Glossary of Terms", plus the numeric code your Partner assigns you. Thanks for participating.

* Organization Name or ID Number:

Organization's primary industry?

Select one...

What region is your organization located within?

Select one...

* What is your corrosion management role within your organization?

First name:

Last name:

Work E-mail:

Phone Number:

Entire Asset Lifecycle

1. Does your corrosion management system ultimately result in the lowest total corrosion cost over the intended life of the asset? (See definition of "total cost" in the glossary.)

- ☐ No, little understanding of lifecycle costs
- ☐ Yes, but our system is more reactive than proactive (corrosion control is "as needed" vs. "designed in")
- ☐ Yes, but improvement is required for complete understanding
- ☐ Yes, our system is robust
- ☐ Don't know

1a. If you responded "Yes" to the previous question, please indicate the elements of the asset lifecycle where you are able to measure the cost of corrosion (check all that apply).

- ☐ Design
- ☐ Manufacturing/Construction
- ☐ Operations/Maintenance
- ☐ Retirement

2. Does your organization have a corrosion management policy?

- ○ No
- ○ Yes, for part of the asset lifecycle
- ○ Yes, for part of the organization
- ○ Yes, for the entire organization and asset lifecycle

3. If yes, would you be willing to provide a copy of your corrosion management policy?

- ○ Yes
- ○ No

4. Does your organization have a corrosion management strategy?

- ○ No
- ○ Yes, for part of the asset lifecycle
- ○ Yes, for part of the organization
- ○ Yes, for the entire organization and asset lifecycle

5. If yes, is your corrosion management strategy linked to your organization's overall strategy?

- ○ No
- ○ Yes, but to technical requirements only
- ○ Yes, but to business performance only
- ○ Yes, comprehensively

6. Are your corrosion management plans linked across the entire asset lifecycle (as opposed to stand-alone)?

- ○ We do not have corrosion management plans across the entire asset lifecycle
- ○ We have stand-alone corrosion management plans
- ○ We have integrated, linked corrosion management plans

7. How is your corrosion management performance monitored and reported?

- ○ Locally, by a corrosion technical professional
- ○ Locally, by corrosion management and organization management
- ○

Within the general/corporate management organization

- ○ At all management levels

8. How is corrosion management performance integrated into organizational performance metrics?

- ○ Corrosion management performance is not integrated into organizational performance metrics (e.g., stand-alone reporting of corrosion management)
- ○ Corrosion management is integrated into local reports or dashboards
- ○ Corrosion management is integrated into reports or dashboards at all levels

9. How is corrosion management compliance with standards, procedures, and regulations monitored?

- ○ Corrosion management compliance is not monitored
- ○ Corrosion management compliance is monitored at your local organization level only
- ○ Corrosion management compliance is monitored at all levels of the organization
- ○ Corrosion management compliance is monitored at all levels of the organization and other stakeholders

10. How is corrosion management non-compliance with standards, procedures, and regulations resolved?

- ○ Corrosion management non-compliance is not tracked to resolution
- ○ Corrosion management non-compliance is managed by local corrosion management
- ○ Corrosion management non-compliance is tracked and resolved by the corrosion management organization
- ○ Corrosion management non-compliance is tracked and resolved by local business management
- ○ Corrosion management non-compliance is resolved by organization-wide management

11. Are corrosion management responsibilities for the entire asset lifecycle clearly linked to the organizational structure?

- ○ No
- ○ Yes

12. How are interactions reflected in the organization structure for those having responsibility for corrosion management defined? (Check all that apply)

- ☐ Interactions are informal
- ☐ Interactions are defined and documented (e.g. RACI charts)
- ☐ A matrix management scheme is in use
- ☐ The matrix extends to external suppliers, vendors, and stakeholders

13. Does a corrosion management group exist to support the asset lifecycle phases across the entire organization?

- ○ A corrosion management group does not exist
- ○ We have local corrosion management groups only
- ○ A corrosion management group exists and reports to another discipline (e.g., safety, integrity, etc.)
- ○ A corrosion management group exists and reports to the executive team

14. Does the corrosion management organization have a role managing suppliers and vendors?

- ○ No
- ○ Yes, but on an ad hoc basis
- ○ Yes, as part of our standard practice

15. Are corrosion management roles and responsibilities clearly defined?

- ○ Few or no corrosion management roles and responsibilities are clearly defined
- ○ Some corrosion management roles and responsibilities are clearly defined
- ○ Most or all corrosion management roles and responsibilities are clearly defined

16. Are corrosion management roles and responsibilities clearly documented?

- ○ No
- ○ Corrosion management roles and responsibilities are identified, but not fully documented
- ○ Corrosion management roles and responsibilities are fully documented
- ○ Documentation is available and current

17. Are corrosion management roles and responsibilities clearly communicated?

- ○ Few or no corrosion management roles and responsibilities are clearly communicated
- ○ Some corrosion management roles and responsibilities are clearly communicated
- ○ Most or all corrosion management roles and responsibilities are clearly communicated

18. Are corrosion management roles and responsibilities integrated into work processes?

- ○ No, corrosion management roles and responsibilities are only integrated into corrosion management processes
- ○ Corrosion management roles and responsibilities are referenced from work processes
- ○ Corrosion management roles and responsibilities are embedded into work processes

19. Is there an organizational understanding of corrosion management roles and responsibilities?

- ○ There is no organizational understanding of corrosion management roles and responsibilities
- ○ There is an organizational understanding of corrosion management roles and responsibilities mostly in the corrosion management organization
- ○ There is an organizational understanding of corrosion management roles and responsibilities only locally
- ○ There is an organizational understanding of corrosion management roles and responsibilities across the organization (horizontally and vertically)

20. Does your organizational leadership take ownership and engage in corrosion management (check all that apply)?

- ☐ Organizational leadership delegates corrosion management
- ☐ Organizational leadership has limited engagement in corrosion management
- ☐ Organizational leadership is actively involved in corrosion management

21. Are there dedicated corrosion management points of contact for external stakeholder (e.g., regulators, the public, etc.) engagement?

- ○ There are no dedicated corrosion management points of contact for external stakeholder engagement
- ○ There are dedicated corrosion management points of contact for external stakeholder engagement, but with multiple points of responsibility (for each stakeholder)
- ○ There are dedicated corrosion management points of contact for external stakeholder engagement with single point of responsibility (for each stakeholder)

22. Are appropriate and achievable corrosion management staffing levels identified?

- ○ Appropriate and achievable corrosion management staffing levels are not identified
- ○ Appropriate and achievable corrosion management staffing levels are identified on an ad hoc, on-demand basis
- ○ Appropriate and achievable corrosion management staffing levels are planned
- ○ Appropriate and achievable corrosion management staffing levels are planned and funded

23. Is budget for the following allocated to support corrosion management staffing levels (check all that apply)?

- ☐ Training
- ☐ Conference attendance
- ☐ Certifications
- ☐ Employee compensation
- ☐ Other

Describe "Other":

24. Are corrosion management competencies clearly defined?

- ○ Corrosion management competencies are not clearly defined
- ○ Clearly-defined corrosion management competencies are part of job descriptions
- ○ Clearly-defined corrosion management competencies are part of career paths

25. Are corrosion management resources (professionals) assigned based on position requirements?

- ○ Corrosion management resources are not assigned based on position requirements
- ○ Corrosion management resources are assigned based on position requirements on an ad hoc basis
- ○ Corrosion management resources are planned
- ○ Corrosion management resources are periodically reviewed and balanced based upon skills, requirements, and career paths

26. Are required corrosion management competencies specified within work processes?

- ○ Corrosion management competencies are not specified within work processes
- ○ Corrosion management competencies are specified within corrosion management processes only
- ○ Corrosion management competencies are embedded in work processes (e.g., job aids, work instructions, etc.)

27. Is professional corrosion management and technical training provided?

- ○ Corrosion management and technical training is not provided
- ○ Corrosion management and technical training is provided only for internal resources
- ○ Corrosion management and technical training is provided only for external resources
- ○ Corrosion management and technical training is provided for both internal and external resources

28. Corrosion management organizational knowledge is captured and transferred via the following mechanisms (check all that apply).

- ☐ There is no formal approach for corrosion management organizational knowledge capture and transfer
- ☐ Mentoring programs
- ☐ Job shadowing
- ☐ Job rotation
- ☐ Networking/community of practice
- ☐ Corporate procedures/standards/work practices
- ☐ Other

Describe "Other":

29. Do corrosion management communications within the organization promote the importance of corrosion management practices?

- ○ Corrosion management communications within the organization rarely or never promote the importance of corrosion management practices
- ○ Corrosion management communications within the organization sometimes promote the importance of corrosion management practices
- ○ Corrosion management communications within the organization frequently or always promote the importance of corrosion management practices

30. Does a process exist to capture employee corrosion concerns and make them visible to decision-makers (vertical communications)?

- No
- Yes

31. Are communications between organizational groups responsible for corrosion management actively encouraged?
   - No
   - Yes

32. Is a process for capturing corrosion lessons learned in place?
   - No
   - Yes

33. Are Key Performance Indicators (KPIs) established to demonstrate effectiveness and improvement of corrosion management?
   - No, no KPIs are established to demonstrate effectiveness and improvement of corrosion management
   - Yes, KPIs are established to demonstrate effectiveness of corrosion management
   - Yes, KPIs are established to demonstrate improvement of corrosion management
   - Yes, KPIs are established to demonstrate both effectiveness and improvement of corrosion management

34. Is a process in place to communicate corrosion management practices to external stakeholders (e.g., regulators, vendors, suppliers, etc.)?
   - No
   - Yes

35. Are corrosion management processes well-defined?
   - No
   - Yes

36. Are corrosion management processes well-documented?
   - No
   - Yes

37. Are corrosion management processes well-communicated?
   - No
   - Yes

38. Are corrosion management processes and tools aligned to and embedded in other disciplines (e.g., Health Safety and Environmental, quality, risk, maintenance, integrity, engineering, etc.)?
   - No, corrosion management processes and tools are not aligned to and embedded in other disciplines
   - Yes, corrosion management processes and tools are aligned to other disciplines
   - Yes, corrosion management processes are embedded in other disciplines
   - Yes, corrosion management processes are aligned to and embedded in other disciplines

39. Do corrosion management processes include risk management (e.g., identification, assessment, and mitigation of both likelihood and consequences)?
   - No
   - Yes

40. Are corrosion management improvements identified, assessed, and prioritized?
   - Corrosion management improvements are not identified, assessed, and prioritized
   - Corrosion management improvements are identified, assessed, and prioritized on an ad hoc basis
   - Corrosion management improvements are identified, assessed, and prioritized as part of our standard process

41. Are selected corrosion management improvements funded, staffed, and measured for intended results?

- ○ Selected corrosion management improvements are not funded, staffed, and measured for intended results
- ○ Selected corrosion management improvements are funded, staffed, and measured for intended results on an ad hoc basis
- ○ Selected corrosion management improvements are funded, staffed, and measured for intended results as part of our standard process

42. Do formal organizational management of change processes exist?

- ○ Formal organizational management of change processes do not exist
- ○ Formal organizational management of change processes exist on an ad hoc basis
- ○ Formal organizational management of change processes exist as a part of our standard process

43. If yes, do your corrosion management improvements comply with the organizational management of change (MOC) process?

- ○ Corrosion management improvements do not comply with the organizational MOC process
- ○ Corrosion management improvements comply with the organizational MOC process on an ad hoc basis
- ○ Corrosion management improvements comply with the organizational MOC process is a standard part of our process

44. Does your organization track the following performance measures (check all that apply)?

- ☐ Failure history
- ☐ Near miss history
- ☐ Cost vs. lifetime
- ☐ Total cost
- ☐ Non-conformance (to corrosion management policies, processes, and standards)
- ☐ Resolution of incidents
- ☐ Impact of resolution or improvements
- ☐ Other

Describe "Other":

Design

45. Which of the following does your asset design strategy address with respect to corrosion (check all that apply)?

- ☐ Regulatory
- ☐ Legal
- ☐ Health, Safety, and Environmental (HSE)
- ☐ Societal
- ☐ Design for manufacture/construction
- ☐ The intended life of the asset
- ☐ Functional requirements
- ☐ Other
- ☐ No asset design strategy exists

Describe "Other":

46. Do you have a corrosion management plan to guide the design for corrosion control and/or mitigation?

- ○ We do not have a corrosion management plan to guide the design for corrosion control and/or mitigation
- ○ We have a stand-alone corrosion management plan to guide the design for corrosion control and/or mitigation
- ○ The design for corrosion control and/or mitigation is part of the overall design plan

47. Is your corrosion management plan integrated with the overall design plan?

- ○ The corrosion management plan is not integrated with the overall design plan
- ○ The corrosion management plan is incorporated and blended into the overall design plan
- ○ The corrosion management plan is integrated with the overall design plan by reference
- ○ The corrosion management plan is integrated with the overall design plan via chapter, appendix, or attachments to the overall design plans

48. How do corrosion professionals interact with the design organization?

- ○ Corrosion professionals do not interact with the design organization; we have a stand-alone corrosion management function
- ○ A central corrosion management professional is allocated to the team
- ○ Corrosion management is part of the design team
- ○ It is a blend of central and embedded

49. Are corrosion professionals involved in supplier/vendor selection and review processes?

- ○ Corrosion professionals are not involved in supplier/vendor selection and review
- ○ Corrosion professionals are involved in supplier/vendor selection and review on an ad hoc basis
- ○ Corrosion professionals' involvement in supplier/vendor selection and review is part of our standard practice

50. Are corrosion professionals involved in supplier/vendor oversight and management?

- ○ Corrosion professionals are not involved in supplier/vendor oversight and management
- ○ Corrosion professionals are involved in supplier/vendor oversight and management on an ad hoc basis
- ○ Corrosion professionals' involvement in supplier/vendor oversight and management is part of our standard practice

51. Who is accountable for corrosion design approval?

- ○

- A corrosion professional is NOT accountable for corrosion design approval
- ○ A corrosion professional is accountable for corrosion design approval

52. Is there a communication plan that explicitly addresses corrosion-related information transfer to external stakeholders?

- ○ The communication plan does not explicitly address corrosion-related information transfer to external stakeholders
- ○ The communication plan addresses corrosion-related information transfer to external stakeholders on an ad hoc basis
- ○ The communication plan explicitly addresses corrosion-related information transfer to external stakeholders as part of our standard practice

53. Are corrosion control practices designed into systems and solutions?

- ○ Corrosion control practices are not designed into systems and solutions
- ○ Corrosion control practices are sometimes designed into systems and solutions
- ○ Corrosion control practices are frequently or always designed into systems and solutions

54. Are supplier/vendor corrosion control practices reviewed and approved by a technically qualified corrosion professional?

- ○ No
- ○ Yes

55. Do corrosion control practices include design for economics/cost effectiveness?

- ○ Corrosion control practices do not include design for economics/cost effectiveness
- ○ Corrosion control practices sometimes include design for economics/cost effectiveness
- ○ Corrosion control practices frequently or always include design for economics/cost effectiveness

Manufacturing/Construction

56. Which of the following does your corrosion manufacturing and construction strategy address (check all that apply)?

- ☐ Regulatory
- ☐ Legal
- ☐ Health, Safety, and Environmental (HSE)
- ☐ Societal
- ☐ Commissioning
- ☐ Functional requirements
- ☐ Total cost
- ☐ Other
- ☐ Does not exist

Describe "Other":

57. Do you have a corrosion management plan to guide manufacturing and construction for corrosion control and/or mitigation?

- ○ We do not have a corrosion management plan to guide manufacturing and construction for corrosion control and/or mitigation
- ○ We have a stand-alone corrosion management plan to guide manufacturing and construction for corrosion control and/or mitigation
- ○ The plan to guide manufacturing and construction for corrosion control and/or mitigation is part of another manufacturing and construction plan

58. Is your corrosion management plan integrated with all other manufacturing and construction plans?

- ○ The corrosion management plan is not integrated with all other manufacturing and construction plans
- ○ The corrosion management plan is incorporated and blended into all other manufacturing and construction plans
- ○ The corrosion management plan in integrated with all other manufacturing and construction plans by reference
- ○ The corrosion management plan is integrated with all other manufacturing and construction plans via chapter, appendix, or attachment to the overall manufacturing and construction plan

59. How do corrosion professionals interact with the manufacturing and/or construction organization?

- ○ Corrosion professionals do not interact with the manufacturing and/or construction organization; we have a stand-alone corrosion management function
- ○ A central corrosion management resource is allocated to the manufacturing and/or construction team
- ○ Corrosion professionals are part of the manufacturing and/or construction team
- ○ It is a blend of central and embedded

60. Is a corrosion professional accountable/responsible for commissioning (start-up) approval?

- ○ Accountability for corrosion management acceptance and commissioning approval is not defined
- ○ A corrosion management professional is accountable for corrosion management acceptance and commissioning approval
- ○ The Corrosion Management group is accountable for corrosion management acceptance and commissioning approval

61. Is there awareness and implementation of corrosion control practices by manufacturing/construction groups?

- ○ There is little to no awareness and implementation of corrosion control practices during manufacturing/construction.
- ○

There is awareness and implementation of corrosion control practices during manufacturing/construction on an ad hoc basis

○ There is awareness and implementation of corrosion control practices during manufacturing/construction as part of our standard practice

Operations/Maintenance

62. Which of the following does your operations and maintenance strategy address with respect to corrosion (check all that apply)?

- ☐ Regulatory
- ☐ Legal
- ☐ Health, Safety, and Environmental (HSE)
- ☐ Societal
- ☐ Asset integrity
- ☐ Life extension
- ☐ Total Cost
- ☐ Other
- ☐ Does not exist

Describe "Other":

63. Do you have a corrosion management plan for operations and maintenance activities?

- ○ We do not have a corrosion management plan for operations and maintenance activities
- ○ We have a stand-alone corrosion management plan for operations and maintenance activities
- ○ The corrosion management plan for operations and maintenance activities is part of another operations and maintenance plan

64. Is your corrosion management plan integrated with all operations and maintenance plans?

- ○ The corrosion management plan is not integrated with all operations and maintenance plans
- ○ The corrosion management plan is incorporated and blended into the overall operations and maintenance plans
- ○ The corrosion management plan is integrated with all operations and maintenance plans by reference
- ○ The corrosion management plan is integrated with all operations and maintenance plans via chapter, appendix, or attachment to overall operations and maintenance plans

65. How do corrosion professionals interact with the operations and maintenance organization?

- ○ Corrosion professionals do not interact with the operations and maintenance organization; we have a stand-alone corrosion management function
- ○ A central corrosion management professional is allocated to the operations and maintenance team
- ○ Corrosion professionals are part of the operations and maintenance team
- ○ It is a blend of central and embedded

66. Who is accountable for corrosion control monitoring, maintenance scheduling, and performance?

- ○ Accountability for corrosion control monitoring, maintenance, scheduling, and performance is not defined
- ○ A corrosion management resource has accountability for corrosion control monitoring, maintenance, scheduling, and performance
- ○ Corrosion management has accountability for corrosion control monitoring, maintenance, scheduling, and performance
- ○ Operations management has accountability for corrosion control monitoring, maintenance scheduling, and performance

67. Are corrosion control practices effectively applied?

- ○ Corrosion control practices are rarely or never effectively applied within our organization
- ○ Corrosion control practices are sometimes effectively applied within our organization

- Corrosion control practices are frequently or always effectively applied within our organization

68. Are there supplier/vendor corrosion control practices audited and overseen?

- Supplier/vendor corrosion control practices are not audited and/or overseen
- Supplier/vendor corrosion control practices are sometimes audited and/or overseen
- Supplier/vendor corrosion control practices are frequently or always audited and/or overseen

69. Do you rely on industry consensus standards for corrosion-related practices?

- No
- Yes

Abandonment, Decommissioning, or Mothballing (ADM)

70. Does your company have corrosion management asset ADM strategy (check all that apply)?

- ☐ Does not exist
- ☐ Regulatory
- ☐ Legal
- ☐ Health, Safety, and Environmental (HSE)
- ☐ Mothball
- ☐ Recycle
- ☐ Other

Describe "Other":

71. Do you have a corrosion management plan for asset retirement (re: safety)?

- ○ We do not have a corrosion management plan
- ○ We have a stand-alone corrosion management plan
- ○ The guidance for corrosion management for ADM is part of another ADM plan

72. Is your corrosion management plan integrated with all asset ADM plans?

- ○ The corrosion management plan is not integrated with all asset ADM plans
- ○ The corrosion management plan is incorporated and blended into the overall asset ADM plans
- ○ The corrosion management plan is integrated with all asset ADM plans by reference
- ○ The corrosion management plan is integrated with all asset ADM plans via chapter, appendix, or attachment to the overall ADM plans

73. How do corrosion professionals interact with those responsible for asset ADM activities?

- ○ Corrosion professionals do not interact with those responsible for asset ADM activities; we have a stand-alone corrosion management function
- ○ A central corrosion management professional is allocated to the ADM team
- ○ A corrosion professional is part of the asset ADM team
- ○ It is a blend of central and embedded

74. Who is accountable for corrosion management in preparation for ADM?

- ○ Accountability for ADM is not defined
- ○ A corrosion management professional is accountable for approval of corrosion management activities in preparation for ADM approval
- ○ A corrosion management group is accountable for approval of corrosion management activities in preparation for ADM approval

75. Does your organization apply corrosion control practices for ADM effectively?

- ○ The organization frequently or always applies corrosion control practices effectively
- ○ The organization sometimes apples corrosion control practices effectively
- ○ The organization rarely or never apples corrosion control practices effectively

76. Does the organization audit and oversee suppliers/vendors with respect to corrosion-related ADM issues?

- ○ No
- ○ Yes

Additional Items

77. Would your organization be interested in participating in a follow-up discussion with APQC and NACE to discuss corrosion management practices and total cost of corrosion-related practices (resources allocated, etc.) in more detail?

