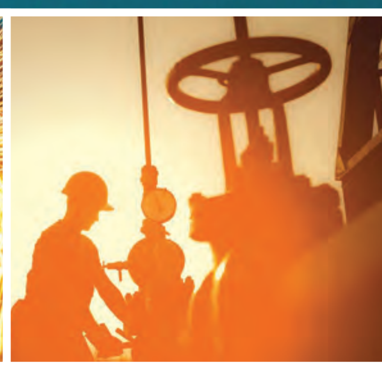
THE LABOR MANAGEMENT COOPERATION INITIATIVE (LMCI)
OF THE INTERNATIONAL UNION OF PAINTERS AND ALLIED TRADES (IUPAT)
AND NACE INTERNATIONAL NORTHERN AREA PRESENT
THE ASSOCIATION FOR MATERIALS PROTECTION AND PERFORMANCE'S

2021 IMPACT CANADA



INTERNATIONAL MEASURES OF PREVENTION, APPLICATION, AND ECONOMICS OF CORROSION TECHNOLOGIES STUDY FOR CANADA

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IMPACT CANADA

INTERNATIONAL MEASURES OF PREVENTION, APPLICATION, AND ECONOMICS OF CORROSION TECHNOLOGIES STUDY

Report prepared by AMPP (Association for Materials Protection and Performance), Houston, Texas

ACKNOWLEDGMENTS

The Labor Management Cooperation Initiative (LMCI) of The International Union of Painters and Allied Trades (IUPAT), NACE International Northern Area, and the Association for Materials Protection and Performance (AMPP) would like to acknowledge the following organizations for their outstanding contribution to the 2021 IMPACT Canada study: NACE International Calgary, NACE International Edmonton, Stantec, and the International Pressure Equipment Integrity Association (IPEIA). The study sponsors are also indebted to the Technical Advisory Panel members who supported the study, including Monica Hernandez, Pierre Crevolin, Nafis Ebrahimi, Rob Phillips, Jack White, A. I. (Sandy) Williamson, and Dennis Zadery.

THE ASSOCIATION FOR MATERIALS PROTECTION AND PERFORMANCE (AMPP) INTRODUCES THE 2021 IMPACT CANADA STUDY

The IUPAT/LMCI and NACE International Northern Area Encourage Industry to Foster Successful Corrosion Management

The Labor Management Cooperation Initiative (LMCI) of the The International Union of Painters and Allied Trades (IUPAT) is pleased to join the NACE International Northern Area and the Association for Materials Protection and Performance (AMPP) to sponsor the 2021 IMPACT Canada Study. This initiative will help industry understand the financial and societal impacts of corrosion on various industry sectors across Canada, and identify opportunities for the public and private sectors to improve corrosion management across the lifecycle of their assets. The cost of corrosion on Canada's bridges, buildings, pipelines,and all major infrastructure is enormous. These costs may seem invisible, but governments, private industry, and all Canadians are all paying the price of industrial deterioration.

Policymakers need evidence to develop policies and programs that help solve costly problems like corrosion. That is why we are supporting this IMPACT Canada research, so we can accurately depict the importance of corrosion management practices to leaders of Canada's public and private infrastructure and work collaboratively on prevention measures like training and quality control standards.

Our collaboration on IMPACT Canada follows another key milestone for industrial coating in Canada. In December 2019, the National Research Council (NRC) published updates to 27 specification sections of the National Masters Specification (NMS)—the primary resource for writing project specifications for construction work by the Government of Canada. Like this industrial coating milestone, we hope that AMPP'S IMPACT Canada Study will be a catalyst for change.

Jack White, Assistant to the General President of the IUPAT / LMCI, Vancouver, British Columbia, Canada

NACE INTERNATIONAL NORTHERN AREA IS HONOURED to work with Labor Management Cooperation Initiative (LMCI) of the International Union of Painters and Allied Trades (IUPAT) and the Association for Materials Protection and Performance (AMPP) to introduce the inaugural IMPACT Study for Canada in 2021. Since 2016 NACE International's global IMPACT study has provided data and analysis used to apprise government officials, regulators, industry, and the general public of leading-edge corrosion management practices and how they translate into reduced corrosion costs. The data has been instrumental in the development of global public policy, standards, and corrosion management planning.

After producing valuable results in the U.S., Europe, Asia, and the Middle East, AMPP has turned to Canada to analyze the financial and societal effects of corrosion on four industry sectors. Our IMPACT Canada report identifies ways in which key industry sectors excel at integrating corrosion management and sustainability processes into preventing and mitigating corrosion across the lifecycle of their assets.

Canada is a global leader in corrosion expertise, and its government and industry experts are highly equipped to seize upon myriad opportunities to improve our infrastructure and save on costs while doing so. We trust that this IMPACT Canada report will provide municipalities and businesses a way forward by pinpointing their strengths and suggesting avenues for improvement.

Dennis Zadery, NACE International Northern Area Treasurer

THE ASSOCIATION FOR MATERIALS PROTECTION AND PERFORMANCE (AMPP) is delighted to publish our 2021 IMPACT Canada study, with the cooperation of the IUPAT / LMCI and NACE International Northern Area. There is no better time than the present for businesses in Canada to strengthen their corrosion management systems and best practices. We invite you to review the results of IMPACT Canada, which explore how business leaders in Canada's Energy, Manufacturing, Mining, and Transportation sectors evaluated their companies' ability to integrate corrosion control and sustainability strategies into their organizational management systems, and where corrosion prevention and sustainability goals fall within their respective management systems.

AMPP was formed in January 2021 after the merger of Houston-based NACE International: The Corrosion Society and Pittsburgh-based SSPC: The Society for Protective Coatings. With more than 40,000 members in 130 countries, AMPP provides services to members in the areas of certification, accreditation, membership, advocacy and public affairs, standards, technical and research activities, conferences, events, education, training, publications, and pre-professional programming.

As you scrutinize the benchmarks explored here, remember that AMPP exists to help businesses create a proactive approach to corrosion control through professional development and corrosion management programs. Through a combined history of 145 years of corrosion control and protective coatings expertise and service, AMPP has contributed immeasurably to the industry training, new standards development, and forums for exchanging best practices in corrosion control and management. We look forward to partnering with you.

Sincerely,

Bob Chalker, Chief Executive Officer of AMPP
Helena Seelinger, AMPP Executive Director and Chief Regulatory and Public Relations Officer
Elaine Bowman, Past President of NACE International
Monica Hernandez, Country Manager for the IMPACT Canada Study and CEO of Infinity Growth Corporation, Vancouver

EXECUTIVE SUMMARY

The 2021 IMPACT Canada Study provides a means for government and industry to coordinate on best practices for corrosion management and planning in diverse industry and municipal sectors.

For several decades, business leaders and asset-owner organizations have considered the practice of corrosion prevention and control as the sole responsibility of materials and corrosion engineering experts, practitioners, and maintainers within their organizations. However, the risks associated with *aging* infrastructure are prevalent and costly, so now it is incumbent upon corporations to assess a broader array of financial risks by placing value on potential corrosion-related consequences and failures. Business decisions should be optimized so that those who develop budgets consider financial gains that inevitably result from investing in corrosion control.

The Cost of Corrosion in Canada

A 2009 study by S.A. Shipilov estimated that Canada's annual, direct cost of corrosion was approximately $41 billion U.S. dollars in 2005. When adjusted for inflation at 26.65 percent between 2005 and 2019, Canada's direct cost of corrosion is estimated to be $51.9 billion, amounting to 2.98 percent of Canada's 2019 gross domestic product (GDP) of $1,736.43 billion USD.

The Purpose and Value of a Corrosion Management System

A Corrosion Management System 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. **To lower the cost of corrosion and increase safety, corporations in Canada must adopt robust corrosion management systems. This process will require them to fundamentally change their corporate cultures to the extent that asset integrity becomes a core value as critical as safety management.** Such a significant cultural change must flow from the top to the bottom levels of each business organization. Asset owners in Canada should also recognize that a strong corrosion management system guarantees a greater return on investment.

Key IMPACT Canada Study Findings

The AMPP study team examined nine management system domains to determine how Canada's Energy, Manufacturing, Mining, and Transportation sectors implemented corrosion management practices across the asset lifecycle, during the phases of Design, Manufacturing and Construction, Operations and Maintenance, and Abandonment. The team also explored benchmarks on Sustainability.