- ○ Yes
- ○ No

* Please indicate your acceptance of these terms by clicking the box below.

Survey Terms of Use

- ☐ Yes, I accept these terms of use.

Houston, Texas USA
US: 1-800-797-6223 | INTL: +1-281-228-6223| FAX: 281-228-6300
firstservice@nace.org

APPENDIX D

Case Studies of 1) A National Oil Company, 2) Pipeline Maintenance Optimization, 3) Use of Bayesian Networks for Corrosion under Insulation, and 4) Examples from the U.S. Department of Defense

D.1 CORROSION MANAGEMENT PROGRAM OF A NATIONAL OIL COMPANY

A case study is presented of corrosion management practices of a national oil company (NOC). An NOC in the Middle East has developed a mature CMP, which is described in a dedicated Corrosion Management Manual. The manual is supported by and linked to corrosion control and integrity management programs, and is intended for all life-cycle phases. The company is currently in the process of implementing the plan for all life-cycle phases. The program is being implemented internally for companywide existing facilities, and for new facilities, where EPC contractors are required to develop a CMP as part of the FEED report.

The CMP manual contains a detailed framework that is similar to the framework shown in Figure 3-4. The CMP enables proactive and risk-based corrosion management, which emphasizes leading proactive actions over lagging reactive actions (i.e., find-it-and-fix-it, repair, etc.) and possible failure.

The CMP framework as described in the manual addresses six essential elements, which are in reasonable agreement with the Management System Elements defined in Section 3.2 of this report, are as follows:

1. Policies and Objectives
    a. Best Practices
    b. Engineering Standards
    c. Industry Standards
2. Organizational Structure and Responsibilities
    a. Accountabilities
    b. Competency
    c. Training
3. Corrosion Risk Assessment and Planning
    a. Likelihood and Consequences Criticality
4. Implementation and Analysis
    a. Inspection and Maintenance Plans
    b. Corrosion Management Strategy
5. Measure System Performance
    a. Monitor trends
    b. Anomaly Tracking
    c. Key Performance Indicators
6. Systematic and Regular Review

The first five steps are aimed to set up the management system, while the sixth step forms part of the verification of the management system, providing a feedback loop to improve performance (continuous improvement) through making appropriate adjustments to policies, objectives, organizational structure/responsibilities, planning, implementation/analysis or performance measures.

Table D-1 shows general agreement of these six essential elements with those developed in the framework, see Figure 3-4, with the exception of Resources and Communication. None of the elements in the Company's framework appears to address either Resources or Communication.

Table D-1. Comparison of Corrosion Management Elements Developed by NOC (vertical) with Corrosion Management Practice Model discussed in Section 4.1.1

	Policy	Content	Organization	Accountability	Resources	Communication	CMP Integrarion	Continuous Improvement
Policies & Objectives	X	X						
Organizational Structure & Responsibilities			X	X				
Corrosion Risk Assessment and Planning							X	
Implementation & Analysis							X	
Measure System Performance				X				
Systematic & Regular Review								X

The six elements developed by the Company are applied to four different steps of an asset's life cycle, i.e.:

- Design
- Manufacturing and Construction
- Operation and maintenance
- Decommissioning

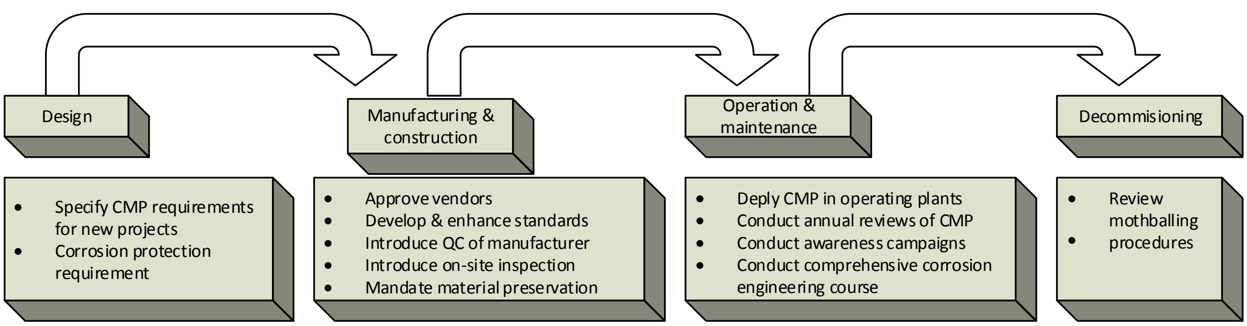


Figure D-1. Corrosion Management Applied to an Asset's Life Cycle

Figure D-1 shows the activities for each life-cycle phase with specific tasks identified in the blocks

The CMP manual follows a "Plan-Do-Check-Act" approach, so that lessons learned are captured and continuous improvement can be achieved. For this purpose, a corporate data base has been established to capture:

- Major corrosion challenges.
- Potential damage mechanisms.
- Performance measures.

- Corrosion management strategies.
- New technologies.
- Recommendations.

The application of the CMP in the assets in any stage of the life cycle is divided into three phases, pre-deployment, deployment, and review. During the pre-deployment stage, a CMP team is put together, and the roles and responsibilities are decided upon.

During the deployment phase, several activities are being defined, i.e.:

- Work process gap analysis
- Plant information review
- Plant assessment
- Corrosion risk assessment
- Corrosion loops
- Plant integrity windows
- Key performance indicators
- Damage mechanism narratives

While the Company currently is in the process of implementing the CMP for existing facilities, each new project or major facility revisions include a CMP in order to reduce the operational, safety, and environmental impact of corrosion and materials failure.

D.2 CASE STUDY OF MAINTENANCE OPTIMIZATION

Reference: D. Mauney, O. Moghissi, N. Sridhar, 'Internal Corrosion Risk Assessment and Management of Steel Pipelines, PRCI Report PR 15-9808 (2001)

The goal of maintenance optimization is to 1) choose implementation of inspect/repair/replace projects that produce positive (i.e., greater than zero) NPV's, and 2) schedule the implementation of these inspect/repair/replace projects so that the overall NPV is maximized. Putting maintenance actions into cash flow and NPV terms allows engineers to present business cases instead of technical bases. Most major industries make decisions using financial analysis methods. It seems reasonable, therefore, to use the same techniques for maintenance decision making because maintenance is competing for similar resources. In most cases, reliability is not the best decision-making criterion because is reflects an engineering concern rather than financial. To make a maintenance case on a financial basis, it seems reasonable to present the case in a way that directly compares to other competing investments. Maintenance optimization is suited to

- Determining optimum scheduling of maintenance projects without limits (constraints) on budget or forced outage rate limits.
- Determining optimum scheduling of maintenance projects using current or established values for budget and forced outage limits.
- 'What-If' scenarios by modifying inputs.
- Determining NPV versus Time curves to understand how NPV changes with time for the current project slate and model assumptions.

One way to monetize maintenance decisions is through risk, which combines probability of failure and its consequence (which can be expressed as cost). Risk management can be used to maximize the return on the invested maintenance dollar. Net Present Value (NPV), as a decision-making criterion, is a way of achieving this objective. NPV also accounts for the cash flow from leak consequences over the service life of a structure.

In the case of maintenance, the 'Net' of Net Present Value Savings is created by looking at the choice between two maintenance decisions. The first possible decision is doing nothing. That is, run the asset component as it is. This is called the base case. Here, we consider the consequence of leaks as a result of keeping the aging equipment operating. The intent of the maintenance action is to avoid this consequence. This is called the benefit of the maintenance action, because credit is taken for preventing the consequence of leaks. The second possible decision is to take a mitigative maintenance action to avoid the potential consequences of leak and downtime. This we call the alternative case. It is the cost of taking maintenance action. Here, we look at the cost of the maintenance action, plus the consequence of a leak that might still occur because of the maintenance action not being perfect.

The Present Value part of Net Present Value Savings considers the effect of taxes and the time value of money. Because maintenance decisions on in-service equipment include scheduling, this is an important consideration in any maintenance decision analysis. Taxes have a significant effect on financial analyses because of tax credits for expenses and losses. Time value of money accounts for inflation and the expected return for the invested dollar after taxes. The discount rate is usually used, so that the expected return for the invested maintenance dollar meets or exceeds a minimum desired return over time to produce a positive NPV.

Example Case Study of Pipeline Internal Corrosion

The proposed problem surrounds the identification of internal corrosion within a pipeline, and installation of a liner is proposed for each of four sections. Assuming that the liner fully mitigates corrosion, is the maintenance action justified? If yes, when is the optimum time to perform the operation based on maximizing NPV?

The pipeline of interest is 24-inch I.D. carbon steel with 0.4-inch wall thickness and is divided into four segments named alpha, beta, gamma, and delta. In segments alpha, beta, and gamma, the operating pressure is 500psi and the pressure drops to 100psi in segment delta. The transported fluids contain gas and water phases. At 500psi, CO_2 partial pressure is 10psi, H_2S partial pressure is 0.1psi, and water pH is 5. At 100psi (segment delta), the partial pressures are reduced relative to the total pressure (2psi CO_2 and 0.02psi H_2S) and the estimated pH rises to 6 (less dissolved 'acid gas'). The water in all segments contains 1% chloride. No corrosion inhibitor is injected, and the operating temperature is 60oF.

First, the corrosion model estimates cumulative probability of wall penetration for each year. Second, the failure probability and consequence are converted into expected consequential cost of failure (or risk) to predict maximum net present value (NPV).

Probability of Corrosion Failure Assessment

To assess risk, a probability of corrosion failure is required. A probabilistic model based on corrosion rate equations can be used. A normal distribution can then be applied in a Monte Carlo simulation. To determine a failure probability, a failure criterion must be defined. This can be a leak (i.e., through-wall) or rupture (i.e., remaining strength). The probabilistic assessment in this case study is based on knowledge about individual internal corrosion rates (and variability) as a function of chemical environment in a pipeline. One expression relates corrosion rate and environmental variables:

$$CR(mpy) = a + b(O_2) + c(O_2)^2 + d(pH) + e(CO_2)(H_2S) + f(CO_2)(O_2) + g(H_2S) + h(H_2S)^2 + i(H_2S)(O_2) + j(O_2)(pH) + k(Cl) + l(CO_2) + m(CO_2)^2$$

Coefficients (and their standard deviation) can be calculated in different ways. In this example, regression analyses of laboratory corrosion rates as a function of water chemistry was performed. Both general and pitting corrosion rates were used. Although uniform and pitting corrosion are treated by two separate equations, pitting is expected to be of greater interest since the predicted penetration rates are higher. For general corrosion, the predicted rate is

$$CR(mpy) = 8.70 + 19.7(O_2) - 0.592(O_2)^2 - 1.31(pH) + 4.93\times10^{-2}(CO_2)(H_2S) - 9.65\times10^{-2}(CO_2)(O_2) - 4.74(H_2S)(O_2) - 2.23(O_2)(pH)$$

For pitting corrosion, the predicted corrosion rate is

$$CR(mpy) = 107.7 - 14.3(pH) - 50.7(H_2S) + 23.2(Cl) + 18.1(H_2S)^2$$

A spreadsheet named CORRMOD.xls was created, and a screen capture with data entered is shown in Figure D-2.

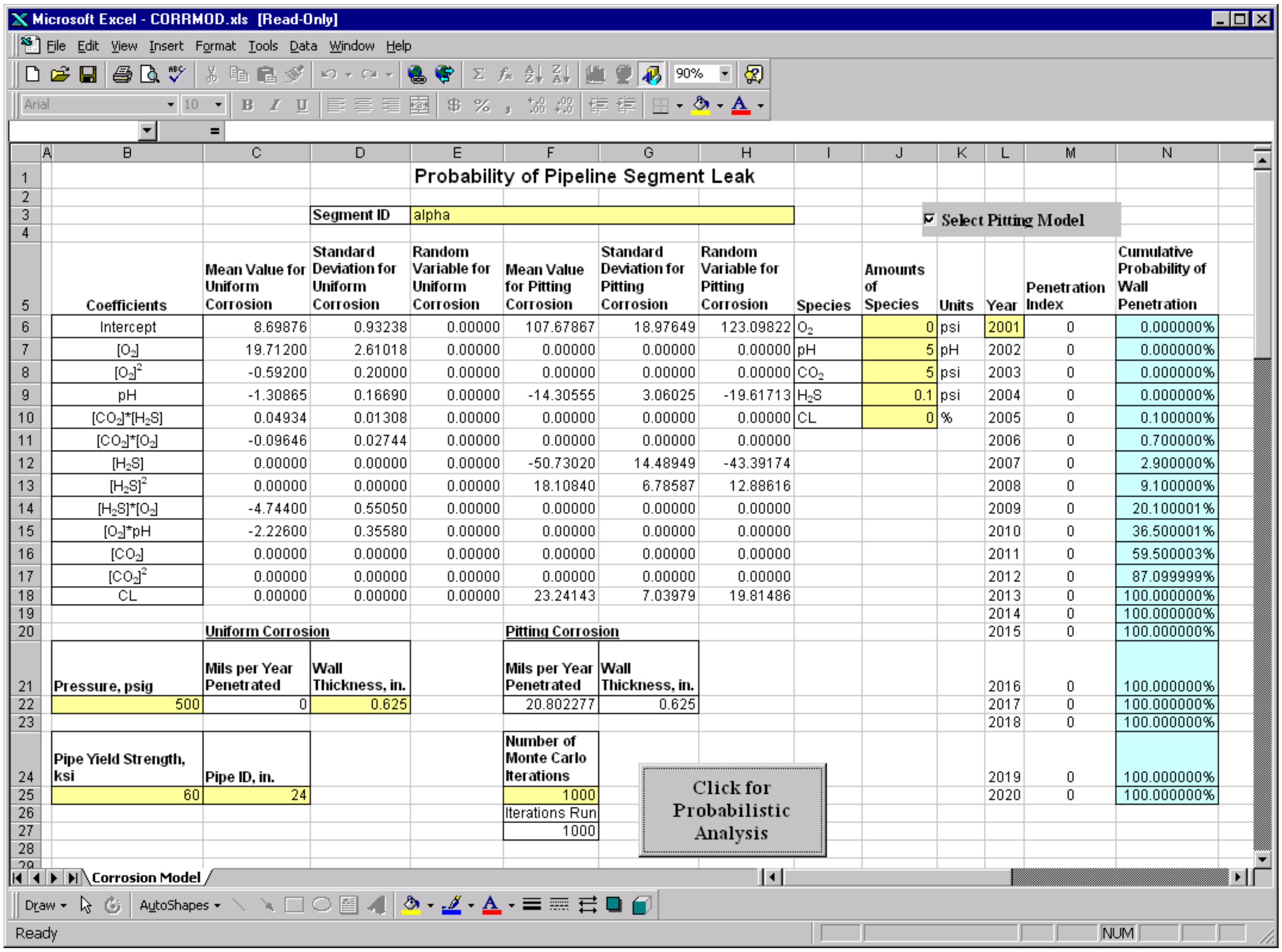
- For segments alpha, beta, and gamma, the following data was entered
  - Concentrations of corrosive species; O2 is zero, pH is 5, CO2 is 5psi, H2S is 0.1psi, Cl- is 0%
  - Year 2001 was used to start prediction
  - Line pressure and wall thickness is 500psi and 0.625 inches
  - Pipe Yield Strength and I.D. size is 60ksi and 24 inch I.D.
- For segment delta, pH was changed to 5, and H_2S to 1psi. Other parameters remain the same.

Risk Assessment and Maintenance Optimization

Maintenance optimization is determined by combining estimated probability of corrosion failure with consequence and NPV. For this example, year 2001 was used to start the analysis with that year's estimated inflation, discount, and tax rates. The proposed liner was considered to be 100% effective so the probability of corrosion after maintenance action is zero. For all segments, leak rate was estimated at 1,000 MCF per hour, cost of lost gas was $2 per MCF, leak suppression time was 2 hours, repair downtime was 4 days, and lost service cost was $1,000. The maintenance expense (i.e., liner installation cost) was made different for each segment; it was $700,000 for alpha, $10,000 for beta, $50,000 for gamma, and $10,000 for delta. Also, leak repair cost was made different for each segment; it was $1,000,000 for alpha, $500,000 for beta and gamma, and $100,000 for delta.

The resulting NPV plot is shown in Figure D-3, where the net present value for each segment is plotted versus the year in which the maintenance is performed (i.e., liner is installed). Since all segments show a period of positive NPV savings, installation of a liner is cost effective if done for any segment when NPV is positive or for the whole pipeline when the sum of the curves are positive. To maximize the savings, the liner should be installed in alpha during 2007 (i.e., maximum NPV) as shown numerically on worksheet 'components.' The plot shows that installation of a liner is cost effective for segment delta over a range of years even though the maximum is at 2007 on worksheet 'components.' The curve also shows that if a liner has not been installed by roughly 2011, it is no longer justified.

Each line represents a different segment. A positive NPV for a given year indicates that the maintenance action is financially justified. The year at which the maximum occurs represents the year that maintenance should be performed to gain the most financial benefit. The higher the positive value of the NPV, the greater the return of performing the maintenance at this time as compared to not performing the maintenance. If all the NPV's are negative, and the maintenance has to be performed in the analysis period, then the maintenance needs to be performed at the least negative NPV time. A positive NPV indicates that not only does performing the activity at the time indicated generate a cost savings, but that investing in this activity generates a positive benefit over an alternate investment of this money that would return the discount rate.



Microsoft Excel - CORRMOD.xls [Read-Only]

Probability of Pipeline Segment Leak

Segment ID: alpha

Select Pitting Model

Coefficients	Mean Value for Uniform Corrosion	Standard Deviation for Uniform Corrosion	Random Variable for Uniform Corrosion	Mean Value for Pitting Corrosion	Standard Deviation for Pitting Corrosion	Random Variable for Pitting Corrosion
Intercept	8.69876	0.93238	0.00000	107.67867	18.97649	123.09822
$[O_2]$	19.71200	2.61018	0.00000	0.00000	0.00000	0.00000
$[O_2]^2$	-0.59200	0.20000	0.00000	0.00000	0.00000	0.00000
pH	-1.30865	0.16690	0.00000	-14.30555	3.06025	-19.61713
$[CO_2]*[H_2S]$	0.04934	0.01308	0.00000	0.00000	0.00000	0.00000
$[CO_2]*[O_2]$	-0.09646	0.02744	0.00000	0.00000	0.00000	0.00000
$[H_2S]$	0.00000	0.00000	0.00000	-50.73020	14.48949	-43.39174
$[H_2S]^2$	0.00000	0.00000	0.00000	18.10840	6.78587	12.88616
$[H_2S]*[O_2]$	-4.74400	0.55050	0.00000	0.00000	0.00000	0.00000
$[O_2]*pH$	-2.22600	0.35580	0.00000	0.00000	0.00000	0.00000
$[CO_2]$	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
$[CO_2]^2$	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
CL	0.00000	0.00000	0.00000	23.24143	7.03979	19.81486

Species	Amounts of Species	Units
O_2	0	psi
pH	5	pH
CO_2	5	psi
H_2S	0.1	psi
CL	0	%

Year	Penetration Index	Cumulative Probability of Wall Penetration
2001	0	0.000000%
2002	0	0.000000%
2003	0	0.000000%
2004	0	0.000000%
2005	0	0.100000%
2006	0	0.700000%
2007	0	2.900000%
2008	0	9.100000%
2009	0	20.100001%
2010	0	36.500001%
2011	0	59.500003%
2012	0	87.099999%
2013	0	100.000000%
2014	0	100.000000%
2015	0	100.000000%
2016	0	100.000000%
2017	0	100.000000%
2018	0	100.000000%
2019	0	100.000000%
2020	0	100.000000%

Pressure, psig	Uniform Corrosion: Mils per Year Penetrated	Uniform Corrosion: Wall Thickness, in.	Pitting Corrosion: Mils per Year Penetrated	Pitting Corrosion: Wall Thickness, in.
500	0	0.625	20.802277	0.625

Pipe Yield Strength, ksi	Pipe ID, in.	Number of Monte Carlo Iterations	Iterations Run
60	24	1000	1000

Click for Probabilistic Analysis

Corrosion Model

Ready

Figure D-2. Screen capture of Corrmod.xls software.