The Energy, Manufacturing, Mining, and Transportation participants excelled at integrating certain corrosion management processes, while showing the need to improve upon the policies, resources, organization, accountability, and communication components that can impact asset preservation and return on investment. **Businesses in Canada that simply excel at managing corrosion at the design or manufacturing stages have significant room to improve compared to global participants from the 2016 NACE IMPACT Study.**

CANADA'S ENERGY SECTOR (OIL AND GAS, PIPELINE, AND ENERGY UTILITY INDUSTRIES) – Within the *Continuous Improvement* domain, energy companies signal, by a large margin, that formal organizational management of change processes do exist. In the *CMP Integration* area, numerous energy businesses attest to the fact that their corrosion management processes include risk management. In the domain of *Resources*, however, Canada's energy sector is challenged across the entire lifecycle of asset preservation. At the *Policy* level, corrosion management is not emphasized across the lifecycle, but it is seriously considered during the asset design strategy phase and the operations and maintenance stages of asset preservation. **This result stems from the fact that leadership does not view corrosion management as an enterprise-wide pursuit.**

CANADA'S MANUFACTURING SECTOR (AUTOMOTIVE, STEEL, AND PULP AND PAPER INDUSTRIES) – This sector exhibited three areas of strength related to the commitment to corrosion management: *Accountability*, *Continuous Improvement*, and *Stakeholder Integration*. But in the domain of *Policy*, Canadian manufacturers must improve by developing a corrosion management strategy across the entire lifecycle of asset preservation, including at the Design, Manufacturing and Construction, Operations and Maintenance, and Abandonment phases. **Manufacturers would benefit from better communication of their corrosion management processes and better alignment of their corrosion management processes and tools with their health, safety, and risk management disciplines.**

CANADA'S MINING SECTOR – In the realm of *CMP Integration*, Mining sector participants included risk management as one of their corrosion management processes, a significant strength. Participants also reported that corrosion control practices are designed into their systems and solutions, another strength. Whereas the domain of *Organization* posed a significant challenge across the entire lifecycle of asset preservation among Mining industry participants, the study team found that corrosion professionals did interact with colleagues in the design organization, within operations and maintenance groups, and among asset abandonment experts. Two other challenge areas for Mining sector participants fell within the domains of *Accountability* and *Resources* across the entire lifecycle of asset preservation.

CANADA'S TRANSPORTATION SECTOR – Throughout the lifecycle of asset preservation, researchers noted that within the domain of *CMP Integration*, survey participants feel that their corrosion management processes are well-communicated. Participants also included risk management as one of their corrosion management processes, a notable strength. As regards *Performance Measures*, participants excelled in that their corrosion management systems resulted in the lowest corrosion cost over the intended life of the asset. These companies excelled at monitoring and reporting corrosion management performance.

SUSTAINABILITY – *Material Sustainability* refers to the way materials are sourced, processed, and manufactured into products, and then maintained through the product lifecycle and redirected at their end of life. Canada's business culture reflects a commitment to Sustainable business practices at the design and manufacturing and construction stages of the asset lifecycle. However, compared to countries who participated in the 2016 NACE IMPACT Study, Canada falls behind in its ability to integrate corrosion management planning across all four stages of an asset's lifecycle. Close to 70 percent of study participants considered *Material Sustainability* during the operations and maintenance phase of asset preservation, a noteworthy strength. More than 60 percent of those surveyed reported that they promoted *Sustainability* during the design phase of an asset's lifecycle. **However, fewer than 48 percent of Canadian companies cite *Sustainability* as a corrosion management priority.** Canadian asset owners suggested that their corrosion management processes would greatly benefit from more robust *Sustainability* policies and strategies at all organizational levels and throughout an asset's lifecycle.

How Industry and Government Can Embrace Enterprise-Wide Corrosion Management

Recognizing that Canada's government, industry, and academic realms have strong corrosion prevention regulations, standards, and training in place, the IMPACT Canada report reviews the merits of Canada's pipeline regulations, the strength of current standards and where they can be improved, and the rich array of education and training programs supported by academia, government, and industry.

To improve upon its current strengths in these areas, all asset-owner companies must shift their corporate cultures toward successful corrosion management from top to bottom, establishing it as a norm analogous to today's safety management culture. Such a shift necessitates a cultural change that must flow from top to bottom. **To bring about change, businesses must translate their corrosion practices into the language of their broader organizations.** The report also explores useful management and financial tools such as IMPACT PLUS, which can help companies build a corrosion management system and integrate it within their existing systems.

ASSESSING THE COST OF CORROSION IN CANADA AMID THE GLOBAL COST OF CORROSION

The government, industry, and universities in Canada collaborate closely to prevent and control corrosion on the nation's rich array of publicly and privately managed assets and infrastructure, setting an example for other North American economies. In certain sectors the Canadian government has created checks and balances for corrosion management, while safeguarding the environment and industry through policies, legislation, regulations, and standards. Some Canadian ministries benefit from strong corrosion management practices, including the Ministry of Environment and Climate Change, the Ministry of Transport, and the Ministry of Defence. Provincial ministries of infrastructure are also key players in implementing certain corrosion management practices.

In spite of these accomplishments, the 2021 IMPACT Canada Study results revealed that four Canadian industry sectors fell behind their global counterparts from the 2016 NACE IMPACT Study in their ability to embrace key corrosion management practices at the highest and lowest levels of their organizations. Specific areas in which Canada's industry participants reported significant operational shortcomings are explored in this report.

A 2009 study by S.A. Shipilov estimated that Canada's annual, direct cost of corrosion was approximately $41 billion U.S. dollars (USD) in 2005.[i] When this figure is adjusted for inflation at 26.65 percent between 2005 and 2019, Canada's direct cost of corrosion is estimated to be $51.9 billion. This figure amounts to 2.98 percent of Canada's 2019 gross domestic product (GDP) of $1,736.43 billion USD.[ii]

> CANADA'S PROJECTED 2019 COST OF CORROSION IS ESTIMATED AT $51.9 BILLION, AMOUNTING TO 2.98 PERCENT OF A PROJECTED GDP OF $1,736.43 BILLION USD.

TABLE 1. *Global Cost of Corrosion divided into economic regions, based on three economic sectors (billion USD 2013). Canada's projected 2019 cost of corrosion is estimated at $51.9 billion, amounting to 2.98 percent of a projected GDP of $1,736.43 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%**

The seminal 2016 NACE IMPACT Study puts the United States' total cost of corrosion at $415.3 billion in 2013, which amounts to 2.7 percent of a GDP of $16.72 trillion. The study concluded that the cost of corrosion worldwide amounts to $2.5 trillion (2013), a figure encompassing the U.S., India, Europe, the Arab world, China, Russia, Japan, the Four Asian Tigers and Macau, and the Rest of the World.[iii] In 1946 Herbert H. Uhlig's pioneering cost of corrosion study (requested by the U.S. Congress) placed the U.S. direct cost of corrosion at $5 billion annually. A comparison of the Uhlig and NACE IMPACT studies suggests that from 1946 to 2013, the U.S. cost of corrosion grew by 8,206 percent.[iv]

For Optimal Safety and Cost Avoidance, Good Corrosion Management Requires a Shift in Canada's Business Culture

As in many other countries, industries in Canada have experienced serious incidents in which citizens have been injured or killed after catastrophic corrosion failures. On October 6, 2011, 52 people were injured during an explosion at the Consumers' Cooperative Refinery Complex in Regina, Saskatchewan. Investigators found a serious failure within a six-inch pipe whose internal walls had ruptured under normal operating pressure—a catastrophe caused by corrosion.

Many corrosion decisions are currently based on technical requirements, allowing decision makers to emphasize compliance over financial optimization. Decades ago, corrosion and corrosion control were viewed as technical considerations and were treated as such in asset-owner organizations. In recent times, the seriousness of the escalated risks associated with aging infrastructure—across almost all industries in North America—means that companies must now weigh financial risks through the monetization of consequences and potential failures related to corrosion. This critical component of decision-making will allow those with budgetary authority to directly compare budgetary gains resulting from corrosion control investments against other kinds of expenditures. The increasing critical nature of corrosion failures—tragedies that cost lives, destroy assets, and do irreparable harm to the environment—calls for business strategies to address the threat of corrosion as a threat to industry and business, as well.

A **Corrosion Management System** 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.