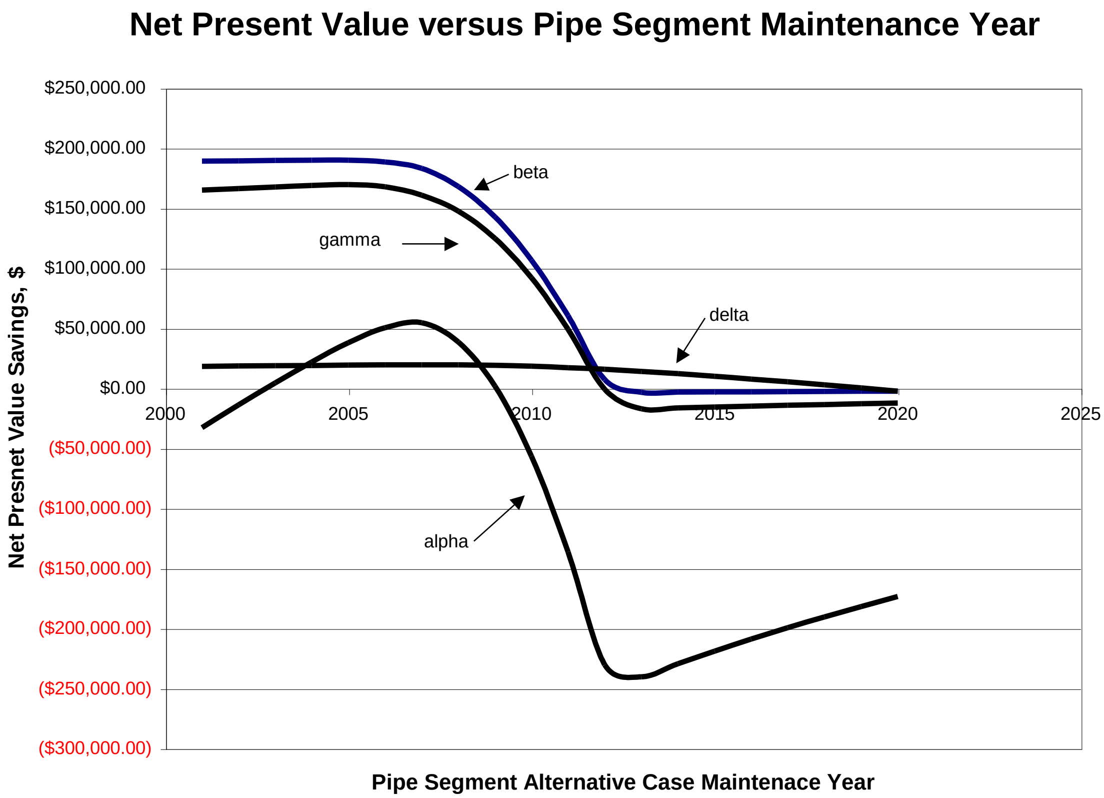


Figure D-3. Results of example problem to determine cost effectiveness of liner installation

D.3 PREDICTING THE IMPACT OF CORROSION UNDER INSULATION FOR AGING PLANTS: A BAYESIAN NETWORK APPROACH

Introduction

Thermal insulation is used refineries, chemical plants, oil and gas production systems, pipelines, and many other applications. Unfortunately, Corrosion under Insulation (CUI) is a common and costly problem in industry. In the case of carbon steel, CUI takes the form of general and localized corrosion. Although the resulting corrosion rate is somewhat low (0.1 to 0.8 mm/y), the corrosion is hidden for long periods of time leading to unanticipated failures. In the case of stainless steel, stress corrosion cracking, often called external stress corrosion cracking (ESCC), can occur under the insulation. Since the rate of cracking can be quite high, ESCC is of great concern to operators. Despite much effort devoted to managing CUI[37,38,39], CUI continues to occur in many industries and is estimated to cost process plants about 10% of their total maintenance budgets[40]. Major equipment outages and unexpected maintenance costs stemming from CUI account for more unplanned downtime than all other causes[41]. Various non-destructive examination methods have been evaluated, but none has been completely satisfactory in assessing CUI. Therefore, complete removal of insulation is the surest way of detecting CUI and adds to the cost.

The management of CUI requires a systems perspective because a number of design, construction, and operational factors interact to cause CUI. Typically, a risk-based inspection (RBI) methodology is adopted to prioritize inspection and maintenance activities in terms of risk. RBI methods rely on past experiences of corrosion and failures using a ranking system to prioritize risk. Although RBI methods have been around for a long time, they have not been completely satisfactory in identifying the most probable locations of CUI.

What is the solution?

Bayesian Network (BN) models are highly suited to assess the performance of complex interactive systems[42] because they try to represent the whole system in terms of its interacting parts through cause-consequence relationships. Furthermore, BN models are probabilistic and observational in nature, so they can represent the uncertainties of the system and can be modified based on inspection and sensor data. Finally, BN is a great tool to capture the diverse knowledge of personnel who work with a system.

---

[37] Pollock, W. I. and J. M. Barnhart (1985). Corrosion of metals under thermal insulation. Corrosion of metals under thermal insulation, San Tntonio, TX, ASTM International.

[38] ASTM (2007). Standard Guide for Laboratory Simulation of Corrosion Under Insulation. 100 Barr Harbor Dr., W. Conshohocken, PA, ASTM International. **G 189-07**.

[39] NACE (2010). Control of Corrosion Under Thermal Insulation and Fireproofing MaterialsA Systems Approach. Houston, TX, NACE International. **SP0198-2010:** 42.

[40] Fitzgerald, B. J., et al. (2003). Strategies To Prevent Corrosion Under Insulation In Petrochemical Industry Piping. Corrosion 2003, Houston, TX, NACE International.

[41] Kurihara, T., et al. (2010). "Investigation of the Actual Inspection Data for Corrosion Under Insulation (CUI) in Chemical Plant and Examination about Estimation Method for Likelihood of CUI." Zairyo-to-Kankyo **59**(8): 291-297.

[42] Fenton, N. E. and M. Neil (2012). Risk assessment and decision analysis with Bayesian networks. Boca Raton, Taylor & Francis.

Bayes rule helps us to calculate the probability of an event given the probability of a causative event. For example, the probability of corrosion in a system depends on water accumulation underneath the insulation, among other factors. However, BN can include physics-based models as well as statistical data to develop the conditional probability table[43].

Bayesian Network model for CUI

The CUI system is much more complex than previously thought[3], and can be represented in a BN as shown in Figure D-4. All the factors that can lead to CUI of carbon steel and stainless steel can be lumped into three major categories: Insulation System, Design, and Environment (shown as color coded sets of bubbles). These factors affect other causative factors, such as time of wetness, that then affect corrosion or ESCC. The corrosion rates are in the range observed by Kurihara et al.[44] (Kurihara, Miyake et al. 2010), but the probability of the corrosion rate being in any one of values within this range depends on all the other factors connected to it. The nodes that have linkages to parent nodes (or causative nodes) have conditional probability tables such as the one illustrated in Figure D-5.

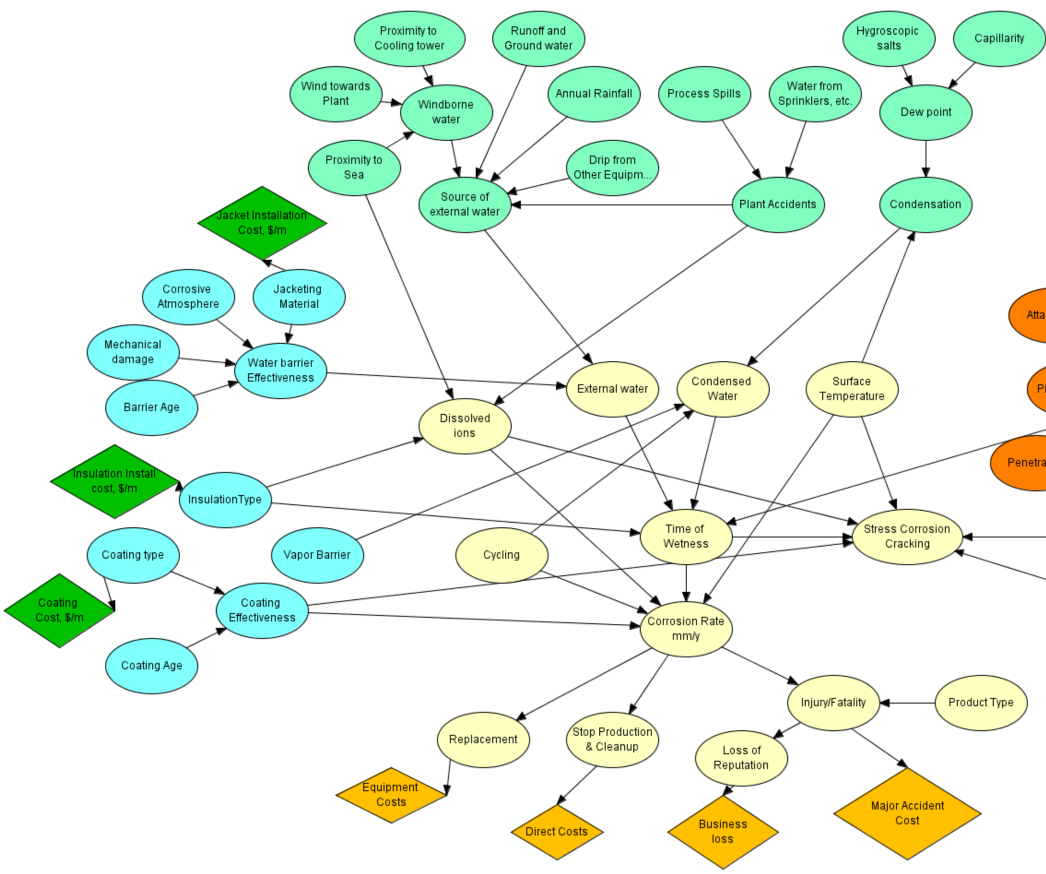


Figure D-4. A BN representation of CUI of carbon steel and stainless steel.

[43] Ayello, F., et al. (2014). "Quantitive Assessment of Corrosion Probability—A Bayesian Network Approach." Corrosion **70**(11): 1128-1147.
[44] Kurihara, T., et al. (2010). "Investigation of the Actual Inspection Data for Corrosion Under Insulation (CUI) in Chemical Plant and Examination about Estimation Method for Likelihood of CUI." Zairyo-to-Kankyo **59**(8): 291-297.

Prediction of the business impact of CUI

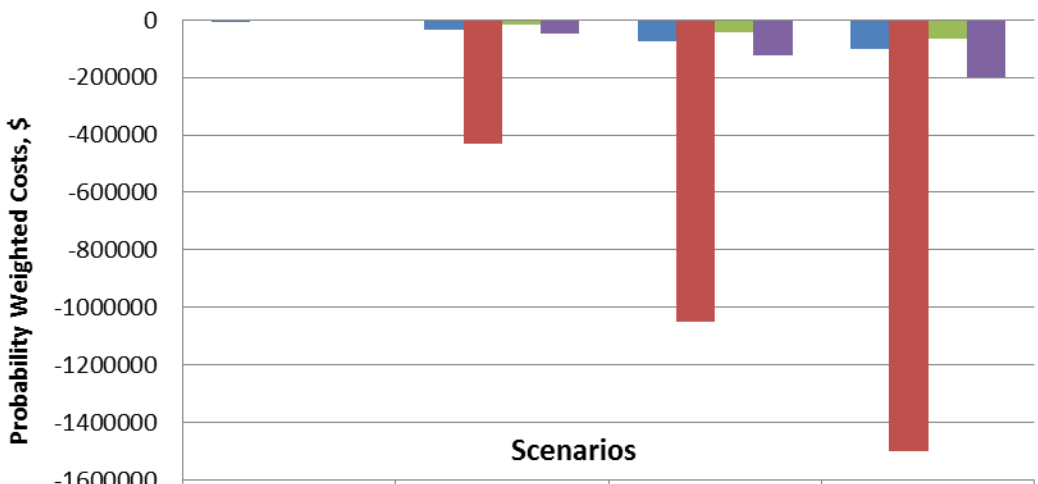
The predicted business impact could be a valuable KPI for operational leaders to make risk-informed decisions, based on their risk appetite and internal decision criteria. The business impact criteria are defined as follows:

- Direct costs: Revenue lost due to down time and clean-up costs from product leaks
- People: Injury or fatality leading to legal fees, escalating insurance costs, and fines
- Repair/ Replace: Cost of parts and labor for repair/replacement
- Major Accident Potential: defined by the Seveso Directive in Europe[45] (Seveso, 2012), covering, any fire or explosion or accidental discharge of a dangerous substance in defined quantities, a fatality of more than six persons injured with hospitalization, massive evacuation, immediate and severe damage to the environment (permanent/long-term), damage to own property (> 2 million euro), or eventual cross-border damage
- Loss of reputation: Reputational damage can lead to loss of clients, additional government oversight, increased borrowing costs, and loss of high value staff

The business impact of CUI is expressed in Figure D-4 through utility nodes (diamond-shaped nodes). By connecting the failure consequence nodes to the corrosion node, the business impact can be calculated in a probabilistic manner. Furthermore, by assigning utility nodes to various maintenance activities such as, improved coating and insulation, the BN enables risk informed maintenance decisions.

A number of scenarios can be constructed on the basis of inputs to BN as illustrated in Figure D-5 and the corresponding business impacts can be estimated (costs are shown as negative numbers). For example, in Scenario 1, the surface temperature is low and therefore the corrosion rate is likely to be low leading to a low probability of failure and injury/fatality. Therefore, most business costs (other than maintenance costs) are low. On the other hand, if the surface temperature is 60^{o} C, there is no coating under the insulation, and the product is flammable, there is a higher probability of high corrosion and failure leading to significant business costs.

[45] Seveso (2012). EU Directive 2012/18/EU of the European Parliament and of the Council of 4 July 2012 on the control of major-accident hazards involving dangerous substances, amending and subsequently repealing Council Directive 96/82/EC.



	T = -4 C	Unknown Surface Temp.	T = 60 C	T=60 C, no coating
Equipment Repair/Replace	-6985	-3.42E+04	-7.39E+04	-1.04E+05
Direct Costs	0	-4.33E+05	-1.05E+06	-1.50E+06
Reputation/Business Loss	0	-18642	-45313	-64655
Major Accident	0	-48615	-122136	-198011

Figure D-5. Examples of Estimated Business Costs for a Number of Scenarios Calculated by BN Shown in Figure D-4. Note: the cost numbers are mainly illustrative and do not represent actual values.

Uses and Limitations of Bayesian Networks

BN allows us to combine expert opinions, data, and analytical models in a single framework.

1. Since many aging plants have missing historical and design data, we can initially assume that the probability of data attaining a certain value is the same (called uniform probability) and proceed with the analysis. Of course, the resulting probability calculations may have significant uncertainty, and have to be updated with suitable data.

In order to obtain more data cost-effectively, BN's can provide analyses of the value of information on the resulting calculation of a variable of interest (e.g., probability of corrosion rate). This permits the user to allocate resources to factors that most impact risk. An example of such a calculation is shown in Figure D-6. The importance essentially reflects the effect of reducing the uncertainty of a factor (e.g., surface temperature) on narrowing the probability distribution of the variable of interest (corrosion rate in this case).

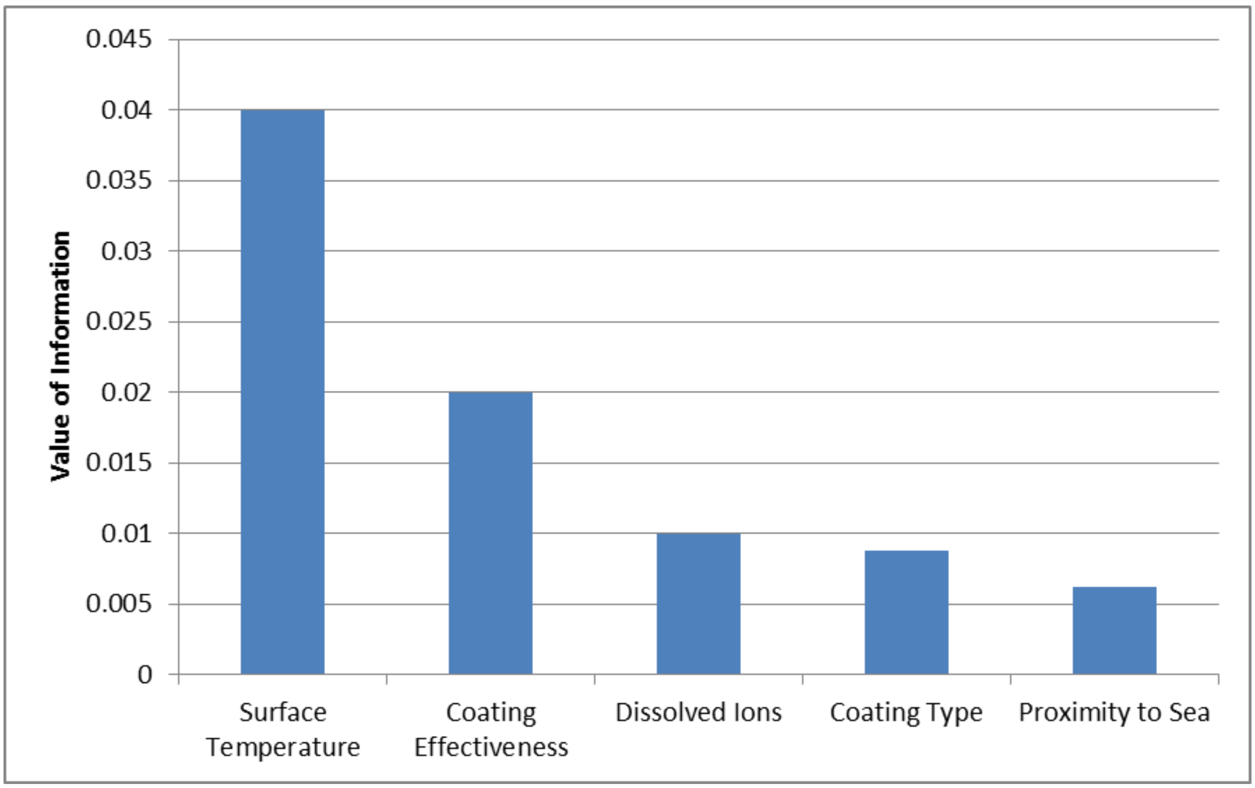
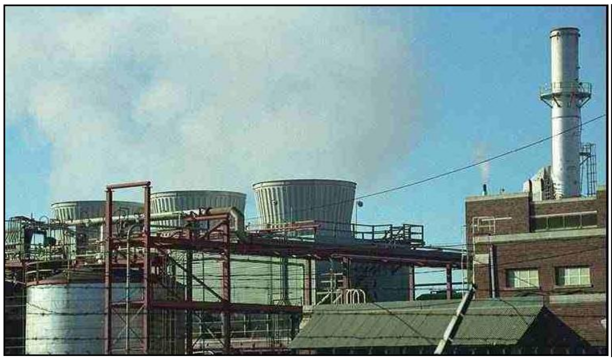