According to Gerry Koch, one of the DNV GL authors of the 2016 NACE IMPACT Study, the acceptance of the Corrosion Management System concept may be likened to the acceptance of today's safety management culture. A few decades ago, safety management merely dealt with occupational safety, which considers relatively high occurrences of slips, trips, and falls. Process safety, on the other hand, with its low likelihood of occurrence and high consequence, received little attention. After a few major process safety-related accidents, a culture developed throughout the oil and gas and refining and petrochemical industries in which safety has become an integral part of the organizations' management systems. All levels of the organizations now speak the same safety language and have the same goal to improve both occupational and process safety. "It is my hope that corrosion will go through the same transition and become part of all organizations' corporate cultures," Koch stated.

> DECADES AGO, CORROSION AND CORROSION CONTROL WERE VIEWED AS TECHNICAL CONSIDERATIONS AND WERE TREATED AS SUCH IN ASSET-OWNER ORGANIZATIONS. IN RECENT TIMES, THE SERIOUSNESS OF THE ESCALATED RISKS ASSOCIATED WITH AGING INFRASTRUCTURE — ACROSS ALMOST ALL INDUSTRIES IN NORTH AMERICA — MEANS THAT COMPANIES MUST NOW WEIGH FINANCIAL RISKS THROUGH THE MONETIZATION OF CONSEQUENCES AND POTENTIAL FAILURES RELATED TO CORROSION.

To broadly accept the corrosion management system model of governance, businesses in Canada must change their corporate cultures. Such a shift necessitates a cultural change that must flow from the top to the bottom. To bring about the most beneficial reduction in direct and consequential corrosion costs, businesses must not only embrace technology, but they must also integrate corrosion decisions and practices within an organizational management system. Throughout government and industry in Canada, expectations for a cultural shift toward the corrosion management system model should be set by policymakers and regulators.

There is no doubt that Canadian citizens stand to benefit when industry improves its corrosion control and management nationwide. Perhaps more than any other country in North America, Canada's business culture reflects a commitment to Sustainable business practices shared by Europe but less widely embraced in the U.S. and other major economies. This is why AMPP offers the first IMPACT cost of corrosion study that includes a section dedicated to Sustainability. Also, companies increasingly are setting corporate goals related to safety, as exemplified by Enbridge's commitment to "safety and reliability targets" that includes a "goal of zero incidents, injuries, and occupational injuries," according to their website.

> TO BROADLY ACCEPT THE CORROSION MANAGEMENT SYSTEM MODEL OF GOVERNANCE, BUSINESSES IN CANADA MUST CHANGE THEIR CORPORATE CULTURES. SUCH A SHIFT NECESSITATES A CULTURAL CHANGE THAT MUST FLOW FROM THE TOP TO THE BOTTOM.

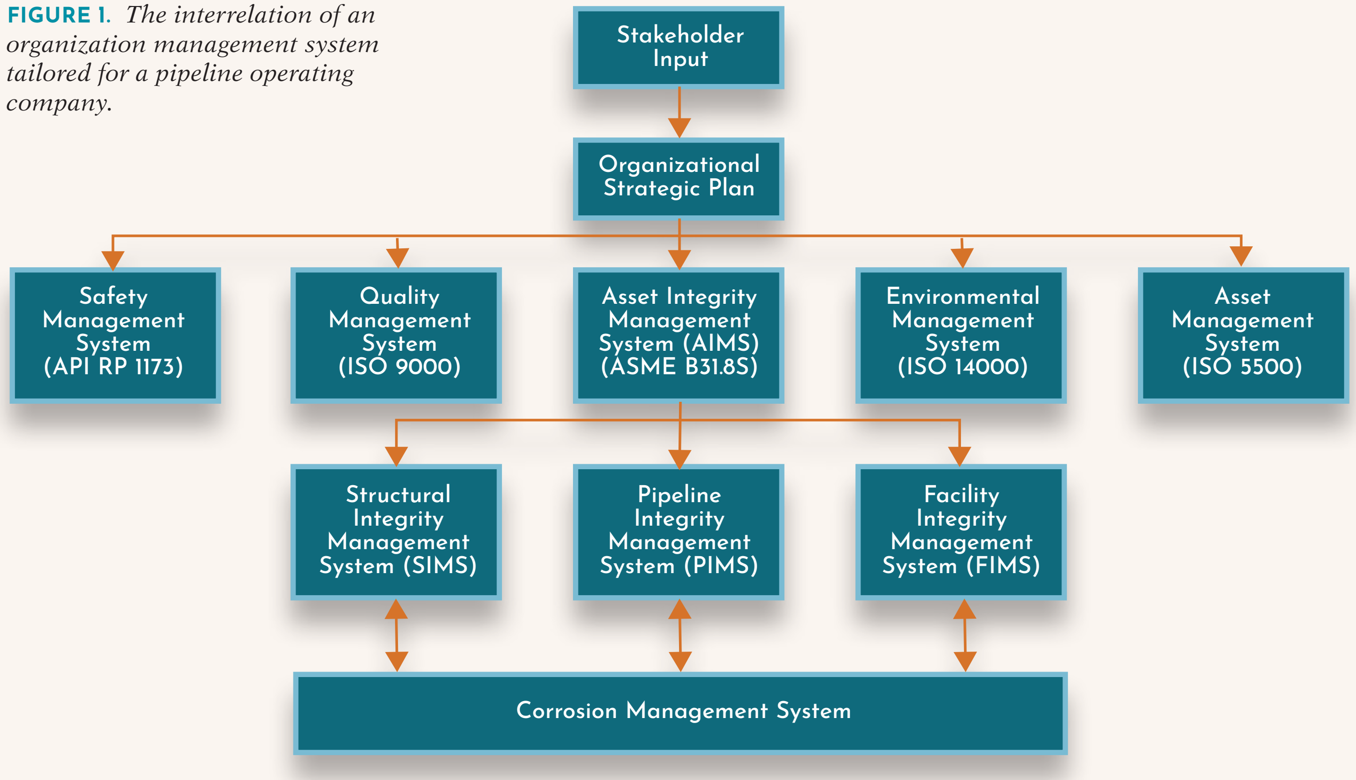
The 2021 IMPACT Canada Study also provides support for government entities seeking to use legislation or regulatory programs to increase asset integrity in areas where failures can have public safety or environmental ramifications. It provides a means for government, industry, and academia to coordinate on best practices for corrosion management and planning in diverse industry and municipal sectors. The study also offers thought leaders an in-depth look at how a range of Canadian industries is faring in the art of corrosion planning across all levels of their organizations.

USING THE CORROSION MANAGEMENT SYSTEM FRAMEWORK TO ADDRESS CHALLENGES AND CREATE OPPORTUNITIES

The 2016 NACE IMPACT Study focused on the global cost of corrosion for such key economic regions as the United States, India, the European Region, the Arab world, China, Russia, Japan, four Asian Tigers and Macau, and the Rest of the World. Considering Canada's status as a highly developed mixed economy with the world's tenth-largest GDP, study experts realized that corrosion cost and management data for a key global contributor was missing. Therefore, the Association for Materials Protection and Performance (AMPP) introduced the 2021 IMPACT Canada Study—sponsored by IUPAT and NACE International Northern Area—with strong support from a community of advisors skilled in materials science and corrosion engineering and the participation of industry members.

The degree to which Canada's asset-owner companies have implemented corrosion management processes varies considerably according to industry sector. In their survey responses, businesses showed

FIGURE 1. *The interrelation of an organization management system tailored for a pipeline operating company.*



> "TO BRING THIS CHANGE ABOUT, BUSINESSES MUST TRANSLATE THEIR CORROSION PRACTICES INTO THE LANGUAGE OF THEIR BROADER ORGANIZATIONS."

an integration of many formal corrosion management processes, while acknowledging the need to improve upon the policies, resources, organization, accountability, and communication components that can impact asset preservation to a financially beneficial degree.

"Most impressively, Canadian industry is solidly committed to sustainable practices at the design and manufacturing and construction stages of the lifecycle," said Monica Hernandez, Country Manager for the IMPACT Canada Study and CEO of Infinity Growth Corporation, Vancouver. "However, compared to countries who participated in the 2016 NACE IMPACT Study, Canada fell behind in its ability to integrate corrosion management planning across all four stages of an asset's lifecycle." (See *Key Findings* for a more detailed analysis of the survey results.)

But by propelling corrosion management and sustainability practices into the high-level *Policy*, *Strategy*, and *Objectives* domains of the corrosion management pyramid, Canada's public and private sector can fully entrench corrosion management into their operations. In doing so, businesses can embrace corrosion management across all stages of a product or asset's lifecycle, allowing it to equal that of the management echelons that address human and environmental safety, risk management, and others. "To bring this change about, businesses must translate their corrosion practices into the language of their broader organizations," said Hernandez.

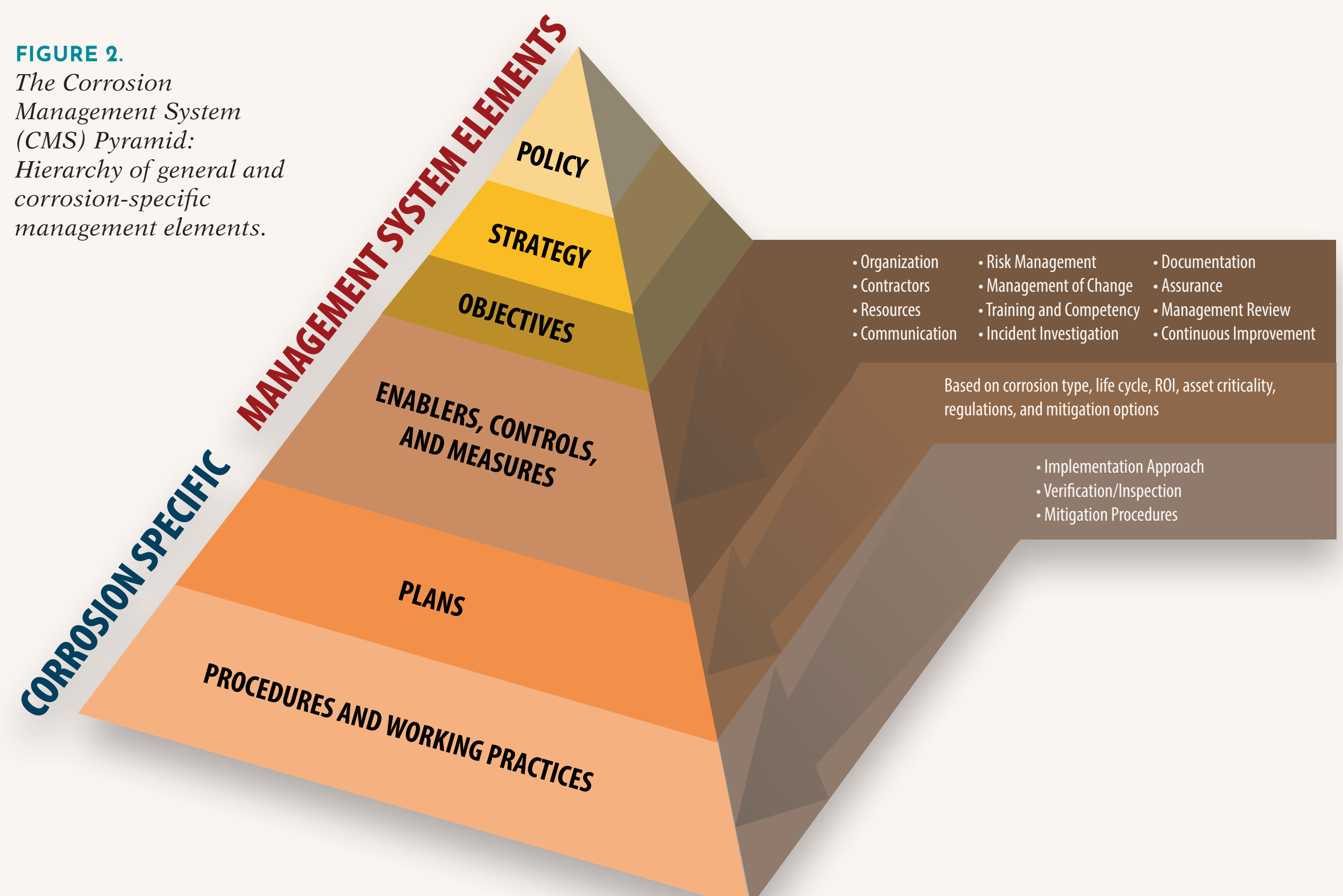
"The IMPACT Canada Study results suggest that the asset-owner companies and municipalities who participated in the IMPACT Canada survey recognize the importance of elevating corrosion management as good business practice across all levels of an organization," said Hernandez. "Asset-owner companies in Canada who simply excel at managing corrosion at the design or manufacturing stages have significant room to improve compared to global participants from the 2016 study. They must become strategic in the way they predict and manage the likelihood and consequence of corrosion-related events with a thought to their long-term return on investment (ROI)."

Companies interested in pursuing a Corrosion Management System (CMS) Framework are encouraged to embrace an organizational structure that allows them to mitigate corrosion effectively, while also achieving a positive ROI. ROI is defined as a benefit (or return) of an investment divided by its cost. Specifically, a CMS must include a documented set of processes and procedures necessary to plan, execute, and continually improve the company's ability to manage the threat of corrosion for existing and future assets and asset systems. Figure 1 shows the interrelation of a pipeline operator's organization management system. Figure 2 is the CMS Pyramid, which became central to the findings and recommendations of the 2016 NACE IMPACT Study.

Canadian corporations that aspire to manage the threat of corrosion must consider the likelihood and consequence of corrosion events. The consequence, or impact, of corrosion is considered the potential or actual monetary loss associated with the safety or integrity of the corrosion event. This value can be quantified when decision makers consider lost revenue, the cost of repairs, or clean up, for example.

"When companies adopt a CMS Framework, they might consider mitigating corrosion threats to the point where the expenditure of resources is balanced against the benefits gained," explained Helena Seelinger, AMPP Executive Director and Chief Regulatory and Public Affairs Officer. "To determine whether a corrosion management investment is appropriate, it can be compared to the potential corrosion consequence through an ROI analysis. For corrosion management, the costs may include inspection and other maintenance costs. The benefit of ROI is not realized through capital gains, but rather through the reduction of consequential expenses frequently resulting from failures in personnel safety, public safety, environment protection, or asset integrity."

FIGURE 2. *The Corrosion Management System (CMS) Pyramid: Hierarchy of general and corrosion-specific management elements.*



IMPACT CANADA DATA COLLECTION AND BENCHMARKING RESULTS

To implement the IMPACT Canada study, researchers used the same Corrosion Management Practice Model developed for the NACE IMPACT Study, while adding new benchmarks on Sustainability. This model provided researchers with a repeatable framework for assessing the structure, approach, and features that comprise a corrosion management system within an organization. Using this model, researchers developed a comprehensive 87-question self-assessment survey that encompassed 10 management system domains, which are defined here:

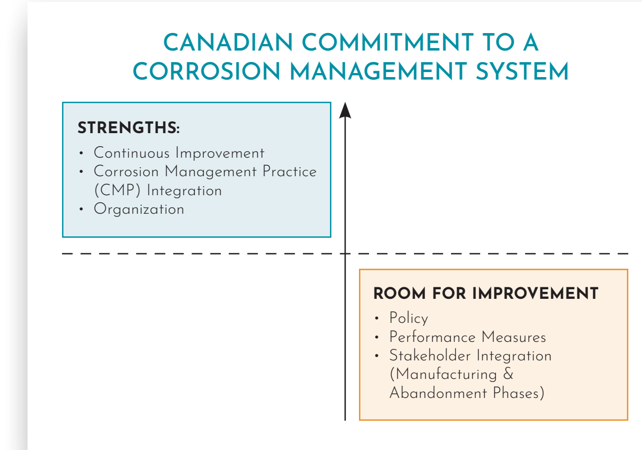
- **Policy, including strategies and objectives** – articulation of overarching business needs, such as regulatory, legal, environmental, and societal
- **Stakeholder integration** – alignment to stakeholder needs, performance monitoring, and compliance
- **Organization** – structure, interaction model, and internal and external engagement with vendors and suppliers
- **Accountability** – roles, responsibilities, and resource allocation
- **Resources** – competencies, training and development, and the formalization of job and work requirements
- **Communication** – awareness, knowledge management, and lessons learned
- **Corrosion Management Practice (CMP) integration** – integration into work processes, alignment to quality and other disciplines, and incident tracking and resolution
- **Continuous improvement** – identification of improvement, prioritization, selection, and change management
- **Performance measures** – quantifiable indications, such as Key Performance Indicators (KPIs) to assess and to measure how well an organization or individual is achieving desired goals
- **Sustainability**, as measured through policy, strategy, and nine organizational benchmarks listed above