Figure D-6. Value of information analysis of Bayesian network for CUI

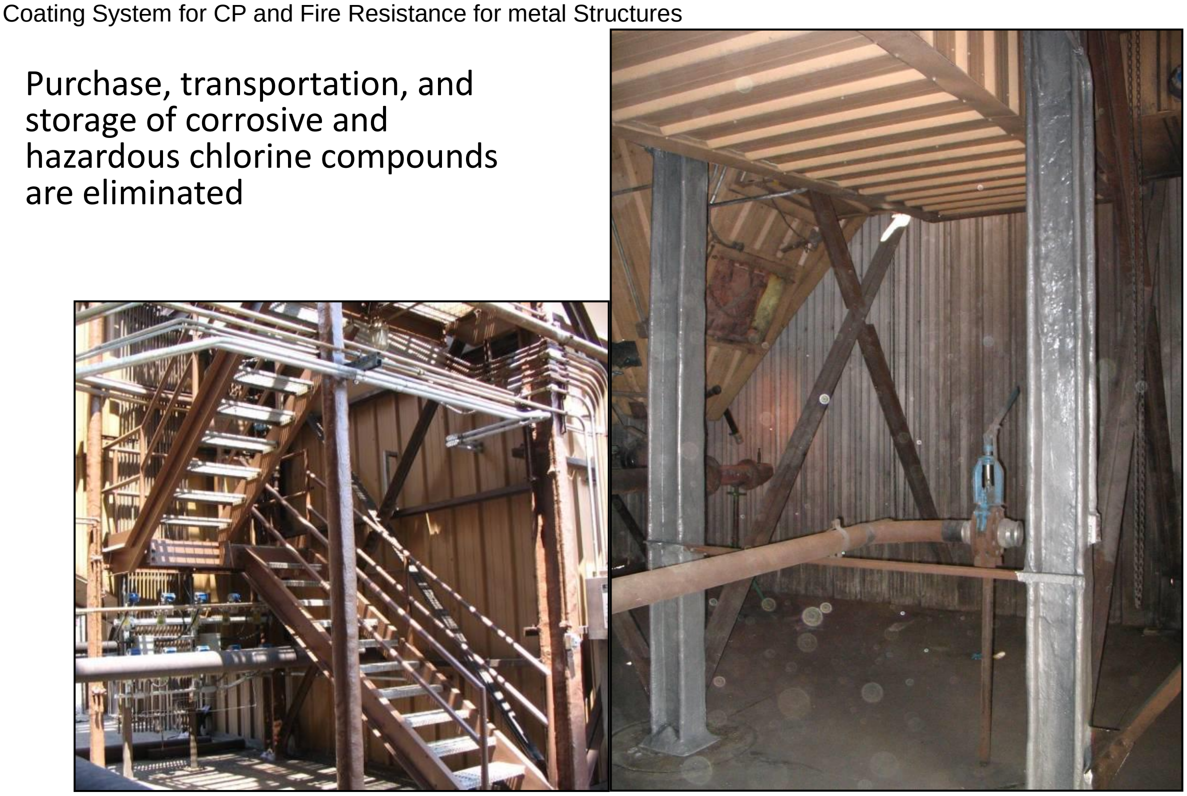
D.4 DEPARTMENT OF DEFENSE CORROSION PROJECT CASE STUDIES WITH CALCULATED ROI

FAR03: Green Water Treatment

Project Number	FAR03
Project Title: Green Water Treatment  The MIOX mixed oxide disinfectant system has been installed in cooling towers at Corpus Christi Army Depot  Purchase, transportation, and storage of corrosive and hazardous chlorine compounds are eliminated	
Fiscal Year	2006
Service	Army
Major Category	Equipment
Purpose	Across the three implementation sites (Ft Rucker, West Point, Ft. Wainwright), the nonhazardous inhibitor formulations and smart-monitoring and control systems will be implemented in an estimated 10 heating and 10 cooling systems. Additional heating and cooling plants at installations in the region will be inspected to assess the efficacy of installing the smart corrosion control system at these sites (ultimately Corpus Christi Army Depot was selected). Specifications for nonhazardous boiler and cooling tower treatments and the smart control system will be developed, and the systems will be installed. Training on system operation and maintenance will be provided to the installations. The operational efficiency of the heating and cooling systems will be determined, and downtime due to corrosion failure, safety and environmental impact will be assessed.
Technology	A new chemical formulations for heating and cooling systems have recently been introduced, most notably in the areas of environmentally friendly, or “green” chemical formulations such as the MIOX mixed oxidant process and glycol alternatives for treating boiler and cooling systems combined with smart monitoring and control systems that use just enough chemicals, when needed to maintain optimal treatment levels for corrosion, scale, and microbiological growth.
Application	This technology was developed in the 1980’s in response to the Army’s solicitation for a simple, portable alternative water purification system. In addition to cooling towers, the technology can be scaled for use in swimming pools, wastewater treatment, and hand-held units for field disinfection of potable water.
Benefits	The goals of the project are: improving the reliability and reducing the cost of operating and maintaining boilers and cooling towers by using nonhazardous corrosion inhibitors and a smart control system. The objective is proper design and installation of the chemical feed and control

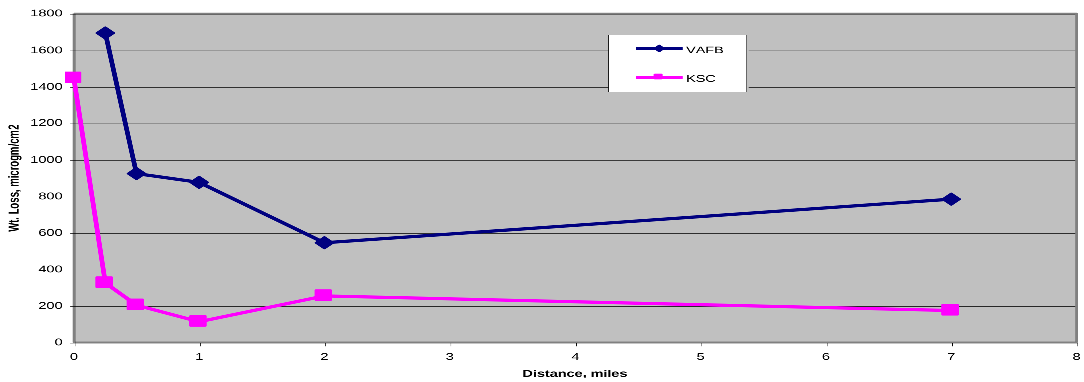
	system, and continuous operation and chemical feed.
Lessons Learned	The type of salt selected for developing the brine may negatively impact system performance. If food-grade table salt is used, it must be mixed in a brine tank containing a settling bed of quartz rocks. The quartz remains chemically inert in the carrier fluid, but the gravel allows suspended salt crystals to settle to the bottom of the tank, where the salt can dissolve quiescently at the intended rate, undisturbed by water turbulence. With-out the settling bed, salt sediment may flow through the system and clog downstream filters. In order to avoid the need for a quartz settling bed in the brine tank, the use of pelletized forms of salt is recommended.
Transition Status: Ongoing ROI: 9.4	ROI Validation states that it is recommended that the managers of U.S. military installations fully utilize a system of MIOX for reduction of microbiological growth in cooling towers. It also states that changes were recommended to UFGS 23 64 26 to incorporate the mixed oxidants process of chemical treatment for cooling tower systems. The revised criteria documents listed above will be submitted to HQ USACE (CECW-CE) for inclusion in the criteria update cycle. Recommended changes to current UFGSs and UFCs will be submitted on line through the Whole Building Design Guide web site.

FAR13: Coating System for CP and Fire Resistance for metal Structures

Project Number	FAR13
Project Title: Coating System for CP and Fire Resistance for metal Structures  	
Fiscal Year	2006
Service	Army
Major Category	Coating
Purpose	The goals of the project are: Reducing the corrosion rate of the structural steel and increasing fire safety for the structures at Rock Island Arsenal, as well as validating the technology for other uses across the DoD.
Technology	Intumescent coatings are based on traditional paint resins, such as solution vinyl, latex, and epoxy, and are applied as thin films like traditional paints. The resins allow the coatings to form tight bonds to structural surfaces. When exposed to fire, the intumescent coating reacts by expanding. It is transformed to a thick, ceramic-like, insulating char that provides thermal protection for the substrate.
Application	Candidate structures at Rock Island Arsenal will be assessed for application of the intumescent epoxy system. The coating system will be applied to one hangar and one additional structure selected by the installation.

Benefits	Because the Pitt Char XP Fire Protective Coating is an epoxy, it resists solvents, acids, alkalis, salts and abrasion while retaining its fire protective properties. The coating bonds tightly and cures to form a dense, impervious barrier that blocks corrosives such as salt spray and moisture. It is a tough coating that withstands damage from impact. The coating is unique in that it is flexible, with elongation over 19%. It will adhere to structural steel and other metals, and fiberglass reinforced composites.
Lessons Learned	Bid/Contract Scope language needs to be very specific. All parties need to agree in writing on the scope of the project. A coating system test panel should be approved by all parties and be retained to serve as a reference for all work on the structures. Plans for movement of material and equipment must be coordinated among all parties. Planned start date should take into consideration the time of year and normal temperatures ranges typically encountered. Placement of waste receptacles onsite and timely pick-up of waste such as spent abrasive media and paint and solvent wastes should be coordinated in advance with an approved local waste disposal company.
Transition Status: Ongoing ROI: 8.8	ROI Validation states that the following impacted criteria documents were identified: UFGS 07 81 00 Spray-Applied Fireproofing and UFC 3-600-1 Fire Protection Engineering for Facilities. Changes were recommended to the UFGS to incorporate epoxy intumescent fireproof coatings. Recommended changes were incorporated into the February 2011 release. It is recommended that a product specification be adopted by The Society for Protective Coatings (SSPC) or the Master Painter's Institute so that the product specification can be referenced as a system. Revisions to UFC 3-600-1 will be submitted to HQ USACE (CECW-CE) for inclusion in the criteria update cycle. An analysis was performed with Army IMA (now IMCOM) to determine the important factors for Army

FAR15: Development of Corrosion Indices and Life-Cycle Protection

Project Number	FAR15
Project Title: Development of Corrosion Indices and Life-Cycle Protection  The MIOX mixed oxide disinfectant system has been installed in cooling towers at Corpus Christi Army Depot	
Fiscal Year	2006
Service	Army
Major Category	Other
Purpose	The proposed FY06 work will develop a life-cycle predictive tool to optimize preventive maintenance cycles based on region and material, for weapons and facilities. The predictive tool will be a location based corrosivity software model that will draw on the data acquired in the FY05 project. The downloadable software package which will assign a corrosion index to a site based on environmental data.
Technology	Corrosion growth can be projected with the use of appropriate models. The mechanical impacts of this damage can then be ascertained using structural models. This approach requires the development of multiple technologies and extensive amounts of data. Not only is extensive corrosion and structural modeling required, but also part specific damage definitions must be developed with the associated NDI techniques. This complex effort will determine microclimate environmental severity factors and the associated corrosion growth rates. The prediction and management of corrosion damage requires first that the initial condition of the specific structure with respect to corrosion be defined. Subsequently the severity of the environment to which the structure is exposed must be measured and the time that the structure is exposed to that environment projected. The corrosion growth can then be projected with the use of appropriate models. The mechanical impacts of this damage can then be ascertained using structural models. This approach requires the development of multiple technologies and extensive amounts of data. Not only is extensive corrosion and structural modeling required, but also part specific damage definitions must be developed with the associated NDI techniques. This complex effort will determine microclimate environmental severity factors and the associated corrosion growth rates. This project will build a software based model of corrosion

Application	Material and process selection can be tailored for both equipment and facilities DoD-wide based on the corrosion index. The efficacy of the corrosion index will also be determined for various environments.
Benefits	The corrosion index will allow the user to develop select appropriate corrosion resistant materials, coatings, cathodic protection and water treatment for use in project specifications and maintenance practices.
Lessons Learned	Tests of the models have shown that a major limitation is that location for the predictions must be in proximity to the location where the weather da-ta are collected. This is particularly true in coastal locations adjacent to saline bodies of water. At this time it is estimated that the point of weather data collection is optimum at 0.25 miles or less from the location of interest.
Transition Status: Implemented ROI: 33.1	ROI Validation states that this work resulted in linear models of an atmospheric corrosivity rate model based on geographic location. These models have been incorporated into a software package. The models can be run from a PC and allow the user to display corrosion rates/severity levels for locations in the database along with confidence intervals on the results. In addition, the user can calculate corrosion rates for new locations that have not been previously monitored provided that the appropriate weather data are available. The software is available through the DoD Corrosion Defense (CorrDefense) web site, www.corrdefense.org.

FAR16: CP of Rebar in Critical Facilities

Project Number	FAR16

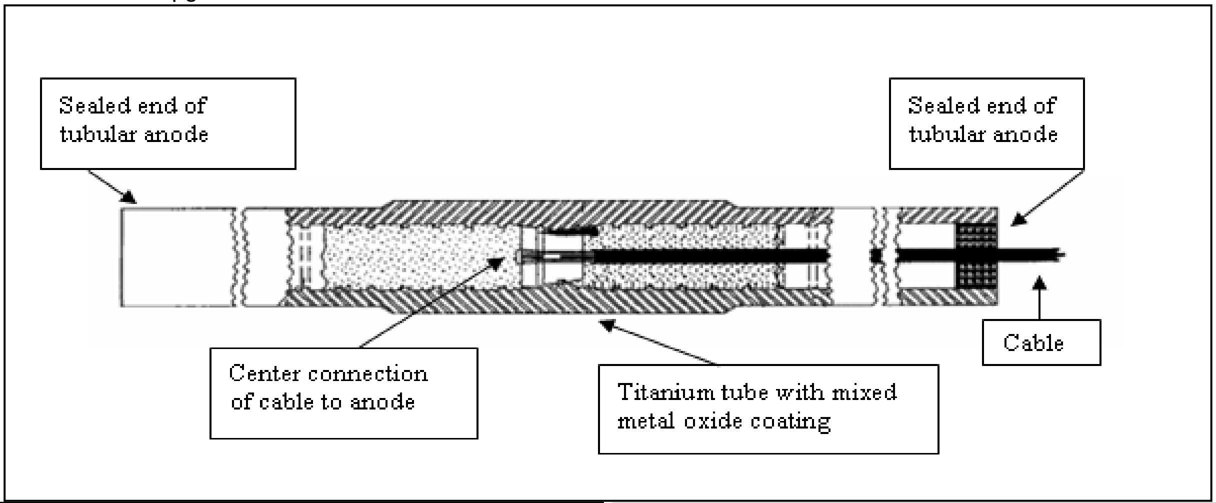
Project Title:
CP of Rebar in Critical Facilities

Fiscal Year	2006
Service	Army
Major Category	Coating
Purpose	Corrosion Prevention of Rebar in Concrete in Critical Facilities Located in Coastal Environments at Okinawa.
Technology	Corrosion protection for the rebar can be established through the use of a zinc-rich cathodic protection compound that can be applied to the concrete deck. The phenomenon of “sacrificial” cathodic protection is based on the ability of a more active metal, such as zinc to easily loose electrons when electrically connected to steel rebar, while an ionic current flows via moisture through the pores of the concrete. This establishes an electrochemical reaction that results in the steel rebar becoming the cathode, while the zinc-rich coating becomes the anode, and is “sacrificed,” and slowly oxidizes over many years. In this case, the rebar is said to be cathodically protected.

Application	The cathodic protection compound can be applied to uneven surfaces and to the underside of structures. It is recommended for bridges, parking decks, ramps, garages, concrete piers, offshore platforms, piles, pillars, pipes, buildings, foundations and underside application to structures of many sizes and shapes. One gallon is used for 160 sq. ft. of the concrete structure.
Benefits	The zinc-rich urethane coating contains particles of magnesium and indium, as well as moisture-attracting compounds that facilitate the protection process. It is applied easily by spraying, brushing, or rolling, and is particularly suited to applications such as bridges, decks, ramps, concrete piers, offshore platforms, and foundations. The coating also can be applied to uneven surfaces and to the underside of structures, as well as to vertical, horizontal, and overhead surfaces, and to structures of many shapes.
Lessons Learned	Corrosion inhibitors are generally applied to clean concrete surfaces and allowed to penetrate and dry. The allocated time and rate are usually a function of the ambient environment and manufacturers recommendations for installation of the particular brand or product. Therefore, the climate and environment the application is used in has to be considered prior to application. Repairs need to be scheduled to coincide with application. It was difficult to use the Galvapulse method to determine the corrosion rate on the LGC coating as the titanium mesh distorted readings. Rilem water tubes will not seal well to a coated surface, and it was difficult to perform the water permeability test following treatment of the structures.
Transition Status: Ongoing ROI: 12.9	ROI Validation states that this corrosion prevention technology is not covered in any UFC or UFGS. ERDC-CERL has prepared the draft Unified Facilities Guide Specification for submission to HQ USACE (CECW-CE) for inclusion in the criteria development cycle. An analysis was performed with Army IMA (now IMCOM) to determine the important factors for Army-wide implementation. This analysis also showed potential for DoD-wide application.

FAR20: Ceramic Anode Upgrades at Ft. Jackson

Project Number: FAR20	
Project Title Ceramic Anode Upgrades at Ft. Jackson	
Fiscal Year	2006
Service	Army
Major Category	Material
Purpose	At Ft. Jackson, a new type of ceramic anode will be used to protect underground pipes, which will be installed in deep wells 50-100 feet deep. The deep-well ceramic anodes will be in soil that has a 20-70 ft. water head, and the connection between the anodes and the cable is the weakest link, which must be protected.
Technology	The solution to the problem of natural gas line protection is the installation of a cathodic protection (CP) system consisting of deep well ceramic anodes. Impressed CP systems protect the buried pipe by supplying electrons from the ceramic anodes that are made to assume a negative potential relative to the pipe. The mixed metal oxide ceramic anodes are to be installed in 4 strategic locations in 200 feet deep below the ground. Installation of deep well impressed current ceramic anode beds help to more widely distribute the protection current from ceramic anodes to protect pipelines.



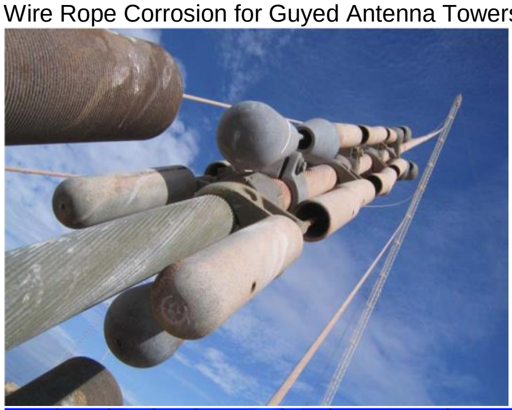
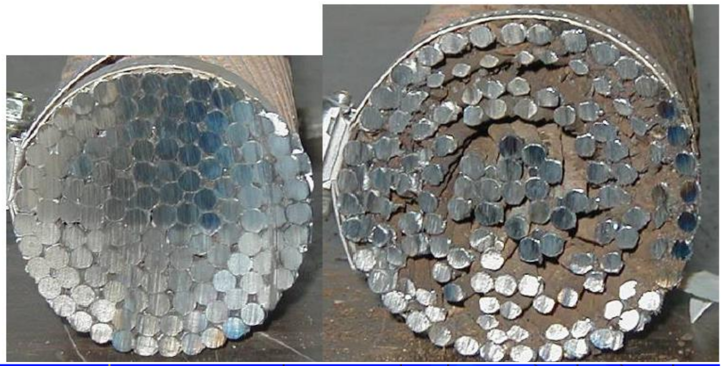
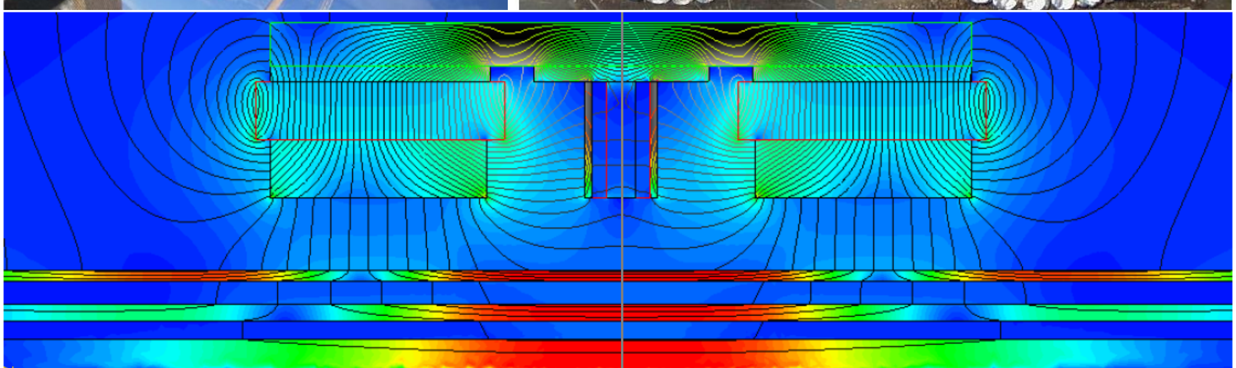
Application	This CPC proposal seeks to demonstrate the efficacy of the CP technology in conjunction with remote monitoring at Ft. Jackson.
Benefits	It is expected that the implementation of these technologies will bring the natural gas piping system into compliance and extend the lifetime of the water tanks.
Lessons Learned	On many installations piping and other underground systems have been replaced or moved and documentation of these changes have not been consistently recorded in one easy to access place. The many variances in the soil types and depths at Fort Jackson presented another need for having contingency plans as bedrock was encountered at varying depths. If the piping system is not properly isolated, cathodic protection of the sys-tem is much more difficult to achieve.
Transition Status: Ongoing ROI: 14.7	The following impacted criteria documents were identified: UFGS -26 42 15.00 10, Cathodic Protection System (Steel Water Tanks), and UFGS -26 42 17.00 10, Cathodic Protection System (Impressed Current). Changes were made to these documents to incorporate ceramic anode technology for deep bed impressed current CP systems. Suggested changes are contained in the final report (ERDC/CERL TR-09-26). The revised criteria documents listed above will be submitted to HQ USACE (CECW-CE) for inclusion in the criteria update cycle. Recommended changes to current UFGSs and UFCs will be submitted on line through the Whole Building Design Guide web site. Transition to American Water Works Association (AWWA) guidance is being explored. An analysis was performed with Army IMA (now IMCOM) to determine the important factors for Army-wide implementation. This analysis also showed potential for DoD-wide application.