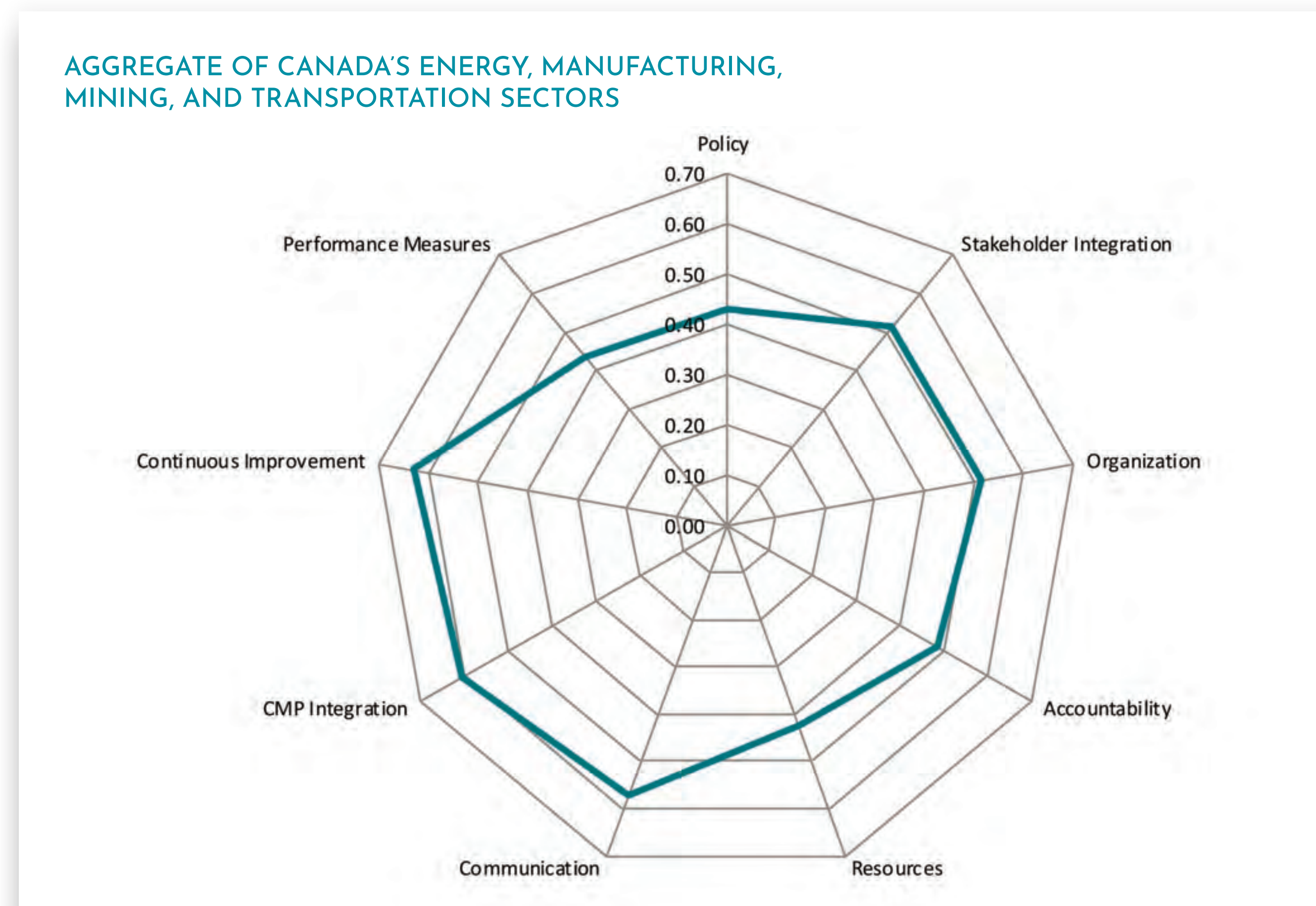
The scores for each of the above practices ranged from 0 to 1. A score of 0 reflected 'No Capability' and a score of 1 reflected the highest level of capability based upon the provided answer options.

AMPP conducted the survey across a wide swath of industries in Canada. These included the offshore, downstream, midstream, and upstream industries subsumed under the Energy sector, as well as companies within the Manufacturing, Mining, and Transportation sectors. Specifically focus groups of personnel from various management and technical levels were organized into several industries to allow researchers to obtain further insight into their corrosion management philosophies and practices, and their understanding and commitment to policies of material sustainability.

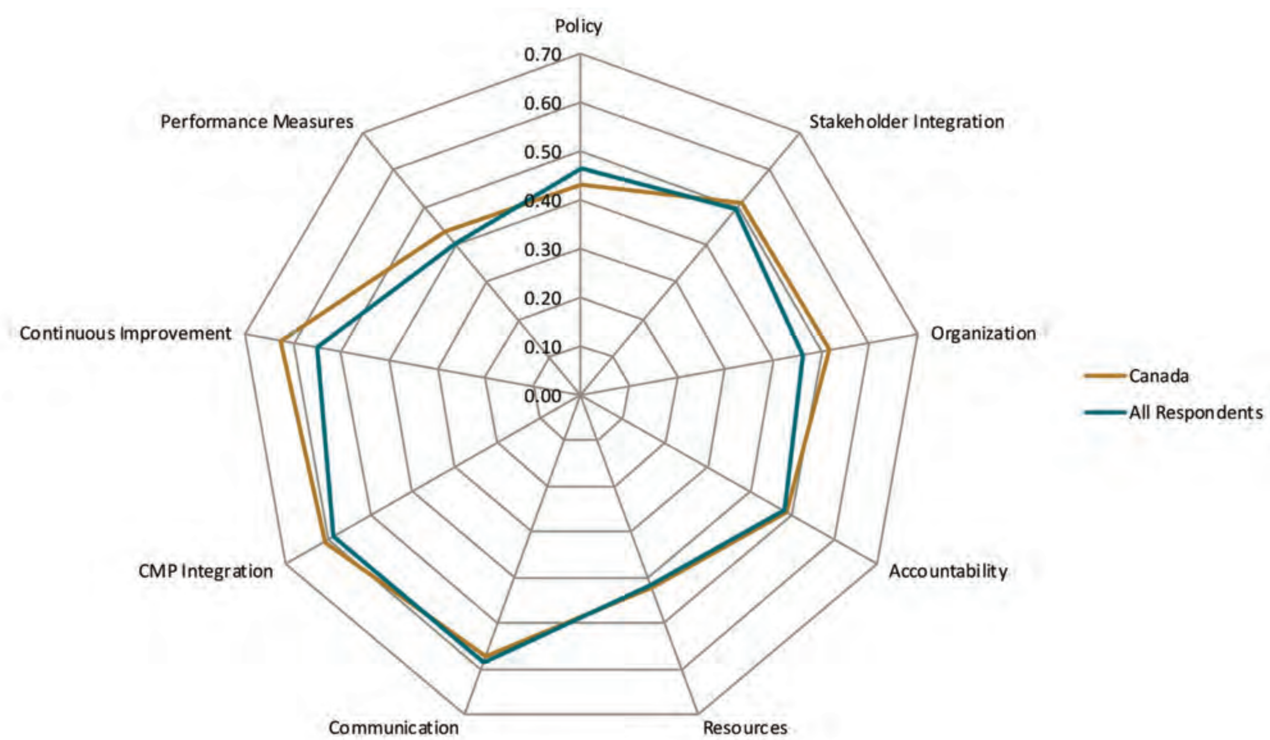
After the data was collected for Canada's industry sectors, the IMPACT Canada Study team examined how four sectors embraced and implemented corrosion management practices across the entire lifecycle of their assets, and within the discrete phases of Design, Manufacturing and Construction, Operations and Maintenance, and Abandonment. The researchers analyzed the industries' commitment to Sustainability independently. From their analyses, they derived a set of observations and recommendations that are detailed here.

The IMPACT Canada researchers abstracted important general observations from the survey's aggregate results. They found three domains in which businesses surveyed in Canada exhibited significant strength: *Continuous Improvement*, *Corrosion Management Practice (CMP) Integration*, and *Organization*. By contrast, the two areas where challenges emerged included *Policy* and *Performance Measures* across the entire lifecycle of asset preservation. "In the domain of *Performance*





CANADA VS. ALL GLOBAL RESPONDENTS ACROSS NINE DOMAINS



Measures, the study team reported that there was room for improvement in Canadian organizations' commitment to a corrosion management system that results in the lowest total corrosion cost over the intended life of an asset," explained Hernandez. "They also saw room to improve the monitoring and reporting of their companies' corrosion management performance, as well as how well corrosion management performance is integrated into their organizational performance metrics."