FNV01: CP Utilizing IR Drop Free Sensors

Project Number	FNV01
Project Title: CP Utilizing IR Drop Free Sensors  	
Fiscal Year	2006
Service	Navy
Major Category	Sensor
Purpose	Improved corrosion (cathodic) protection (CP) monitoring systems are needed for cross-country pipelines such as the pipeline on Guam that runs from the Navy fuel distribution pipeline manifold at Tiyan to the Andersen Air force Base Tank Farm.
Technology	Potential measurements of underground structures made with portable reference electrodes placed on the surface or buried permanent reference electrodes often contain an error known as IR Drop error. IR Drop error results from the interaction of the cathodic protection current with the soil resistance. One way of accounting for this error is to momentarily interrupt the cathodic protection current and measure the potential immediately after interruption. This so-called instant-off potential can be substantially free of IR Drop error. It is nearly impossible to feasibly interrupt cathodic protection current on structures protected with distributed sacrificial anodes. Even in cases where current interruption is possible, there may be other sources of current at

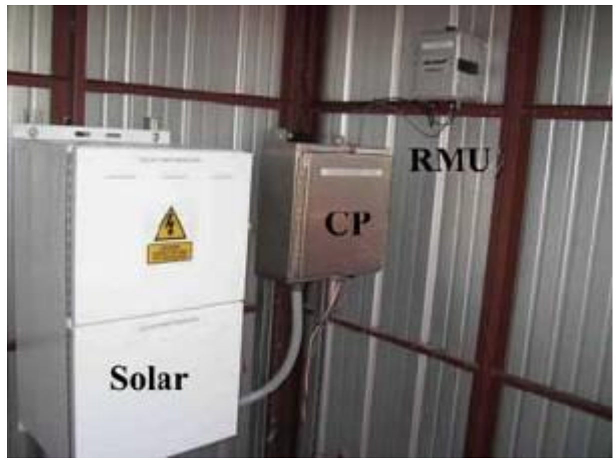
	that location such as those from nearby cathodic protection systems, stray currents or telluric currents. Cathodic protection coupons, sometimes called instant off sensors, have been developed as a means to make instant off potential measurements under virtually all conditions. A transponder/data logger has been implemented in metropolitan street environments where access to cathodic protection system test points is limited by vehicle traffic and pavement. In this project we will be utilizing this technology a step further for novel application in a cross-country environment with severe conditions.
Application	Successful implementation of this technology system on the Tiyan pipeline in Guam will validate its transition for use on other Navy and DOD cross-country pipelines, as well as other critical facilities that utilize cathodic protection systems. These facilities include waterfront structures, potable water tanks, and utility piping.
Benefits	Due to the difficulty in locating the test stations in this severe cross country environment with overgrown brush and constant movement of soil that bury the test stations, IR drop free sensors will be integrated and installed with interrogator transponders and data loggers that will record output over time and will enable identification of location and wireless measurement of desired parameters.
Lessons Learned	.
Transition Status: Implemented ROI: 11.4	ROI Reassessment states that based on the test results to date, we can conclude that the IR free coupons are functioning well, and valid IR drop error free structure to electrolyte potentials are being obtained. This provides valuable data that can assist in the prevention of pipeline leaks and avoid high environmental cleanup costs. The use of the drive by data interrogation system theoretically reduces annual testing costs. Ideally, utilizing such data acquisition system would reduce the man power and survey time. Radio frequency transmission modules, however, have exhibited problems. Even when the units were operating, the time and manpower required to obtain the data exceeded that of the traditional cathodic protection survey. In situations where battery or component failure was encountered, many man-hours were spent mitigating the problems. Therefore, the cost savings associated with reducing annual system testing costs were not realized, and the originally estimated ROI of 13.27 is not considered to be valid. A new calculation without this cost savings yields an ROI of 11.41.

FNV06: Wire Rope Corrosion for Guyed Antenna Towers

Project Number	FNV06
Project Title: Wire Rope Corrosion for Guyed Antenna Towers   	
Fiscal Year	2006
Service	Army
Major Category	Equipment
Purpose	We propose to develop a corrosion control process that reliably measures and monitors guy wire corrosion over time and space. In particular, we will develop a reliable corrosion inspection tool that will ride remotely along each guy wire and measure the corrosive state along the full length of each and every guy wire.
Technology	We will develop the tools for inspecting each guy wire along its full length. We currently rely on telescopic visual inspection from the ground and the tower. Due to the length of the guy wires there is only a short section of each guy that is accessible for meaningful visual examinations, this being the lower and upper sections of guy wire. Such visual inspections are also incapable of measuring swelling or determining internal corrosion along most of the guy. We will determine which set of techniques work best for our larger diameter (~ 4 inches) guy wires, and then package these methods on a “vehicle” that can travel along each of our guy wires.
Application	After verifying the effectiveness of this wire rope inspection tool in the lab, we will use it in the field to measure the corrosive state of all 357 guy wires that hold up the antenna at Holt, NW Cape, Australia.
Benefits	The primary deliverable will be a guy wire inspection tool and a process for managing corrosion of the guy wires at all VLF/LF antenna sites. As a secondary deliverable, we will generate a timetable for guy wire replacement at our Holt antenna that will help manage guy wire replacement by minimizing cost and maximizing antenna availability.

Lessons Learned	Initially, we had hoped to cover the entire cost of buying and testing the guy inspection Tool with DOD-CPC funds, and then use matching NNWC funds to inspect as many guys as possible at the Holt (Australia) antenna. Unfortunately, the Tool is made of materials (rare earth magnets, copper, etc.) that have recently become very expensive, so the original goal was not achievable. In addition, the large magnets needed for a large-diameter Tool generate very large internal forces, making them difficult to handle safely for development and testing purposes.
Transition Status: Ongoing ROI: 55.6	The ROI Validation states that the project plan was implemented at a smaller diameter prototype than large diameter guy inspection tool needed for full intended fleet use. Implementation became part of second CPCP project for large diameter guy inspection Tool. Fleet implementation is still valid as planned. Since completion of project, guy corrosion has accelerated more rapidly than assumed in original project plan, making implementation of final large diameter guy inspection tool ever more critical. Project is being continued under F09NV09.

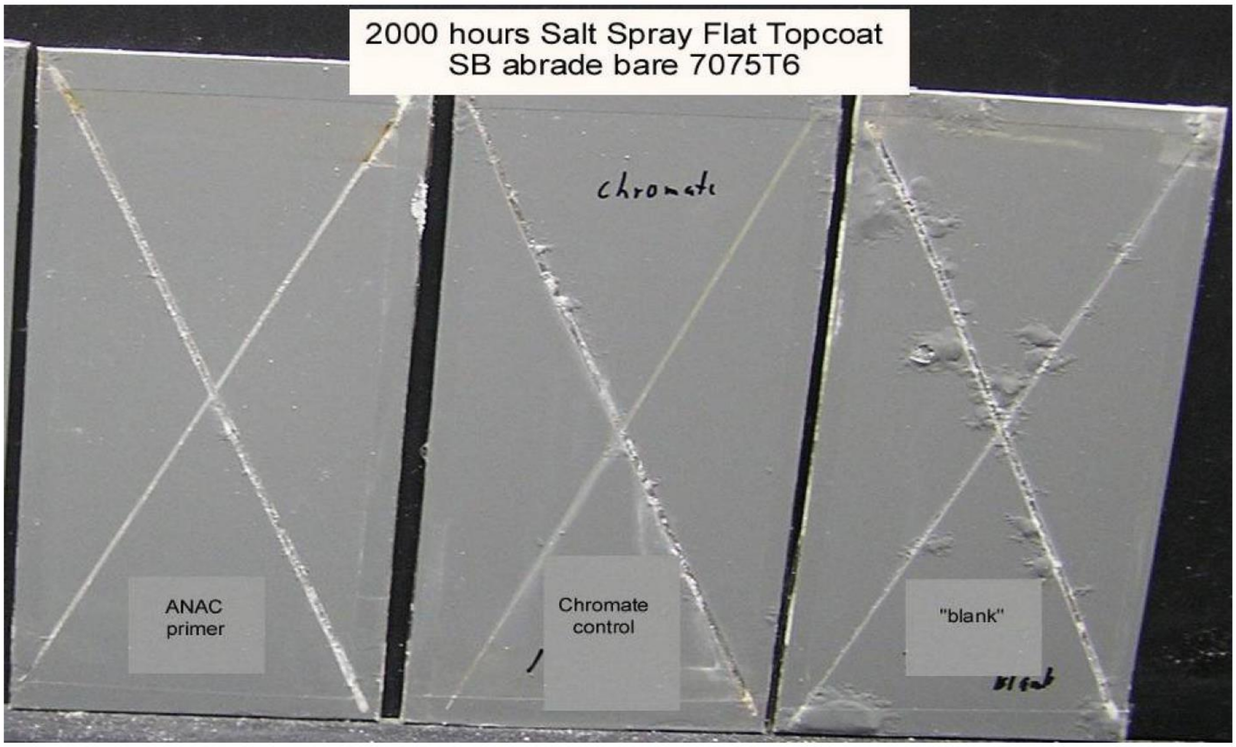
FNV07: Solar Powered Cathodic Protection System

Project Number	FNV07
Project Title: Solar Powered CPS 	
Fiscal Year	2006
Service	Army
Major Category	Equipment
Purpose	This project proposes to demonstrate a solar powered CP system using recently developed high efficiency (96-98%) controls that have flexibility to match the anode ground-bed (and its fluctuating conditions).
Technology	The CP system would be a straightforward impressed current CP system design and installation with the exception of the power supply. Instead of a conventional AC powered rectifier, a solar-power supply and control system would be specified. Design and installation will be accomplished by existing contracts.
Application	Installation of a Solar Powered CPS at Guantanamo bay. Underwater water utility and fuel pipelines traverse Guantanamo Bay, Cuba in service of the Naval Station Guantanamo Bay. Recent studies have indicated that the pipelines are not adequately protected on the eastern side of the bay by the cathodic protection (CP) on the western side of the bay. Installation of an additional conventional impressed current CP system on the eastern side of the bay would be relatively simple if AC power was readily available. However, demolition of obsolete housing units as a result of base realignment caused the deletion of the electrical distribution system in this vicinity of the base. AC power is therefore no longer readily available.
Benefits	The primary deliverable for this project will be a well- controlled solar powered cathodic protection system that will fully and adequately protect water and fuel distribution pipelines from corrosion and result in expected pipeline service lives of 20+ years with little risk of detrimental impacts to personnel safety and environmental damage associated with corrosion caused leaks.
Lessons Learned	Design agency engineers and technical exerts should carefully review the design drawings and specifications. Award for the MACC contract was delayed for three months because the difficulty the contractor encountered in obtaining bid bonds for the Guantanamo Bay area. Construction was delayed for nearly six months due to difficulties in shipping construction materials to Guantanamo Bay. Periodic monitoring of the system operation was difficult due to the remoteness of the site.
Transition Status: Implemented ROI: 3.0	The initial estimated ROI has been revised to reflect estimated power consumption savings, based on current operating status. The original power cost savings was based upon full output of the previously existing CP rectifier. The solar CP system is operating at a lower output. After the three plus years the remote monitoring unit (RMU) battery was found to be depleted. Findings

	were similar for other RMUs from the same manufacturer. The new system costs have been revised to include the cost of battery replacement every three years. The revised ROI is 3.02. A new type of RMU will likely be installed to eliminate this battery replacement requirement or decrease the frequency of battery replacements.

WAF01: Magnesium Rich Primer for Chrome Free Aircraft Coating Systems

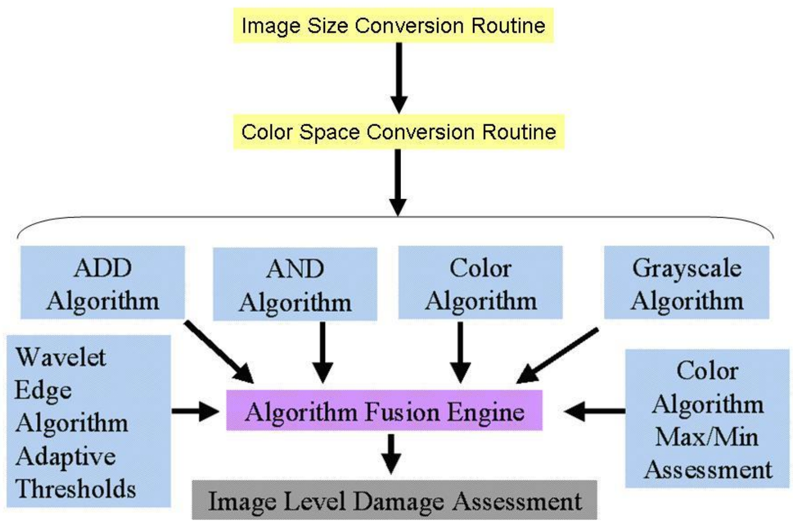
Project Number	WAF01
Project Title: Magnesium Rich Primer for Chrome Free Aircraft Coating Systems	



Fiscal Year	2006
Service	Air Force
Major Category	Coating
Purpose	A one-year OSD funded project is proposed for corrosion prevention and control that will: 1. Facilitate the refinement of Mg-rich primer prototype formulations to MIL-SPEC qualified commercial products, 2. Evaluate the performance of resultant Mg-rich primers with existing non-chrome surface treatments and topcoats as completely chrome-free coating systems, and 3. Obtain field-level performance evaluation of down-selected Mg-rich based chrome-free coating systems.
Technology	Because Mg is more active (i.e., anodic) in the galvanic series than aluminum and its alloying constituents, it will cathodically protect the substrate until the Mg particles present in the coating film are consumed. Prototype Mg-rich primer formulations that were initially developed and tested at NDSU displayed effective AA 2024-T3 corrosion protection out to 3,500 hours of B-117 salt spray.
Application	Mg-rich based chrome-free coating systems on non-critical Air Force and Navy aircraft components (e.g., hatches, access panels).
Benefits	The reduction and eventual elimination of chromate containing coatings for corrosion inhibition is of utmost importance to ensure the safety of DoD personnel and significantly reduce the financial burden related to hazardous materials handling and disposal.

Lessons Learned	Coatings must be evaluated and qualified on a system level basis rather than individually. Development of new coating formulations is an extremely difficult balance of obtaining desired properties that are often times mutually exclusive. There is a critical need for advanced accelerated corrosion testing methods that accurately predict long-term outdoor performance. When completely new classes of coatings are developed (such as Mg-rich), they may have unique testing idiosyncrasies that are not covered by current state of the art protocols. Hexavalent chromium is a better corrosion inhibitor than most give it credit and sets a very high standard for performance in development of a suitable replacement. In the search for Cr(VI) replacements, some performance trade-offs may need to be considered in order to be successful.
Transition Status: Ongoing ROI: 56.5	ROI Validation states that no organization is using the technology but the C-130 and B-52 program offices have approved field demonstration plans and will field test the technology on operation aircraft within the next year for consideration for implementation. Also, the F-16 is pursuing further testing of the Mg-rich technology for their weapon system. Implementation has not yet occurred but field test plans by two USAF weapon systems for a field test on an operation aircraft has been developed and approved. Aircraft will be coated within the 2011 year. Full implementation on an aircraft has not occurred but testing on aircraft continues.

WNS11: Corrosion Detection Algorithm for Ship's Topside Coatings

Project Number	WNS11
Project Title Corrosion Detection Algorithm for Ship's Topside Coatings 	
Fiscal Year	2006
Service	NAVY
Major Category	Sensor
Purpose	The intention of the Corrosion Detection Algorithm for Ship's Topside Coatings would be to utilize current and future image databases maintained by others as a source and archive for analyses performed by a Topside-CDA (TCDA).
Technology	Remote tank inspection devices have been successfully utilized to perform coating inspections in tank and voids spaces. This work has a tailored computer algorithm called the CDA to quantitatively determine from video imagery the corrosion damage in tanks from 0.0-20% damage. The primary objective of the work in this proposal is to deliver a modified CDA which could be used to conduct damage assessments and to analyze images taken with a variety of hand-held digital cameras that meet minimal requirements.
Application	For tank and void spaces, conventional inspection practices were comprised principally of trained human inspectors. More recently, video inspection technology has allowed for the creation and implementation of image based analysis of corrosion and coatings damage. The Naval Research Laboratory (NRL) has designed and demonstrated such a system called the Insert able Stalk Imaging System (ISIS) and the adjoining software analysis package called the CDA. The current document proposes to leverage this technology for topside spaces in order to allow condition-based maintenance.
Benefits	This would allow for the routine inspection, imaging and analysis of topside spaces.
Lessons Learned	It is recommended that the Navy institutionalize a single Fleet wide "Topside Maintenance Protocol" for assessing topside coatings and defining where preservation is required. The methods that have been developed and demonstrated under this program should be capable of being directly applied, today in support of this type of Protocol when it is developed.
Transition Status: Ongoing	ROI Validation states that NRL has performed several full scale demonstrations of this technology on active Navy vessels which has aided in the development of a detailed inspection

ROI: 16.2	protocol for performing AFTCAT Inspections. This effort was supported by a NAVSEA PCoE program in 2011 and 2012. This protocol will be incorporated into the Topside and Freeboard Assessment Guide requirements owned by the Carrier Planning Activity (PMS312) during the next revision. Updated ROIs include additional funding received to support project transition and a plan for Fleet transition and implementation. NRL is currently working with the Carrier Planning Activity to update their topside and freeboard inspection requirements to include AFTCAT as the primary method for collecting coating and corrosion data of exterior surfaces.

APPENDIX E
Corrosion Costing Models

E.1 INTRODUCTION

In order to meet the corrosion management objectives, tools or methodologies have been developed to calculate the cost of corrosion over part of an equipment's or asset's lifetime or over the entire life cycle. Methods that range from cost adding to life-cycle costing and constraint optimization are described in the following sections.

E.2 CORROSION COSTING METHOD USED IN THE U.S. DEPARTMENT OF DEFENSE

E.2.1 Background

- Past corrosion cost studies have had difficulty separating corrosion costs from non-corrosion costs. The DoD has developed a methodology where only direct and auditable costs are calculated and no attempt is made to determine the cost implications of corrosion-induced readiness issues or safety concerns. Accurate cost information was considered by DoD to be extremely useful by itself to facilitate decision making, and it was concluded that decision makers could not use readiness and safety information to judge the cost-benefit tradeoffs on a project-by-project basis; nor could they use this information to measure the scope of the corrosion problem or judge the overall effectiveness of a chosen corrosion mitigation strategy. Thus, when focusing on cost information only, the difficult task of turning non-cost measurements into costs was eliminated, and only the direct cost of corrosion is now being considered. As an added benefit, by just addressing the direct corrosion costs, these cost become transparent and auditable.
- The costing methodology and resulting determination of Return on Investment (ROI) is discussed in the following sections.

E.2.2 Corrosion Cost Determination

E.2.2.1 Assumptions

Going on the assumption that the direct corrosion costs are sufficient to demonstrate the benefits of corrosion control in a transparent fashion, the following specific cost elements of corrosion are identified:

- Labor hours (e.g., for inspection, repair, and treatment).
- Materials and parts usage.
- Premature replacement of the assets/equipment or its major components.
- Corrosion facilities.
- Training.
- Research, development, testing, and evaluation (RDT&E).

DoD included RDT&E costs, although these costs may occur before a weapon system or facility is placed into operation, because DoD is able to separate expenditures specifically for corrosion from other RDT&E spending.

E.2.2.2 Identifying Corrosion Cost Elements

Within DoD, maintenance required as a result of corrosion is rarely identified as such in reporting systems. Therefore, it is necessary to develop a list of typical corrosion-related maintenance activities, such as cleaning, sand blasting, and painting.

E.2.2.3 Characterization of Corrosion Costs

The corrosion costs are divided into categories that provide additional insight into the nature of these costs. The two most useful characterizations are corrective and preventive costs:

- Corrective costs are incurred when removing an existing nonconformity or defect. Corrective actions address actual problems.
- Preventive costs involve steps taken to remove the cause of potential non-conformities or defects. Preventive actions address future problems.

From a corrosion management standpoint, it is useful to determine the ratio between corrective costs and preventive costs. Over time, it is usually more expensive to fix a problem than it is to prevent a problem; however, it is also possible to overspend on preventive measures.

Figure E-1 shows that classifying the cost elements into categories helps decision makers to find the proper balance between preventive and corrective expenses to minimize the overall cost of corrosion.

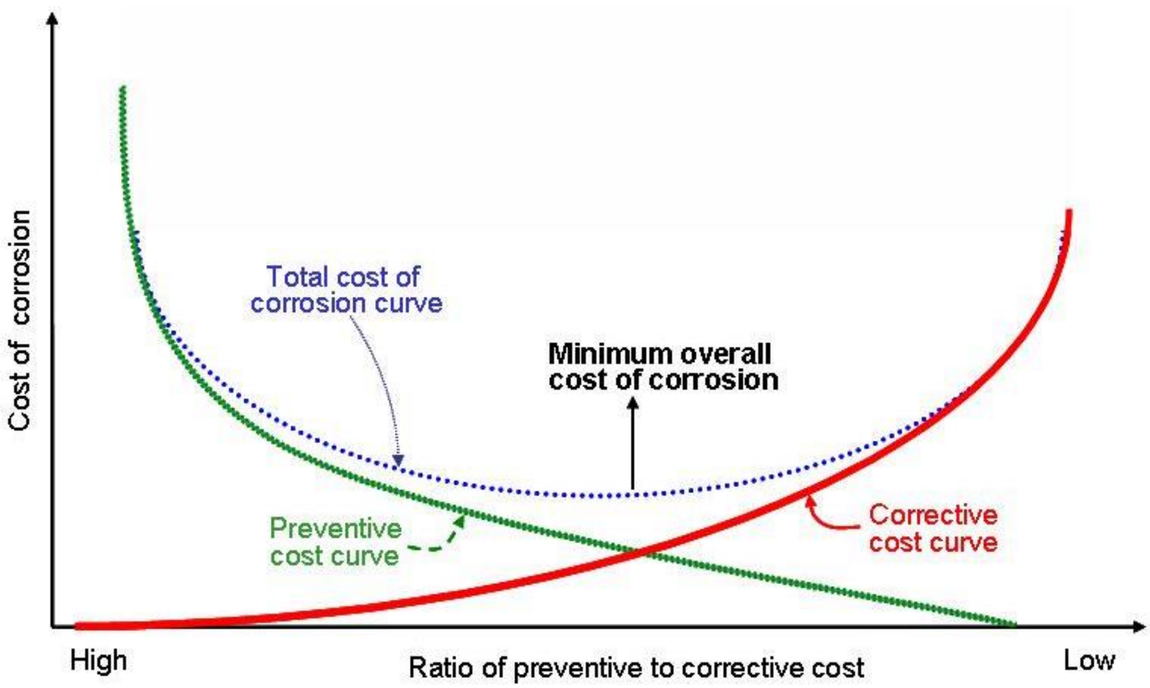


Figure E-1. Preventive and Corrective Corrosion Cost Curves

The task of classifying each cost element in the DoD as either preventive or corrective, would be an enormously challenging undertaking using standard methods, which would involve thousands of people trying to classify millions of activities at billions of dollars of cost. The DoD argues that the real value of characterizing costs into preventive and corrective categories is to determine the ratio between the nature of these costs, and that the classification does not require precision. To simplify, the preventive and corrective cost elements are characterized as shown in Table E-1.

Table E-1. Classification of Corrosion Cost Elements into Preventive or Corrective Natures

Cost Element	Classification
Labor hours	Corrective or preventive
Materials	Corrective or preventive
Premature replacement	Corrective
Corrosion facilities	Preventive
Training	Preventive
RDT&E	Preventive

The classification of the labor hours and the associated materials as corrective or preventive must be determined on a case-by-case or project-by-project basis, and order to ensure consistency, DoD classifies direct labor hours and the associated material costs based on the following rules:

- Hours and materials spent repairing and treating corrosion damage, including surface preparation and sandblasting, were classified as corrective costs.
- Hours and materials spent gaining access to equipment that has corrosion damage so that it can be treated are classified as corrective costs.
- Hours spent on maintenance requests and planning for the treatment of corrosion damage are classified as corrective costs.
- Hours and materials spent cleaning, inspecting, painting, and applying corrosion prevention compounds or other coatings are classified as preventive costs.
- Hours spent at a facility built for the purpose of corrosion mitigation (such as a wash facility) are classified as preventive costs.

E.2.2.4 Structure and Parts Costs

DoD characterizes corrosion costs as either structure or parts costs. All direct materials and direct labor costs are sorted into one of these two categories. Direct costs can be attributed to a specific system or end item.

Structure and parts are defined as follows:

- Structure is the body frame of the system or end item. It is not normally removable or detachable.

Parts are items that can be removed from the system or end item, and can be ordered separately through government or commercial supply channels.

By segregating direct corrosion costs into structure and parts categories, decision makers can give the design community more precise feedback about the source of corrosion problems.

DoD has a major concern about the effects and costs of aging of weapon systems. The age of a typical weapon system is calculated starting with the year of manufacture of the individual piece of equipment—essentially, the age measures the structural age of the weapon system. The age of a removable part is not tracked, with the exception of major, more expensive components like engines. Separating the corrosion costs related to the structure of the weapon system (which has an age measurement) from the corrosion costs related to removable parts (which do not have an age measurement) may give further insight into the relationship between structural costs and the effects of aging on weapon systems.

E.2.3 Corrosion Cost Measurement Methodology

In order to quantify a verifiable cost of corrosion, DoD uses a methodology called the '*top-down/bottom-up'* approach. In order to explain this methodology, an analogy of a household budget is used.

When analyzing a monthly household budget, it may be of interest to determine how much of this budget is spent on meat. Normally, it would not be possible to determine the amount spent on meat by just looking at the information at hand, i.e. check book logs and credit card records. Even if the expenses are logged diligently, it is highly unlikely that 'meat' expenditures could be recorded in their own separate category. This is also the reason that corrosion costs are not easily found – they simply are not identified in maintenance databases in their own category. In order to determine the amount spent on meat, "top-down/bottom-up" analyses are conducted as described in the following sections.

E.2.3.1. Top-Down Analysis

In this analogy, the top-down portion of the analysis begins with identifying the combined net household monthly income. For illustration purposes, this is $4000 per month. The next step is to separate this income amount into the major categories of spending that are visible in the check book logs, credit card records and other normal expense recording done in the household. A typical example might be similar to the "cost-tree" diagram shown in Figure E-2.

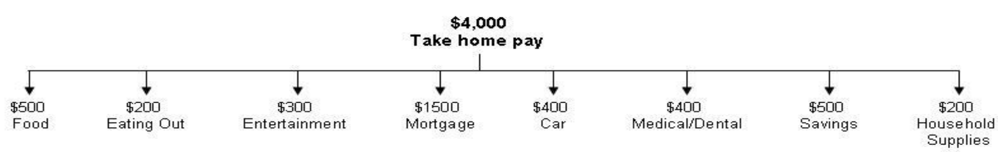


Figure E-2. Top-down Analysis using Household Budget Example

Note that the typical categories of spending in the second level of the cost tree account for the entire $4000 monthly household income. This will always be the case in the top-down portion of the analysis, where each level of the cost tree has to account for the entire spending amount of the level above it. Once the expenses are clearly visible, those categories that could not possibly contain any spending for meat can be eliminated. These categories do not receive any further attention, and the three remaining categories (food, eating out and entertainment) will be focused on. Although the exact amount spent on meat is still unknown, the diagram in Figure E-3 clearly shows that the amount spent on meat cannot exceed $1,000.

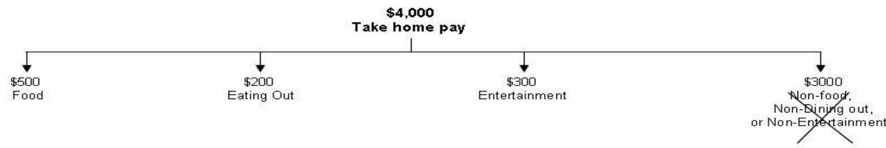


Figure E-3. Consolidation of Budget Categories Showing those that Potentially Contain Meat.

The spending within these three categories can be further examined in more detail as shown in Figure E-4.

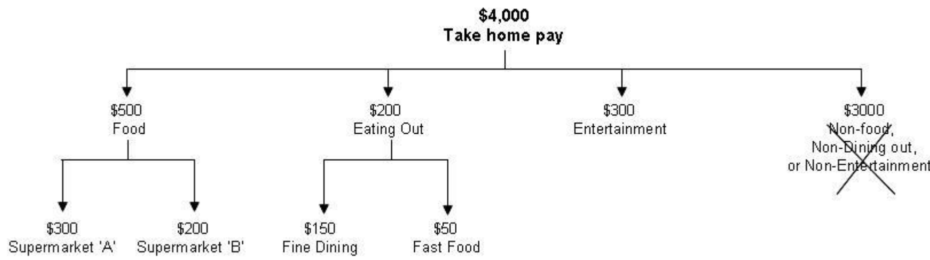


Figure E-4. Expansion of Potential Meat Spending in More Detail

Note how each level of the cost tree below accounts for all the spending in the level above. In the example, this is a far as the top-down analysis can go, although there is still no definitive answer to the question about meat spending. The corrosion cost calculation can now be completed with the 'bottom-up' portion of the analysis.

E.2.3.2. Bottom-Up Analysis

Figure E-4 shows that all spending on meat is contained in the five categories at the lowest level of the cost tree:

- Supermarket 'A'.
- Supermarket 'B'.
- Dining out.
- Fast food.
- Entertainment.

The bottom-up portion of the analysis requires obtaining as many detailed receipts for the spending in each of these five categories as possible. It requires grocery receipts for supermarket 'A' and 'B', restaurant receipts for dining out and fast food spending and receipts for all the entertainment expenses. The methodology does not require every receipt to be obtained but the more of the spending that can be accounted for with the receipts, the more accurate the spending estimates become.

E.2.3.3. Combined Top-Down/Bottom-Up Analysis

Once all the receipts that can be acquired for the month in question have been obtained, it is possible to determine the answer about how much is spent on meat. The next step is to examine every entry for every grocery receipt and extract the spending on meat. It is also possible at this step to categorize the meat spending by type. For example, categories of meat could include pork, chicken, beef, etc. Figure E-5 shows the analysis to this point.

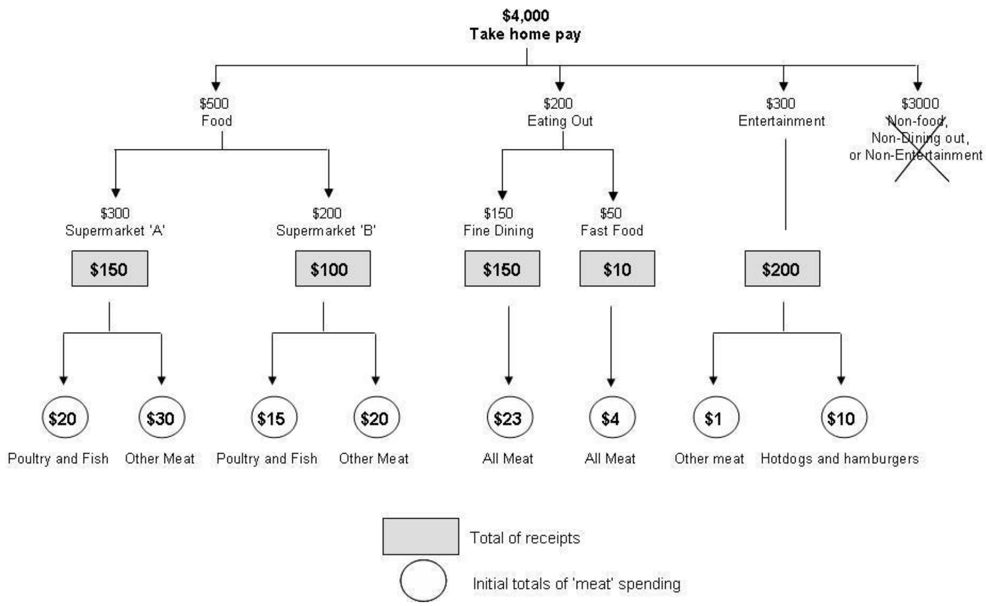


Figure E-5. Initial Calculation of Meat Spending

It is important to not only quantify the amount of spending on meat, but also to calculate the total amount of the receipts for each of the five categories of spending. By comparing the top-down amount for each category (the 'should have' amount) with the total of the receipts for each category (the 'did have' amount), it is possible to identify gaps in the bottom-up data collection, or to re-examine some of the top-down assumptions should the two totals not converge.

Once the calculations have between verified, the final step in the analysis is performed as illustrated in Figure E-6.

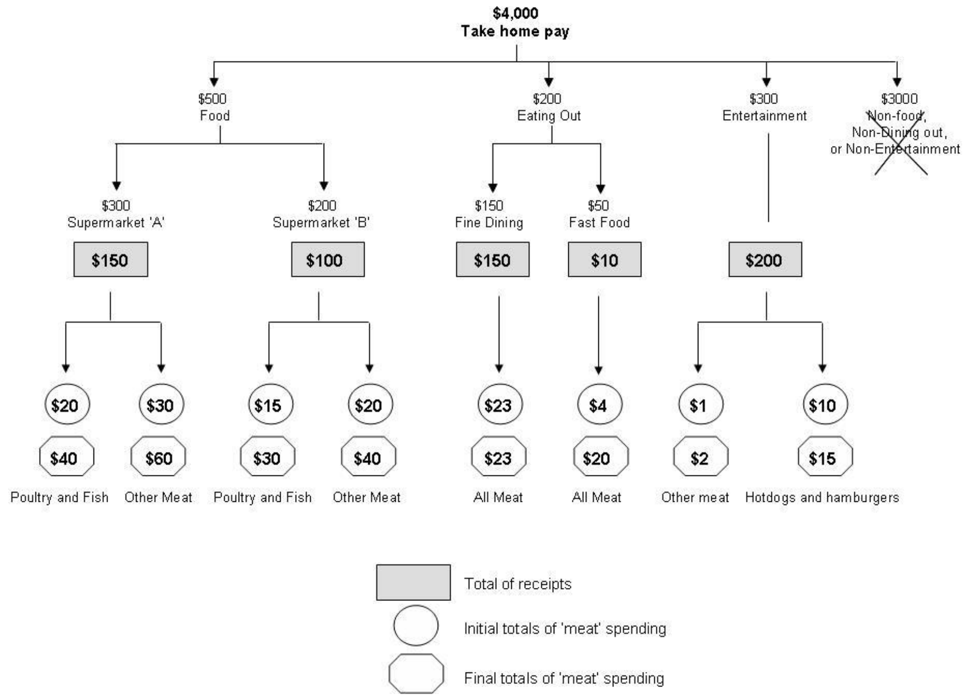


Figure E-6. Final Calculation of Meat Spending

Based on the ratio of obtained receipts ($150) and the top-down spending at Supermarket 'A' of $300, the ratio of 1:2 is determined. To compensate for the fact that the obtained receipts (bottom up) account for only 50% of the top-down spending amount, the 'poultry and fish' and "other meat' totals are multiplied by two.

The total meat expenditures for poultry and fish from Supermarket 'A' are therefore $40, and for "other meat", $60.

Finally, this multiplication is repeated for each spending category in Figure E-6 and determines the total monthly spending on meat to be $230.

E.2.3.4. Application of the Costing Model to Corrosion

The example above is a simplified explanation of determining the cost of corrosion, which can be readily applied to actual cost of corrosion determination, where corrosion takes the place of spending on meat, while the different types of maintenance expenditures are the categories of spending on food. Figure E-7 shows a cost tree from a completed DoD corrosion study.

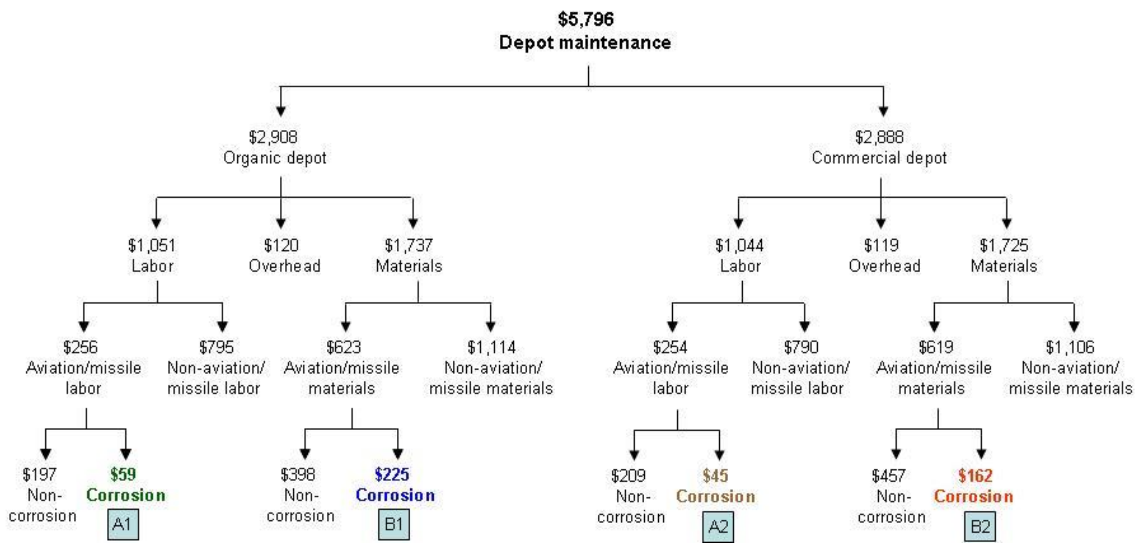


Figure E-7. Cost Tree from a DoD Corrosion Cost Study

The cost diagram in Figure E-7 outlines the spending on corrosion during depot maintenance of a military aircraft[46]. The logic and appearance of this diagram is similar to that of the "meat" example with each lower level of the cost tree summing to the level above it. The real challenge here is to conduct the bottom-up analysis – in essence, extracting the corrosion-related costs from the operations and maintenance activities.

Conducting the bottom-up analysis to extract corrosion costs involves millions of maintenance labor, parts and other material supply records. DoD has built a computerized search algorithm that is based on the corrosion activities, subject matter expert input, applicable coding of the maintenance records for corrosion, work center information and any other details contained in the records that would help identify corrosion-related work. Once all available bottom-up corrosion data has been acquired and placed into a standard format, the search algorithm is executed, and work records which involve corrosion-related work are flagged.

For certain types of corrosion-related activities, a percentage is applied based on discussions with the maintenance technicians to determine the final amount of corrosion-related work. The flagged records with their labor and materials totals are added to determine the initial totals. Like in the meat example, the final step is to apply the top-down to bottom-up ratio to account for data that was not obtained.

Both the top-down and bottom-up methods by themselves have their flaws. Determining the total cost of an enterprise can be a challenge by itself (in the meat example above, this was the total household income). Starting with an incorrect "all there is" estimate will almost guarantee an incorrect top-down outcome. The results of a well implemented top-down analysis can yield a good estimate of overall costs, but that estimate can lack the detail necessary to pinpoint major cost drivers within the enterprise. The bottom-up method can produce very accurate, auditable information so long as maintenance data collection systems accurately capture all relevant labor and materials costs, identify corrosion-related events, and are used with discipline. If any of these three boundary conditions are

[46] Materiel maintenance requiring major overhaul or a complete rebuilding of parts, assemblies, subassemblies, and end items, including the manufacture of parts, modifications, testing, and reclamation as required. - **Department of Defense Directive 4151.18, *Maintenance of Military Materiel*, 12 August 1992, Enclosure 2.**

missing, corrosion costs are likely to be determined incorrectly, and in most cases, they will be understated. By combining both the top-down and bottom-up methods and determining if the results are approaching each other, the overall method and assumptions can be validated. If the two results initially do not converge showing a large top-down to bottom-up gap, the approach must be corrected in order to prevent erroneous cost information, assumptions, or incomplete data from corrupting the final outcome.

Using the combined top-down/bottom-up cost estimation method yields some significant advantages over other corrosion cost estimation methods:

- In addition to understanding total corrosion cost, the corrosion cost by type of equipment or component (i.e. weapon system) and subcomponent can be determined.
- The costs by level of maintenance and by work center, i.e. who is doing the work, can be understood.
- The method allows DoD to characterize cost by their preventive and corrective natures, as well as by parts and structure. This characterization applies not only to corrosion-flagged records but each of the millions of maintenance records in the bottom-up data.
- The methodology allows subject matter experts to help build the recipe (extract the meat from the receipts), which leads to a high level of ownership of the data once it is finalized.
- Not only corrosion but total maintenance costs can be understood by type, by weapon system. This has shown to be surprisingly useful for maintenance managers at all levels, because there is no central system that compiles complete maintenance cost information by weapon system.

In order to accommodate the anticipated variety of decision makers and data users, DoD designed a corrosion cost data structure that maximizes analysis flexibility, as shown in Figure E-8 below.

Using this data structure, the data can be analyzed under the following work breakdown structure headings:

- Equipment type.
- Age of equipment type.
- Corrective versus preventive costs.
- Depot, field-level, or outside normal reporting costs.
- Structure versus parts cost.
- Material costs.
- Labor costs.

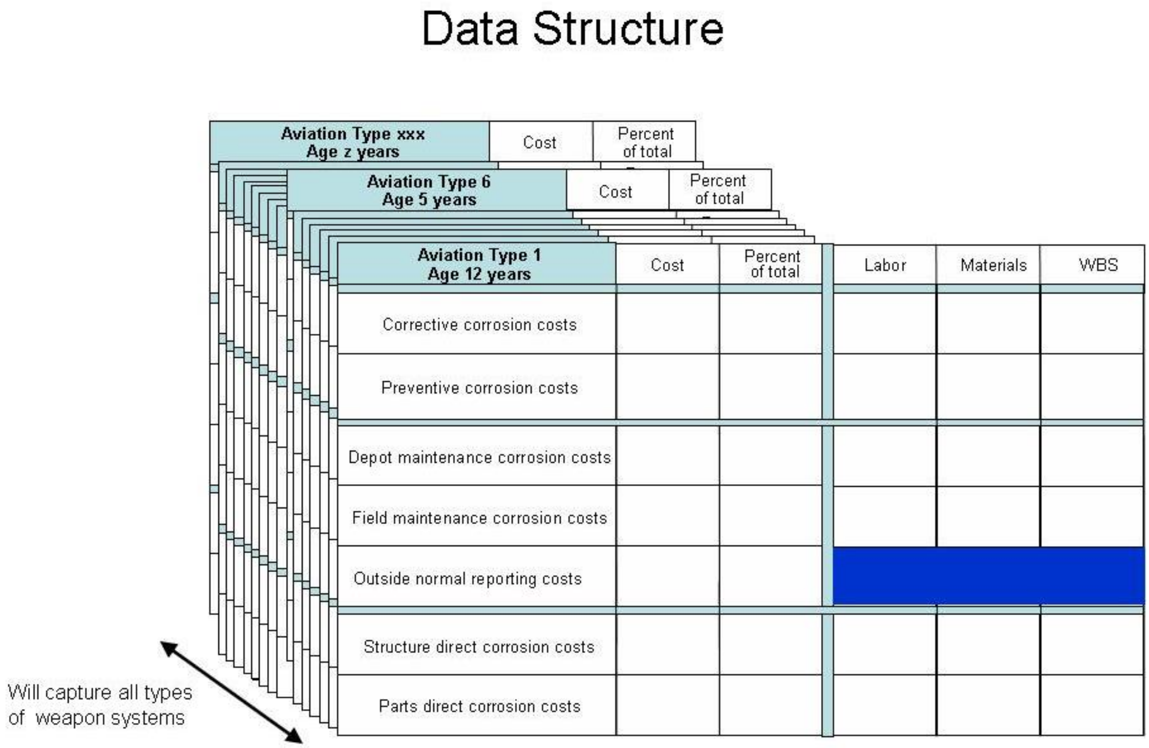


Figure E-8. Corrosion Cost Data Structure and Methods of Analysis - Work Breakdown Structure (WBS).47

Any of these WBS data elements can be grouped with another (with the exception of outside normal reporting costs) to create a new analysis category. For example, a data analyst can isolate corrective corrosion costs for field[48] level maintenance materials if desired.