Researchers also observed that IMPACT Canada survey participants scored similarly across nine domain areas compared with participants in the 2016 IMPACT Study survey. In particular, they compared Canada's self-assessment responses within industry sectors to those of global participants from equivalent industries in Asia, Australia, Europe, the Middle East, and North America. In the two areas of *CMP Integration* and *Continuous Improvement* (across all areas of the lifecycle), Canada's participants scored equally with global participants. When assessing their commitment to *CMP Integration* compared to global participants, participants noted a significantly greater establishment of key performance indicators to demonstrate the effectiveness and improvement of corrosion management.

On the other hand, Canada lags global participants in its integration of corrosion management planning across the lifecycle of its assets. "Specifically, Canadian survey participants noted that within the domain of *Stakeholder Integration*, companies needed to improve their corrosion management planning in the Manufacturing & Construction and Abandonment phases of an asset's life," said Hernandez. "Within these two phases, Canadian participants recognized the need to align with their stakeholder needs, performance monitoring, and compliance."

Within the *Policy* domain related to asset design, Canada also out-performed industries across the globe in the 2016 NACE Impact Study. Another area under the *Policy* domain in which Canada demonstrated slightly better performance than global participants pertained to its strategies addressing the abandonment, decommissioning, and mothballing of assets.

ASSESSMENT OF CORROSION MANAGEMENT PRACTICES ACROSS CANADA'S INDUSTRIAL SECTORS KEY FINDINGS

ENERGY SECTOR – OIL & GAS, PIPELINE, AND ENERGY UTILITY INDUSTRIES

> NEARLY 100 FEDERALLY REGULATED PIPELINE OPERATORS IN CANADA MUST FOLLOW STRICT TECHNICAL STANDARDS FOR THE DESIGN, CONSTRUCTION, OPERATION, MAINTENANCE, AND RETIREMENT OF ALL OIL AND GAS PIPELINES.

For the purposes of this study, Canadian asset-owner companies in the energy sector primarily include businesses within the oil and gas industry's upstream sector, the energy utility power industry in the downstream sector, and the pipeline industry in the midstream sector. For upstream oil and gas facility operators inland and offshore in Canada, protecting assets from corrosion can be very costly. Oil and gas companies engaged in upstream operations in Canada practice a variety of corrosion-control methods to protect their wells, risers, drilling rigs, and offshore platforms. In the province of Alberta, for example, the boiler tube equipment used by oil sands producers who use steam generation to extract oil from oil sands deep below the earth's surface is subjected to harsh, corrosive conditions. (See Case Study: *The Importance of Feeding Purified Water into a Steam Generator in an Oil Sands Operation*.)

As an integral part of the midstream level, pipeline operators must safely transport oil and gas over hundreds of miles through pipeline assets requiring continuous maintenance and corrosion prevention. Nearly 100 federally regulated pipeline operators in Canada must follow strict technical standards for the design, construction, operation, maintenance, and retirement of all oil and gas pipelines.

At the downstream level, owners of refineries and liquefied natural gas terminals encounter challenges from corrosive agents in feedstock, crude oil, and refining processes. In addition, energy utility companies that operate hydro-electric, nuclear, coal, and fossil fuels-driven power generation systems attend to a variety of corrosion control measures related to material selection, coatings, electrical insulation, and cathodic protection. Steam power plant operators, for example, must control boiler feed-water chemically to prevent heat-transfer surfaces from being fouled and to keep components reliable.

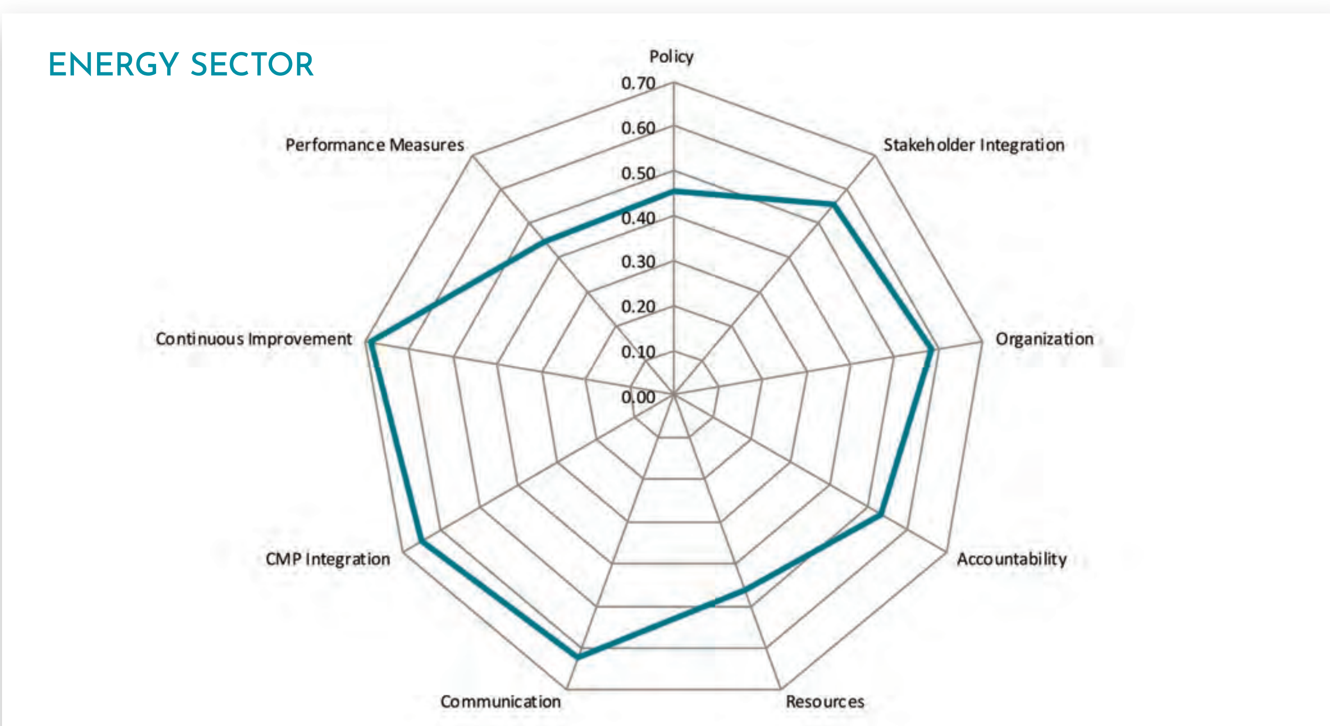
The study results for Canada's Energy Sector are based on responses from a diverse group of asset-owner companies engaged in upstream, midstream, and downstream operations. Study analysts recognized three areas of strength related to the commitment to corrosion management within Canada's Energy sector: *Continuous Improvement*, *(CMP) Integration*, and *Communication*. Within the *Continuous Improvement* domain, energy companies signal, by a large margin, that formal organizational management of change processes do exist. In the *CMP Integration* area, numerous energy businesses attest to the fact that their corrosion management processes include risk management. As regards the *Communication* domain, energy companies excel at the active encouragement of communications between organizational groups.

In the domain of *Resources*, Canada's energy sector is challenged across the entire lifecycle of asset preservation. Here, companies acknowledged specific challenges in the realm of a) identifying appropriate and achievable corrosion management staffing levels; b) the clear definition of corrosion management competencies; c) the assignment of corrosion management resources based on position requirements; d) the requirement of corrosion management competencies within work processes; e) the provision of professional corrosion management and technical training; and f) the capturing and transferring of corrosion management organizational knowledge by way of several mechanisms.

The results also showed that at the *Policy* level, corrosion management is not emphasized across the lifecycle, but it is seriously considered during the asset design strategy phase and the operations and maintenance stages of asset preservation. "It is likely that the energy sector's need for improvement in the *Resources* and *Policy* domains stems from the fact that corrosion management is not yet viewed and implemented by leadership as an enterprise-wide pursuit yet," said Hernandez.

The study team also compared Canada's self-assessment responses within the energy sector to responses by global participants from energy-related industries who responded to the 2016 NACE IMPACT study in Asia, Australia, Europe, the Middle East, and North America. Canada's energy sector's encouragement of *Communication* between organizational groups responsible for corrosion management was strong, albeit equivalent to the performance of worldwide participants in this area, from the 2016 IMPACT Study. "Moreover, Canadian energy businesses slightly exceeded global participants in the domain of *CMP Integration*—specifically in their inclusion of risk management in the corrosion management processes of identification, assessment, and the mitigation of likelihood and consequences," noted Hernandez.