E.3 LIFE-CYCLE COSTING

Life-Cycle Costing (LCC) is a commonly used cost evaluation tool that provides a long-term outlook in the expenditures of a facility over its lifetime by examining:

- Capital cost (CAPEX).
- Operating and maintenance cost (OPEX).
- Indirect cost caused by equipment failure.
- Material residual value.
- Lost use of asset (i.e., opportunity cost).
- Any other indirect cost, such as damage to people, environment and structures as a result of failure.

[47] Work breakdown structure coding determines the weapon subsystem on which work is being performed. We use the work breakdown structure convention established in *DoD Financial Management Regulation*, Volume 6, Chapter 14, Addendum 4, January 1998.

[48] Field level maintenance is more limited in scope than depot maintenance and is normally performed close to the owning units' area of operations.

The LLC approach makes it possible to compare alternatives by quantifying a long-term outlook and determining the return on investment (ROI).

E.3.1 Capital Expense

Capital Expense (CAPEX) is part of the direct cost incurred during the initial stage the life cycle which includes:

- Design.
  - Design and selection of corrosion prevention systems.
    - Corrosion protection, such as cathodic protection and coatings/paint.
    - Corrosion mitigation, such as the use of corrosion inhibitors and other chemicals.
    - Corrosion prevention by the use of corrosion resistant materials.
    - Corrosion allowance on non-corrosion resistant materials.
    - Corrosion monitoring systems.
  - Corrosion experts and engineers who carry out corrosion and materials selection related studies.
  - Laboratory corrosion tests or other technical assessments.
  - Techno-economic analysis of alternatives.
- Acquisition of materials of construction and corrosion prevention materials and devices.
- Construction costs.

E.3.2 Operational Expense

Operational Expense (OPEX) is part of the direct cost incurred during the operational stage of the life cycle and includes:

- Corrosion prevention and monitoring.
  - Corrosion inhibitors and other corrosion control chemicals.
  - Monitoring probes.
  - Electric power for dosage point and cathodic protection.
  - Replacement.
- Technical support.
  - Personnel for routine maintenance and corrosion control.
  - Cost of routine maintenance and corrosion control (e.g. painting, NDE, inline inspection for pipelines, cathodic protection).
  - Specific studies and activities to be carried out to address non-routine corrosion issues.
  - Emergencies as result of corrosion.
- Additional operating cost as a consequence of a corrosion-related incident.
- Insurance against corrosion-related risks.

In some industry sector demobilization, decommissioning, and mothballing, which are the final stage of the life cycle are considered to be part of OPEX.

E.3.3 Indirect Expense

In addition to the direct expense that can be determined by assessing CAPEX and OPEX, indirect expense over the life of a structure or facility must also be considered. The financial losses or penalty charges, which are associated with losing production, because of corrosion-related failures, and include the cost of lost revenue and costs associated with lost revenue. Other indirect costs associated with failures include societal cost, environmental cost, and damage to brand and reputation. One way to aggregate these costs and scale them by likelihood of occurrence is through risk assessment.

E.4 DETERMINISTIC APPROACH TO LIFE-CYCLE COSTING (LLC)

When optimizing both direct and indirect costs of corrosion in a deterministic approach, it is important to account for benefits and costs of all the options. Such benefit-cost analysis (BCA) determines the net present value of options. In addition, the BCA helps to determine the cost per unit of service, which is, in fact, the highest aggregation of costs and benefits.

If the service level defined within a certain constraint can characterize the benefits, life-cycle costing (LCC), which is essentially a cost effectiveness analysis, is equivalent to BCA. If the goal of a cost-effectiveness analysis is to obtain a service level that is equal to the optimal service level under BCA, then the LCC analysis will arrive at the same solution as BCA. LCC is therefore equivalent to a cost-effectiveness framework that seeks to minimize the cost of achieving a specified goal. A well-executed LCC is essentially the cost side of BCA; however, LCC does not seek to address environment and society, but rather minimizes the costs.

LCC analysis in corrosion management can be used to assess corrosion management alternatives. Since LCC analysis is a cost minimization methodology, it is a good method to compare the cost of different options for corrosion management. It determines the annualized equivalent value (from the present discounted value) of each option and compares these with the lowest cost option. Since in this analysis it is assumed that all options meet the same service requirement, the lowest cost option is therefore the most-cost effective option to achieve the service requirement. While LCC is an appropriate method to compare the costs of different options, it simplifies the benefit side by only considering the benefits of the specified service level.

For example, if the required service level is a four-lane bridge designed to last for 60 years, the benefit of the bridge will be very different for one serving 5,000 cars per day than for one serving 50,000 cars per day. An analysis of the former case would probably conclude that a two-lane bridge was sufficient, while an analysis of the latter case would conclude that a six-lane bridge was required.

Structures and facilities are built to serve a desired function. Since there is more than one way to achieve the requirement of the structure, LCC can be used to compare the cost of different options that satisfy the service requirement. It is important to emphasize the LCC approach as illustrated in the following paragraphs:

- Costing of project alternatives cannot be based on their first estimate costs. For example, an uncoated carbon steel pipeline (first option) costs less at construction then a coated carbon steel pipeline (second option); however, the latter option lasts longer. Therefore, for the correct comparison, the construction cost must be annualized over the entire lifetime of the pipeline. A comparison of the two options is therefore based on the annualized value of each.

- It is further incorrect to simply sum up all corrosion-related costs that occur during the lifetime of the structure. Continuing the above example, assume that both options have rehabilitation scheduled at two-thirds of their lifetime (year 13 for the unprotected pipeline and year 27 for the protected pipeline). For simplicity, assume that the rehabilitation costs are the same for both options. In the case of simply adding up all costs, the bare carbon steel pipe may look better since its initial cost was lower. However, when the different costs are expressed in an annualized form, rehabilitation of the coated pipe will result in lower costs.

E.4.1 Current Cost of Corrosion

The current cost of corrosion is defined as the sum of the corrosion-related cost of design and construction or manufacturing, the cost of corrosion-related maintenance, repair, and rehabilitation, and the cost of depreciation or replacement of structures that have become unusable as a result of corrosion. The current cost of corrosion is the difference between the approach where no consideration is given to corrosion and corrosion control and the current approach. It is calculated by LCC analysis and characterized by the annualized value.

Measurement of the current cost of corrosion is carried out in the following steps:

- Determine the cash flow of corrosion.
- Describe corrosion control practices (materials, actions, and schedule), determine the elements of corrosion cost, and assign cost to all materials and activities that are corrosion related.
- Calculate present discounted value (PDV) of cash flow.
- Calculate annualized value for the PDV.

These steps are discussed in more detail in the following sections.

E.4.2 Cash Flow

After the corrosion management practices are analyzed, the direct and indirect elements of the corrosion costs are identified. The corrosion cash flow of a structure includes all costs, direct and indirect, that are incurred due to corrosion throughout the entire life cycle of the structure.

E.4.3 Corrosion Control Practices

Determine Current Practice**.** The current practices to control corrosion vary greatly between the different industry and government sectors that are described in this report (see Sections 4 and 0). Even within a sector, there are different approaches to design, maintenance, and depreciation of similar facilities or structures. A reasonable approach to determine the total corrosion cost is to extrapolate from a typical corrosion cost to the entire sector.

Elements of Corrosion. As discussed previously, corrosion costs can be direct or indirect. Direct costs are defined by the following elements:

- Amount of additional or more expensive material used to prevent corrosion damage multiplied by the (additional) unit price of the material.
- Number of labor hours attributed to corrosion management activities multiplied by the hourly wage.
- Cost of the equipment required as a result of corrosion-related activities. In case of leasing the equipment, the number of hours leased multiplied by the hourly lease price.
- Loss of revenue due to lower supply of a good. For example, consider the case of a leaking liquids pipeline. When as a result of the leak the pipe needs to be shut off for repair, the revenue loss due to this interruption in service is accounted for as a cost of corrosion. If the market is such that other organizations in the industry at the same cost can satisfy the demand, then the revenue loss of one organization is the additional revenue gain of another, a transfer within the industry, therefore, not counted as corrosion cost.
- Cost of loss of reliability. Repeated interruption in the supply of a good or a service could lower the reliability of the service to such a level that consumers select an alternative and possibly a more expensive service. For example, if repeated interruption in the supply of natural gas forces consumers to rely on electricity for heating, then the cost of this revenue loss is accounted for as a cost of corrosion for the oil sector, but it is a gain for the electricity sector. If consumers choose other petroleum products as their new energy source for heating, then the cost would be transferred within the oil sector from natural gas to petroleum; therefore, it would not be accounted for as a cost of corrosion for the oil sector.
- Opportunity cost of lost production because an asset is no longer suitable for its purpose.

As previously defined, indirect costs are incurred by others (i.e., not the owner or operator). Examples of indirect costs are:

- The loss of trust in the reliability of product or service delivery by the company.
- increased costs for consumers of the product (lower product supply on the market result in higher cost to consumers).
- lost tax revenues.
- effect on local economy (loss of jobs).
- effect on the natural environment by pollution.
- effect on reputation.

Once a monetary value is assigned to these items, they are included into the cash flow of the corrosion management and treated the same way as all other costs.

E.4.4 Present Discounted Value of the Cash Flow

Structures are designed to serve their function for a required period of time, which is referred to as the design service life. More than one option can be utilized to satisfy service level for the required service time. These options, that already satisfy the service requirement, have different lengths of life, depending on, among other things, design and overall management. Once the cash flow for the whole lifetime is determined, the value of each option for the entire life cycle can be determined. One cash flow cycle (a complete life cycle) of a structure is as follows:

- Year zero.

  Direct cost is the total initial investment of constructing a new structure or facility. If there is an old structure, its removal cost is not included. User cost is associated with the construction of a new structure. If there is an old structure, user cost associated with its removal is not included.

- During service.

  Direct cost includes all costs associated with maintenance, repair, and rehabilitation. User cost can be generated by worsening conditions of the structure that reduces the level of service by temporary being out of service of the structure during any maintenance, repair, or rehabilitation.

- Last year.

  Direct cost includes all cost of structure removal. If the old structure is replaced with a new one, the cost of the new structure is not included. User cost is associated with the removal of the structure. After the removal of the old structure, a new life cycle begins.

All materials and activities that are corrosion related during the lifetime of the structure must be identified, quantified, and valuated. Direct costs of the corrosion management activities, or cost to the owner or operator, include material, labor, and equipment costs. When determining their costs, all related activities need to be accounted for. For example, if a corrosion-related maintenance activity on a bridge deck requires traffic maintenance, its cost needs to be included. The price of labor, material, and equipment are assumed to be the same for all design and all corrosion management alternatives.

The corrosion management schedule of the structure determines the direct cost cash flow. In the following sections the calculation of the present value the cash flow entries is presented.

The initial investment occurs in the "present"; therefore, no discounting is necessary.

Annual maintenance is assumed to be constant throughout the life cycle of the structure. This is the present discounted annual value, PDV{AM}, and is calculated back to the present as follows:

$$PDV\{AM\} = AM * [1 - (1 + i)^{-N}] / I,$$

where

AM = cost of annual maintenance ($ per year)
N = the length of the structures service life in years
i = interest rate

For the calculation of the present value of activities that grow annually at a constant rate (g), a modified interest rate needs to be calculated by the following formula:

$$i_0 = (i - g) / (1 + g) \text{ and } i > g,$$

where

i_0 = the modified interest rate
i = interest rate
g = constant annual growth rate

If the first payment (P_1) occurs in year one, the present value of a cash flow that grows annually at a constant rate over n years is calculated by the following formula:

$$PV\{P\} = [P_1 / (1 + g)] * [1 - (1 + i_0)^{-n}] / i_0$$

PV{P} is the present value of a cash flow series that starts at P_1 in year one and grows at a constant rate g for n years when interest rates are i, which are equivalent to the present value of an annuity of $[P_1/ (1 + g)]$ for n years when interest rates are i_0, where i_0 is given by the equation above.

The first payment for repair activities, however, usually does not occur in year one, but, rather, in year t; therefore the above formula calculates a value at year (t-1) that is equivalent of the cash flow series of repair through n years. This value needs to be calculated back to year zero of the life cycle to determine the present discounted value of the repair:

$$PDV\{P\} = PV\{P\} * (1 + i)^{-(t-1)}$$

The PV of one-time costs, such as one-time repairs (R), rehabilitation (RH), or removal_of an old structure (ROS) is calculated as follows:

$PDV\{R\} = R * (1 + i)^{-tR}$
$PDV\{R\} = RH * (1 + i)^{-tRH}$
$PDV\{ROS\} = ROS * (1 + i)^{-tROS}$, where

R = the cost of the repair
RH = the cost of the rehabilitation
ROS = the cost of removing the old structure
T = the year in which the cost is acquired

The present value (PV) of alternatives is calculated as the sum of the PV of its cash flow:

$$PV = I + PV\{AM, P, R, RH, ROS\}$$

E.4.5 Annualized Value of the Cash Flow

In calculating the lifetime cost of alternative corrosion management approaches, the irregular cash flow of the whole lifetime is transformed into an annuity (a constant annual value paid every year) for the same lifetime. The annualized value (AV) of the alternative approach is calculated from the PV by the use of the following formula:

$AV = PV * i / [1 - (1 + i)^{-N}]$, where

N = service life of the structure

The annuity of the initial investment (I) made in year zero is determined such that its present discounted value is equal to the present discounted value of its annuity:

$\Sigma_{n=1}^{N}$ [A{I} / $(1+r)^{N}$] = PDV{I} = PDV[A{I}], where

A{I} = annualized value of the capital investment
A{CM} = annualized value of all corrosion management costs
R = annual discount rate
N = service year, n = 1… N,
N = entire service life
PDV{I} = present discounted value of the initial investment
PDV[A{I}] = present discounted value of annuity of the initial investment

The actual corrosion management costs throughout the "n" years of the structure's service life will fluctuate. The fluctuating cash flow is replaced with an equivalent uniform cash flow of its annuity. The annuity of the corrosion management yearly cash flow is determined such that the present discounted value of the original cash flow is equal to the present discounted value of the annuity:

$\Sigma_{n=1}^{N}$ [A{CM} / $(1+r)^{N}$] = PDV[{A{CM}] = PDV{CM}, where

PDV{CM} = present discounted value of the original cash flow of corrosion management
PDV[{A{CM}] = present discounted value of the uniform cash flow or annuity

The annuity of the original cash flow is then:

A = A{I} + A{CM}

This annuity or "annualized cost" is a constant annual value paid every year whose present discounted value is equal to the present discounted value of the irregular cash flow for the whole lifetime of the structure.

In summary, the current cost of corrosion is the sum of the amount spent preventing corrosion at the design and construction phase, the amount spent on maintenance, repair, and rehabilitation to control and correct corrosion (cost of corrosion management), and the amount spent on removing and replacing structures that become unusable due to corrosion (depreciation or cost of replacement).

Measuring the current cost of corrosion requires the following steps:

- Determine the cash flow of corrosion.
    - ♦ Describe corrosion management practice (materials, actions, and schedule), determine the elements of corrosion cost, and assign cost to all materials and activities that are corrosion related.
- Calculate present discounted value (PDV) of cash flow.
- Calculate annualized value for the PDV.

E.4.6 Past Trends of Corrosion Management Costs and Benefits

The current cost of corrosion is merely one point in time that is the result of past trends and developments. If the history of corrosion management practices can be determined, current practices can be placed in perspective. By examining the past, the following questions may be answered:

- Have material options and their costs changed?
- Have corrosion management practices and their costs changed?
- What is the effect of different materials and corrosion management practices on the lifetime of a structure?
- Has the number of failures due to corrosion (incidents, injuries, fatalities, and property damage) changed?
- Has the cost of failures caused by corrosion changed (cost of environmental cleanup, litigation)?

E.4.7 Cost Saving through Improvement of Corrosion Management

Within a specific industry sector there is a range of current practices in dealing with corrosion, from old technology to state-of-the-art. The cost and results of each of these practices are different. While one of the practices achieves the most for its cost, i.e., is the most cost-effective, others could be improved to be more cost-effective. An important question is whether improvement of currently used practices could indeed lower the current cost of corrosion. As better ways are developed to protect against corrosion, the potential for saving will increase.

The goal of corrosion management is to achieve the desired level of service at the least cost, including user costs. Finding the CMP that has the greatest net benefits, including user costs, to society requires an understanding and careful analysis of all the direct and indirect costs involved. Cost benefits could be demonstrated by changing optimal corrosion management and more corrosion resistant materials.

Similar treatment could be performed for other sectors, but because of the complexity of corrosion control and corrosion management issues, there is usually insufficient information available to identify the design-maintenance option with the lowest annual cost, including user costs. However, the results of the surveys and associated interviews for the various industry segments have indicated a wide range of corrosion management practices, suggesting that.

E.5 RISK-BASED APPROACH TO LIFE-CYCLE COSTING

E.5.1 Bayesian Networks

With good design and construction, and diligent corrosion maintenance control, the deterministic LLC approach can be used to decrease the likelihood of corrosion. However, corrosion management can be complex, and hence corrosion-related decisions involve a considerable amount of uncertainty. By using a deterministic approach to calculate CAPEX and OPEX, lack of information or poor quality of information may lead to incorrect corrosion cost estimates.

Because of the considerable amount of uncertainties associated with corrosion decisions, deterministic approaches to conduct corrosion LLC may not be accurate. A probabilistic approach provides a means for quantifying these uncertainties and makes the outcomes of options that might otherwise not even be considered transparent. A probabilistic or risk-based approach to LLC enables the following risk questions to be answered:

- What can go wrong?
- How likely is it?
- How does it affect us?

Given by the mathematical expression:

Risk = $\{S_i, p_i, C_i\}$, where

S_i = a set of scenarios or threats (what can go wrong?)

P_i = the probability of occurrence (how likely is it?), and

C_i = the consequence (how does it affect us?)

In this definition of risk, for a given system or a design option, there may be a set of scenarios, each with its own pair of probability (frequency) and consequence, which then can be portrayed as a curve of probability vs. consequence, see Figure E-9.

There are two major schools of thought defining risk, the frequentists and the subjectivists (Bayesians). The two schools generally define probability differently. The frequentists' or statistical view of probability is that probability is an objective number that can be approached if a sufficiently large number of controlled observations are made. The relationship between frequency and probability is defined by the well-known Bernoulli's limit theorem:

$$p(|f(x) - p(x)| > \varepsilon) \rightarrow 0 \text{ as } N \rightarrow \infty ,$$

where the frequency, f(x), of a population of data approaches the probability, p(x), of that same data as the number of trials approaches infinity. Stated another way, frequency is a measurable quantity based on repeated observations, whereas probability represents the degree of belief or confidence in the measured frequency, also referred to as probability of frequency.

The subjectivists on the other hand, refer to probability as simply a degree of belief in an event. This view stems from the idea that not all phenomena can be repeated in a controlled manner to derive statistical distributions. This is especially true of complex systems. Therefore, probability can be assigned to the strength of an expert's belief about an event and then can later be corrected using repeated observations. This is at the heart of the Bayes theorem and it is often referred to as a belief network.

In reality, the frequentist and subjectivist perspectives can be combined—where possible statistical distributions are derived through the use of mechanistic models that are, in turn, based on experimental data with their associated uncertainties — but we also include direct probability distributions representing the degree of belief of an expert in a given observation. These two streams of probabilities are linked in a Bayesian network that can be updated through laboratory or field observations.

The Bayes theorem states that the posterior probability of an event (i.e., probability of the event after an observation is made) is related to the prior probability of the event (i.e., before the observation is made) through the probability of observing the event and the conditional probability of observation given the event occurred, as given by the following equation:

$$p(A) = p(B) \cdot \frac{p(A|B)}{p(B|A)}$$, where

A and B are two causal dependent events,

P(A) and P(B) their respective probabilities,

P(A|B) the conditional probability of A given B and P(B|A) the conditional probability of B given A.