But in contrast to global participants, the Canadian energy sector saw challenges in the domain of *Stakeholder Integration*, especially as it involved the use of corrosion management plans and plan integration during a) the manufacturing and construction phases of asset preservation, and b) the abandonment phase of the lifecycle, when assets are decommissioned and put out of service.



CASE STUDY

BY MONICA HERNANDEZ, INFINITY GROWTH CORP. AND SANKARA PAPAVINASAM, CORRMAGNET CONSULTING INC.

THE IMPORTANCE OF FEEDING PURIFIED WATER INTO A STEAM GENERATOR IN AN OIL SANDS OPERATION

The following case study illustrates the importance of maintaining the quality of water used to generate steam during steam-assisted gravity drainage operations that occur when producers extract oil from oil sands located deep below the earth's surface. Energy sector participants in the IMPACT Canada Study observed that their industry would be better served if producers would institute corrosion management practices across their enterprises. Taking a more systematic approach to corrosion prevention would empower business leaders to put rigorous processes in place to ensure that optimal water quality is maintained for the steam-generation process.

A steam-assisted gravity drainage (SAGD) operation is typically carried out to produce oil from oil sands, which are present about 500 meters beneath the earth's surface. In the SAGD plants, which are typical operations used in the northern part of Canada in the province of Alberta, pairs of stacked horizontal wells are drilled into the oil sands formation. Steam at temperatures ~ 250ºC is injected through the top well, which heats the bitumen and separates it from sand. The separated bitumen, along with water and some sand, is collected through the bottom well. The bitumen is then pumped to the surface and water is subsequently separated from it. The separated water is further treated and reused.

It is important to maintain the quality of the water that is originally used to generate the steam, as well as the recycled water that is separated from the bitumen. If the water quality is not maintained, it will lead to failures in the equipment known as once-through-steam-generators (OTSG), as demonstrated in this case study.

FAILURE AND FAILURE ANALYSIS

The failure of OTSG tubes in SAGD plants has been reported on numerous occasions. Our exploration of how and why these boiler tubes fail reveals a process that is typical of these types of failures. This phenomenon is commonly found in SAGD plants.

A visual examination of the steam generator tubes will typically exhibit a bulging or blistering on the hot side of the tubes. In addition, the blistered areas will often show small fissures on the external surface, while the remainder of the tube surface remains in good overall condition and free from corrosion, erosion, or deposition.

In this particular instance, a cross-sectional examination of the tubes indicated some necking (reduction in wall thickness) in the blistered area, as well as heavy deposit or scales of about 0.1 inch (about 2.5 mm) in thickness on the internal surface. An examination of the deposits indicated the presence of hard scales, consisting of iron and different forms of silicon compounds such as aegirine, paectolite, xonolite, and richterite, as well as mud-like scales consisting of calcium carbonate, calcium silicate hydroxide, and magnesium silicate hydroxide.

Moreover, a microstructural examination of the tubes revealed that the tube temperatures would have eventually reached between 1,000 to 1,500ºF (537-815 ºC).

The bulging of the boiler tubes was a consequence of short-term overheating. Such short-term overheating is generally caused by the deposits on the tube's interior (a phenomenon that happens over time), which affect the heat transfer and leads to high tube wall temperatures. Both excessive heat flux and abnormal coolant flow also might have contributed to the failure in this instance, but the main cause of the tube bulging was the internal deposits.

Our review of the operating history of the plant indicated that the quality of the feed water that was fed to the boiler was poor, due to solids contamination, high hardness and ions, all of which are parameters that have a tendency to form scales. The intermittent increase in the contaminants was found to be caused by an ineffective pre-treatment of the water, which in conjunction with the minimal control of other parameters mentioned above, resulted in the failure of the tubes.

ACTIONS TAKEN

Based on its experience with the consequences of overheated boiler tubes, the company established rigorous procedures to maintain optimal water quality for its steam-generation process. This included the removal or minimization of sand contamination and ions that could lead to internal deposits, as well as the incorporation of certain measures to observe and prevent future incidents. These include water sampling, better chemical injection control, and the development of integrity operating windows. These efforts resulted in a significant improvement during subsequent operations, in which the failure of the boiler tubes that generated steam for the SAGD operation was either avoided or minimized.

The lessons learned from the company's effort to maintain water quality in order to protect the steam-generating boiler tubes could be applicable to the standard operation of any OTSG.

MANUFACTURING

> THE MANUFACTURING SECTOR IS A 'CORNERSTONE' OF THE CANADIAN ECONOMY, AND IT ACCOUNTS FOR APPROXIMATELY $174 BILLION—MORE THAN 10 PERCENT—OF CANADA'S TOTAL GDP.

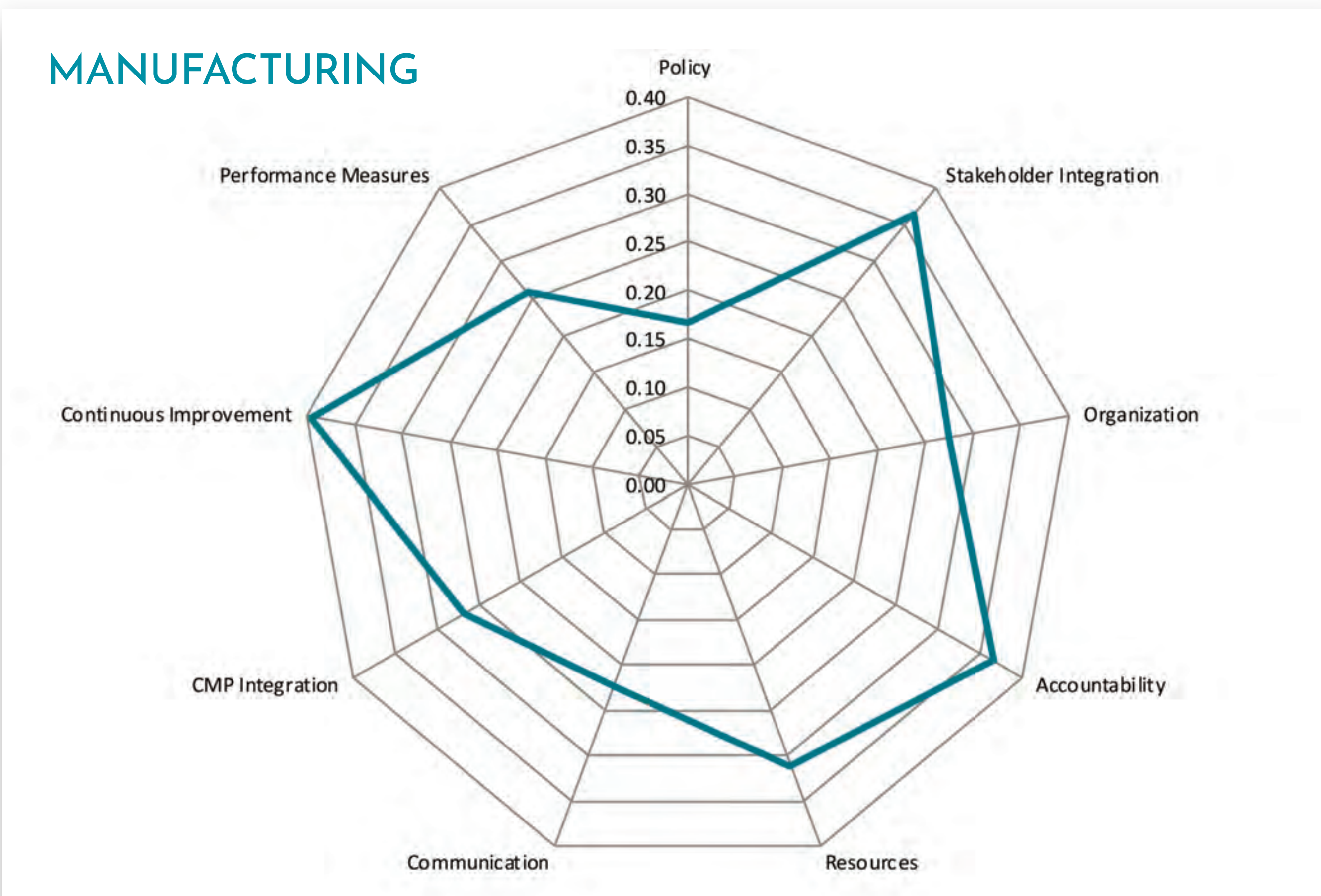
The manufacturing sector is a "cornerstone" of the Canadian economy, and it accounts for approximately $174 billion—more than 10 percent—of Canada's total GDP, according to the Government of Canada.[v] The country's manufacturing industries consist of mining, gas, oil, and machinery; aerospace; meat and seafood processing; tractors and agricultural machinery; printing; shipbuilding; automobile manufacturing; and the production of wood paneling and plastics. Manufacturers regularly contend with preventing and controlling corrosion on metal equipment that is exposed to chemicals, acids, water, and continuous sanitation through a variety of processes in every industry.