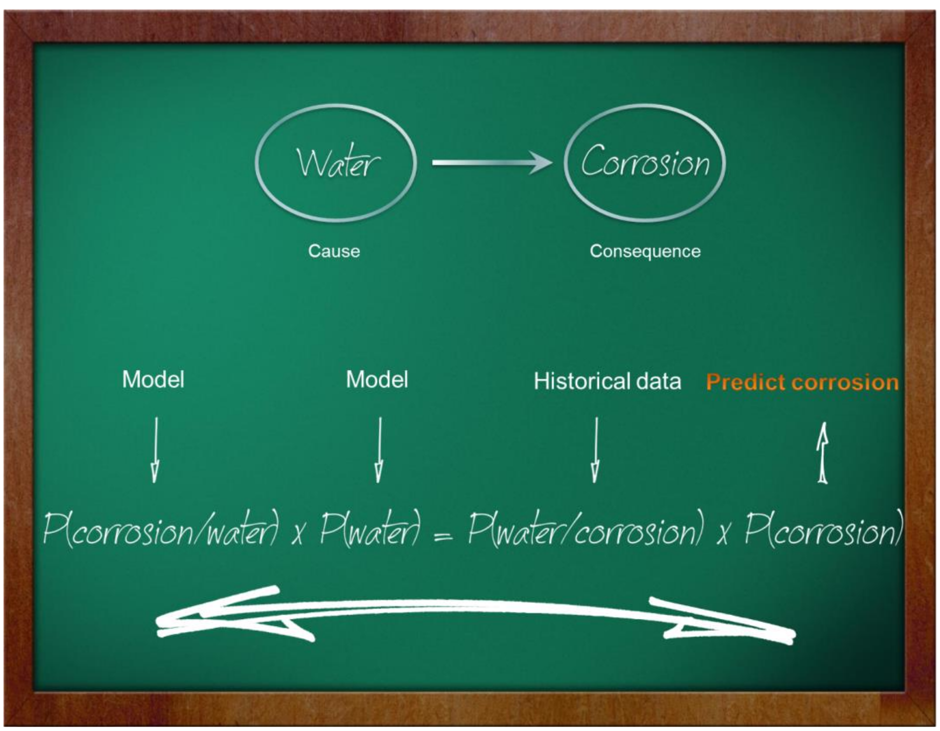


Figure E-9. Simplified Bayesian Network

This simple but powerful theorem allows us to compute the probability changes every time we obtain a new piece of evidence, data or observation. The use of Bayesian network in the context of risk assessments has several advantages:

- ***A Bayesian network does not require a fixed set of inputs and outputs***. Any information can be used by the model even if it is not an input. The more information is added to the network, the less uncertainty in the final probability.
- ***A Bayesian network can run forward*** (from cause to consequence) ***or backward*** (from consequence to cause). Any information can be used by the model to update the states of its consequences and the probability of its causes. For example, the model can run forward to calculate possible corrosion threats probability or backward to perform failure analysis.
- ***Bayesian networks can estimate future events by combining data and knowledge of the system***. Many future estimates use past inspection data only to forecast future performance. This practice could be compared to driving a car by only looking at the rear-view mirror. To forecast threats, one has to understand the underlying mechanisms of degradation, which are complex and almost never linear. Bayesian networking can consider complex processes, such as the corrosion LLC illustrated below.

E.5.2 Bayesian Network Approach to Corrosion Life-Cycle Costing (LLC)

While a Bayesian approach to LCC can quantify the uncertainties in calculating direct and indirect corrosion costs associated with OPEX and CAPEX, there always exists the additional risk of unanticipated corrosion threats. The significant variability in corrosion threats associated with the uncertainties in corrosion mechanisms as well as inspection data, leads to the conclusion that a probabilistic approach (implied in risk assessment), rather than a deterministic approach, is highly desirable. A detailed example of the Bayesian Network approach to determine the cost of corrosion due to the mechanism of corrosion under insulation (CUI) is given Appendix D; CUI is a problem in refineries, petrochemical, chemical plants, etc.

Because of the uncertainties, the probabilistic analysis method chosen must meet a number of challenges:

- The probabilistic analysis should include models that represent various corrosion failure mechanisms.
- The probabilistic method should be able to include different types of uncertainties.
- The probabilistic model must be constructed in a transparent manner so that all assumptions and the logical connections between causes and consequences can be seen.
- The probabilistic model should provide the ability to make decisions even with imperfect or missing data.
- The analysis should have the ability to correct the analyses by observations.

- The results of probabilistic calculations, assuming that they are properly validated, must be presented in a simple visual interface so that decisions can be made more easily and updated based on further observations or remedial actions.

A Bayesian network can meet these challenges. This is a graphical model that encodes probabilistic relationships among variables of interest. When used in conjunction with statistical techniques, the graphical model has several advantages for data analysis.

- The model encodes dependencies among all variables, and it readily handles situations where some data entries are missing. Bayesian analyses provide an effective way of reasoning under uncertainty, which is not always intuitive.
- A Bayesian network can be used to learn causal relationships, and hence can be used to gain understanding about a problem domain and to predict the consequences of intervention.
- The model has both causal and probabilistic semantics; it is an ideal representation for combining prior knowledge, which often comes in causal form, and data.
- The model has a principled approach for avoiding the over fitting of data.

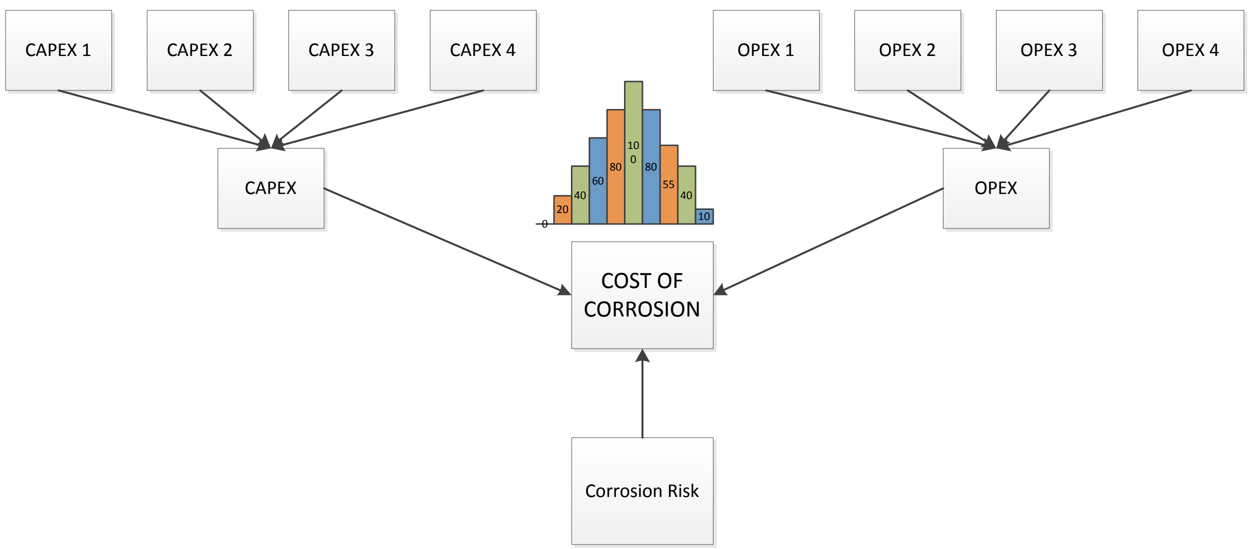


Figure E-10. Cost of Corrosion of an Asset Showing the Three Main Contributors

The probabilistic approach described above will allow determination of the life cost of equipment/assets with and without corrosion control, and identify cost savings that can be made over the life of equipment or an asset with proper and cost effective corrosion control.

E.6 CONSTRAINT OPTIMIZATION

A constraint optimization framework is used to determine the optimal corrosion management practice for a specific structure or facility.

Developing the constrained optimization framework takes three major steps:

1. Optimizing expenditures of the structure.
2. Maximizing service level subject to budget constraint.
3. Build constrained optimization model.

In the first step, in optimizing expenditures of the structure, the goal is to find the combination of inputs that produces the outcome at a minimum cost. There is a relationship between the inputs (CM and I) and the output (SL). This relationship is called the production function, which is like a cooking recipe that tells us how to get SL with the use of CM and I. There are many combinations of CM and I that would give us SL. But each of these combinations has a different price. We want to find the combination of CM and I that costs us the least, yet does the job. Maximizing the production function subject to a budget constraint means to determine the most optimal way of using the inputs (CM and I) to produce the requested output (SL). Therefore, in our optimization, we establish the most optimal expenditure (AEV{I} + AEV{CM}) for a given service level (SL_0). For example, one may "gold plate" the bridge and have no maintenance or may invest less in the capital, but apply extensive CM program. Both of these options could result in the same service life length, but not for the same life-cycle cost. The one with the lower LCC is preferred.

Thus the first step established the relationship between inputs and output (the production function) and optimized production by finding the cheapest combination of inputs to produce *any* levels of output.

In the second step, in maximizing service level subject to budget constraint, the goal is to produce the highest service level with the already optimized two inputs (I and CM) if only limited funds are available. Expressed in analytical terms the maximization of service level subject to budget constraint (all terms are in present value) is as follows:

$$\text{Max SL} = \text{Max SL}(I, CM) - \lambda\,(I\,P_I + CM\,P_{CM} - B) \quad | \; I, CM, \lambda$$

Determining the first order conditions:

$$\partial Y / \partial I = \partial SL / \partial I - \lambda\,P_I = 0$$
$$\partial Y / \partial CM = \partial SL / \partial CM - \lambda\,P_{CM} = 0$$
$$\partial Y / \partial \lambda = -(I\,P_I + CM\,P_{CM} - B) = 0$$

from which:

$$\partial SL / \partial I = \lambda\,P_I$$
$$\partial SL / \partial CM = \lambda\,P_{CM}$$

therefore:

$$(\partial SL / \partial I) / P_I = (\partial SL / \partial CM) / P_{CM}$$

Executing the calculations determine the optimal I and CM amounts subject to budget constraint.

In the third step, the constrained optimization model is established, with the objective to lowering expenditure. The constraint is an engineering definition to minimize financial input subject to engineering constraint. Or more precisely, minimize the cost of production subject to the service requirements.

$$\min_{AEV\{I\},\, AEV\{CM\}} \alpha = AEV\{I\} + AEV\{CM\} + \lambda \left[SL(AEV\{I\}, AEV\{CM\}) - SL_0 \right]$$

where SL_0 desired service requirement

or the same equation with Present Values

$$\min_{PV\{I\},\, PV\{CM\}} \alpha = PV\{I\} + PV\{CM\} + \lambda \left[SL(PV\{I\}, PV\{CM\}) - SL_0 \right]$$

In summary, the constrained optimization satisfied two constraints: minimizing expenditure and achieving service level, in the following three steps:

1. The first step, optimizing expenditures of the structure, provided that the service level SL(PV{I}, PV{CM}) is produced by the optimal/most effective combination of inputs. Or in other word, the minimum amount of input (PV{I}, PV{CM}) is used to produce SL.
2. The second step, maximizing service level subject to budget constraint, provided that the service level used here is achievable given the available budget.
3. Therefore, the third step achieves the required service level (within given budget) by minimizing expenditures (of the optimal combination of inputs).

Calculating the first order conditions (by taking the first derivative to minimize the function) from the equation with present values (FOC's):

$$\partial\alpha / \partial I = 1 + \lambda (\partial SL / \partial I) = 0$$
$$\partial\alpha / \partial CM = 1 + \lambda (\partial SL / \partial CM) = 0$$
$$\partial\alpha / \partial \lambda = SL(I, CM) - SL_0 = 0$$

The tradeoff between the initial investment and the corrosion management efforts during service can be written as follows:

$$\partial SL / \partial I = \partial SL / \partial CM$$ when I and CM are measured in dollars.

The above equilibrium means that the marginal expenditure of corrosion management is equal to the marginal expenditure of building/replacing the structure. (In order to make the statement about the marginal tradeoffs we need to know the time period a structure is expected to be in service.) This equation of marginal tradeoff stands for new and existing structures as well.

- For a new structure the marginal cost of corrosion management for the planned useful life is equal to the marginal cost of building (investing into capital) the structure.

- For an existing structure first the corrosion management options need to be optimized and the optimal practice determined. The marginal cost of this optimal corrosion management for the remaining planned useful life is equal to the marginal cost of replacing the structure T years from now in the future.

In the final step, externalities are included in the constraint optimization framework. Since determining social cost is not the focus of this report, it is assumed that indirect cost (externalities) can be measured and valued in monetary terms.

$$\min_{AEV\{I\},\, AEV\{CM\}} \alpha = AEV\{I\} + AEV\{CM\} + AEV\{SC\} + \lambda\,(SL[AEV\{I\}, AEV\{CM\}] - SL_0)$$

where: SC indirect cost of the CM practice analyzed

AEV{SC} annualized value of the indirect cost of CM

Externalities are additional expenses that need to be minimized along with initial investment and corrosion management expenses. Therefore, it is included in the objective function (the first part) of the constrained optimization equation.

APPENDIX F
Status of Education

F.1 EDUCATION AND TRAINING RELATED TO THE CORROSION MANAGEMENT SYSTEM PYRAMID

There are several opportunities for Education and Training (E&T) for corrosion management:

- Provide translation of enhanced practices and plans from Level 2 ("Plans") to Level 3 ("Enablers, Controls, and Measures").
- Provide E&T for corrosion management at Level 3 ("Enablers, Controls, and Measures"), e.g. risk management tools, performance assessment tools and methods, and life-cycle cost analysis.
- Provide Awareness Training in corrosion management to higher levels of policy and decision makers, Levels 5 and 6 ("Policy" and "Strategy").
- Provide E&T in corrosion management to corrosion professionals on how to talk/present to higher level policy and decision makers, Levels 5 and 6 ("Policy" and "Strategy").
- Broaden corrosion E&T beyond the industries perceived to be corrosion-intensive industries.
- Develop E&T products on corrosion management practices that can be incorporated into corporate business and management E&T programs.

In the following sections, the status of E&T at each the CMS pyramid levels shown in Figure 7-1, and relevant opportunities to expand into CMSs, are presented.

F.1.1 Policy and Strategy (Levels 6 and 5)

Currently, there are little or no E&T materials pertaining to corrosion management at these higher management levels. Policies often have broad statements related to Health, Safety and Environment (HSE), and Strategies are developed to meet the HSE policy and also for effective and profitable operations. However, in many cases (see survey results in Section 4) corrosion management policies do not exist.

At these management levels, relevant strategies could include:

> *The Organization provides policy statement (s) reflecting Management's commitment to achieving its purpose, objectives and goals with respect to corrosion management.*

Learning modules should be developed for CMSs at the policy level, and the resulting potentially sound practices should then be demonstrated by means of case studies. Such corrosion management modules should be considered for incorporation in business school and management development courses, or for inclusion in other management development programs.

F.1.2 Objectives and Enablers, Controls and Measures (Levels 4 and 3)

As with the Policy and Strategy levels, there are only limited E&T materials at these levels that pertain to corrosion management. In some industry sectors, e.g. oil and gas pipelines, there is increasing interest in and need for formal performance assessment of corrosion mitigation systems. Often this need is driven by regulatory requirements.

There is also a growing movement to consider corrosion management from a Risk Management perspective. Such risk perspective integrates well with other management systems, Asset Integrity Management, and Occupational Health Management. It also has the ability to inform an organization's management on the financial and reputational impact, including return on investment (ROI), reliability and availability, repair-replace-abandon and life extension. There are emerging Education materials and tools for corrosion risk analysis; however, there is a need further development and expansion.

At these levels, many of the strategies discussed in Section 3 are relevant, and they make up the core of an integrated CMS. Effective practices and implementation are critical and will depend upon communication to upper and to lower levels in an organization. In order to progress on CMS implementation, CMS learning modules and courses must be created to develop, execute and report on these items. Practical experiences can be demonstrated through case studies. To be effective, corrosion management E&T course materials must be incorporated in the general management development courses and training. Finally, there is a need for E&T in methodologies to measure success of a CMS at these critical levels.

F.1.3 Plans and Procedures/Practices (Level 2 and 1)

These two levels in the CMS pyramid form the foundation of a CMS. At these levels the corrosion and corrosion mitigation technology resides and is executed, and these levels, the majority of E&T materials addresses practices and procedures. Increased awareness and the need for more effective corrosion management give rise to remarkable growth of E&T to gain basic understanding of corrosion mechanisms, corrosion mitigation processes, monitoring and inspection, failure analysis, etc.

These levels have been the main focus of current E&T materials' development and delivery. The portfolio of E&T materials and the rate of growth on new products are vast and impressive. The needs are:

- To continue to expand the breadth of materials to more industries and a broader range of applications.
- To continue to enhance the delivery systems for E&T, e.g. on-line, remote access, simulated hands-on experience, corrosion management tools and apps.
- To train practitioners at these levels, clarifying their role in an overall CMS. A critical piece is for communication of corrosion and corrosion mitigation information to higher levels in terms that are expressed and understood at these levels.

F.2 REPRESENTATIVE EDUCATION AND TRAINING OFFERINGS

Corrosion fundamentals, corrosion processes and corrosion mitigation are a common theme for all sources and providers of corrosion management E&T, while E&T for CMS methods in the framework of an over management system are sparse. Filling holes and extending the coverage of the former to more industries and more applications is needed. Moreover, there is a great need is for E&T products for integration of corrosion management into the mid and upper levels of the CMS Pyramid.

The following section describes E&T offered by Technical Associations and commercial organizations.

F.2.1 Technical Association Education and Training Offerings

Understandably, the Technical Associations dealing with corrosion as their main focus, e.g. NACE International, have the most extensive E&T products relevant to corrosion control. Associations dealing with specific corrosion mitigation methods, such as the Society for Protective Coatings (SSPC), are next in corrosion relevant content in their E&T products. Broad standards developing organizations, such as ASTM International, can provide significant corrosion E&T products. Metals-centric materials associations, such ASM International, can have corrosion-specific E&T products and relevant products. Specific industry focused associations, e.g. ACI (American Concrete Institute) and AWWA (American Water Works Association), have limited corrosion E&T products.

As stated above, it is recommended that corrosion management course material be developed that addresses middle to upper management in a broad range of industries and government organizations.

F.2.2 Education and Training Courses

These courses are offered in a variety of formats: 3 to 5 day courses, on-line courses, webinars, etc. Often the courses offer Continuing Education Units for professional development, and they can be partial requirements for certification programs. Several entities offer On-site training.

F.2.3 Standards and Recommended Practices

Standards and Recommended Practices for materials specifications, materials production, performance and testing, inspection and monitoring are an important component of a CMS. Several regulations are incorporating specific standards as part of the standard, e.g. specifying that a certified corrosion specialist is required.

F.2.4 Certifications

E&T courses and practical experience are used as requirements for professional development and certification in relevant areas for the CMS. In a number of applications and industries, certified personnel are required

F.3 UNIVERSITY BASED EDUCATION AND TRAINING

Corrosion is a multi-disciplinary process that derives contributions from materials science, chemistry, and electrochemistry. All deal with the corroding material, the corrosive environment and the electrochemical reactions at the corroding surface. The largest segment of University faculty teaching Corrosion resides in Materials Science and Engineering followed in numbers by Chemical Engineering, Mechanical Engineering, Chemistry, and others. There are several universities that have groups of affiliated faculty for corrosion in Centers and informal groups. In many cases, corrosion is the interest of a single professor at the university.

F.3.1 Graduate Degrees

Typically, the graduate student research is conferred in the faculty advisor's department. The graduate student E&T this is primarily focused on advanced science and technology of corrosion processes and mitigation, rather than corrosion management. This pertains to the foundational levels (1 and 2) of the CMS pyramid, and there is little or none related to the mid and upper levels of the pyramid (Levels 3 to 6).

F.3.2 Undergraduate Degrees

In the U.S., only The University of Akron confers a B.S. degree in Corrosion Engineering. In the Capstone courses, aspects of corrosion management are covered; however, this pertains to the foundational levels of the CMS pyramid. Corrosion E&T at most universities is from a course or two and may include an undergraduate project in corrosion. There is little or no corrosion E&T related to the mid and upper levels of CMS pyramid.

F.3.3 Associate Degrees and Certification

There are a few colleges and universities that offer associate degrees in Corrosion. These are typically 2-year programs. Some include a corrosion-related certification along with the associate degree or as a stand-alone offering. As above, the corrosion pertains to the foundational levels of the CMS pyramid and does not address the mid and upper levels of the pyramid.

F.3.4 Student Cooperative and Internship Experience in Industry/Government

Undergraduate students can receive corrosion E&T through formal CoOp or internships working with on company or government corrosion project. This provides valuable hands-on experience.

F.3.5 Short Courses

Several universities offer corrosion E&T via short courses on the fundamentals of corrosion, corrosion processes, corrosion mitigation methods and corrosion testing. The corrosion E&T pertains to the foundational levels of the CMS pyramid and does not address the mid and upper levels of the pyramid.