The principal Canadian manufacturers who participated in the IMPACT Canada Study included business leaders within the automotive, steel, and pulp and paper industries. Study analysts recognized three areas of strength related to the commitment to corrosion management within Canada's Manufacturing sector: *Accountability, Continuous Improvement*, and *Stakeholder Integration*. In the domain of *Accountability*, the study team found that Canada's participants reported that their organizational leadership tended to take ownership and engage in corrosion management. Within the realm of *Continuous Improvement*, participants excelled because their businesses engaged in the formal organizational management of change processes. In the area of *Stakeholder Integration*, study analysts noted that manufacturers had made progress in linking their corrosion management plans across the entire asset lifecycle. "Manufacturers also excelled at the practice of having a corrosion management plan to guide the design for corrosion control and/or mitigation," said Hernandez.

In the domain of *Policy*, Canadian manufacturers can improve by developing a corrosion management strategy across the entire lifecycle of asset preservation, including at the Design, Manufacturing and

Construction, Operations and Maintenance, and Abandonment phases. Study researchers also found that manufacturers have room to improve their *CMP Integration* practices across the entire lifecycle. "In particular, manufacturers would benefit from better communication of their corrosion management processes and better alignment of their corrosion management processes and tools with their health, safety, and risk management disciplines, for example," said Hernandez.

Whereas study participants noted a need to improve in the *Communication* domain, they showed progress in having a communication plan that explicitly addresses the transfer of corrosion-related information to external stakeholders. "*Communication* is one domain in which Canadian manufacturers could significantly improve upon in comparison to global participants from the 2016 NACE Impact Study," noted Hernandez.



CASE STUDY

BY JUSTIN HEBNER, PURE TECHNOLOGIES LTD., AND RUSS DUECK, CITY OF CALGARY

ADVANCED CONDITION ASSESSMENT STRATEGY FOR CRITICAL MAINS: CITY OF CALGARY[1]

Since 2004 the City of Calgary Water Resources division has compiled and improved upon a database of knowledge concerning its feedermain system. As its feedermain inspection program has evolved, its technology has improved considerably, allowing the city to combine state-of-the-art inspection and monitoring techniques to identify and replace pipe destined for catastrophic failure. Other municipalities throughout Canada could benefit from Calgary's proactive approach to managing corrosion on their feedermain networks, thereby potentially avoiding the expenditure of millions from economic, social, and environmental impacts.

The City of Calgary has long taken a proactive approach to the management of its feedermain network. This includes an advanced condition assessment strategy that combines an inspection program and risk analyses to develop a better understanding of the safety and reliability of the network. The current program began in 2004, after a 1200 mm feedermain catastrophically failed and released 20 ML of water, flooding a roadway and disrupting service to over 100,000 customers.

An investigation determined that the failure occurred on an AWWA C301-L pipe section where the mortar coating was compromised in part by sulfate rich soils, allowing water to seep in and corrode the steel structure of the pipe. Over the years successful condition assessment inspections have allowed the City to proactively repair damaged pipes. The case study below provides an overview of Calgary's long-term strategy for critical water transmission pipe management.

The City of Calgary Water Resources (WR) carries out an annual asset inspection program of its water feedermains to ensure the safety and reliability of its water network. The program began in 2004 after a 1200 mm (48 in) diameter prestressed concrete cylinder feedermain burst apart in McKnight Boulevard in Calgary's northeast section flooding the roadway and releasing over 20 megaliters (5 million gallons) of water. Due to the early hour, only one car was caught in the flood and the occupant had to be rescued by firefighters. Nevertheless, 100,000 citizens experienced low pressure because of the break until the break was isolated. Investigations of the failure led to sulphate attack being the root cause. The sulphate-resistant concrete coating on the feedermain was not resistant enough to handle the local conditions of 5,000 PPM sulphate in the surrounding soil. Over time the coating had degraded, letting groundwater and chlorides seep in and corrode the steel wires that provide most of the strength of this material.

CALGARY'S CONCRETE FEEDERMAIN CONDITION ASSESSMENT STRATEGY

Following the 2004 failure, the City of Calgary conducted a risk assessment of its feedermain network looking at material type, existing cathodic protection, age, failure mechanisms, soil parameters, pipe criticality and social impact of a failure. Following this initial risk assessment, the City's inspection program focused on feedermains that were in the same soil type, age bracket, and material classification as the 2004 break, an event that was the first of its type to bring significant consequences. In 2011, the program focus expanded to additional materials after a 600-mm (24 in)-diameter bar-wrapped concrete feedermain burst, damaging a nearby garage and flooding alleyways.

The catastrophic failure of the McKnight Feedermain in 2004 prompted additional research into critical water infrastructure, and culminated into the condition assessment program WR has today for high-risk feedermains. The incident made it clear that the City of Calgary needed a new proactive approach to the condition assessment of its transmission network to prevent similar failures. WR defines a catastrophic failure of a pipe as a sudden and complete loss of pipe function.

Concrete feedermains are the primary focus of the condition assessment program, as there have been a number of catastrophic failures on concrete lines, and the method of failure is typically sudden and catastrophic. Additionally, the City's concrete feedermains pose a challenge to repair compared to other materials. In particular, the City's concrete feedermains have been found to be highly vulnerable to degradation when installed in adverse soil conditions. In Calgary soils containing higher amounts of chlorides or sulphates —or soils with low resistivity—are known as "hot" and can quickly deteriorate the condition of feedermains. When the outer mortar coating has been compromised, the inner steel is vulnerable to corrosion attacks.

The analysis completed by WR prioritized which concrete feedermains were most at risk. WR then developed a condition assessment strategy for its concrete feedermains. Soil sampling has been conducted to determine soil types surrounding feedermains. Internal electromagnetic inspection is recommended for pipes with "hot" soils nearby to assess baseline corrosion, wire breaks, or bar breaks. For C-301 feedermains found to have wire breaks, acoustic monitoring may be installed to track further deterioration. Pipes that are found to be critically unstable should be excavated, verified, and replaced. Some of these processes are detailed in the original NACE International paper, "Advanced Condition Assessment Strategy for Critical Mains: City of Calgary"[1] and in an earlier *Materials Performance* article, "Feedermain Rupture Sparks Pipeline Assessment Program."[2]

CASE STUDY: MEMORIAL FEEDERMAIN CONDITION ASSESSMENT

In May 2013, following another catastrophic rupture, the City of Calgary inspected 2.2 kilometers of the 750 mm C-303 BWP Memorial Feedermain, which was installed in 1970/72. PureRobotics™ inspection technology, a powerful robotic system equipped with an electromagnetic array, was used to identify and locate bar breaks and cylinder corrosion.

Utilizing this non-destructive inspection method, the City of Calgary was able to assess the condition of one of their critical pieces of infrastructure:

- 3 of 232 (1.3%) inspected pipe sections were identified to have electromagnetic anomalies consistent with bar break damage.

In August 2013, the most distressed pipe section was excavated for verification. The results had predicted bar breaks and cylinder corrosion, which can eventually lead to pipe failure if not repaired or replaced. The validation confirmed the broken bars and a large area of cylinder corrosion. Based on these results, a portion of the feedermain was replaced and constructed in a new alignment to avoid future property damage if another failure were to occur.

CONCLUSION

Since 2004, the City of Calgary Water Resources has been building a baseline database of knowledge on the feedermain system. From the inception of the feedermain inspection program, the technology used has improved leaps and bounds. WR has inspected more than 36% of its concrete feedermain network, and from that, identified and replaced over 22 sections of main. A combination of soil sampling, inspection, monitoring, and verification digs have successfully identified pipe that otherwise would have failed catastrophically with little disruption to the network, saving the City of Calgary millions of dollars in economic, social, and environmental impacts.

This case study is an edited excerpt of longer article (cited below) that was presented at the NACE International Northern Area Western Conference in 2019.

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MINING SECTOR

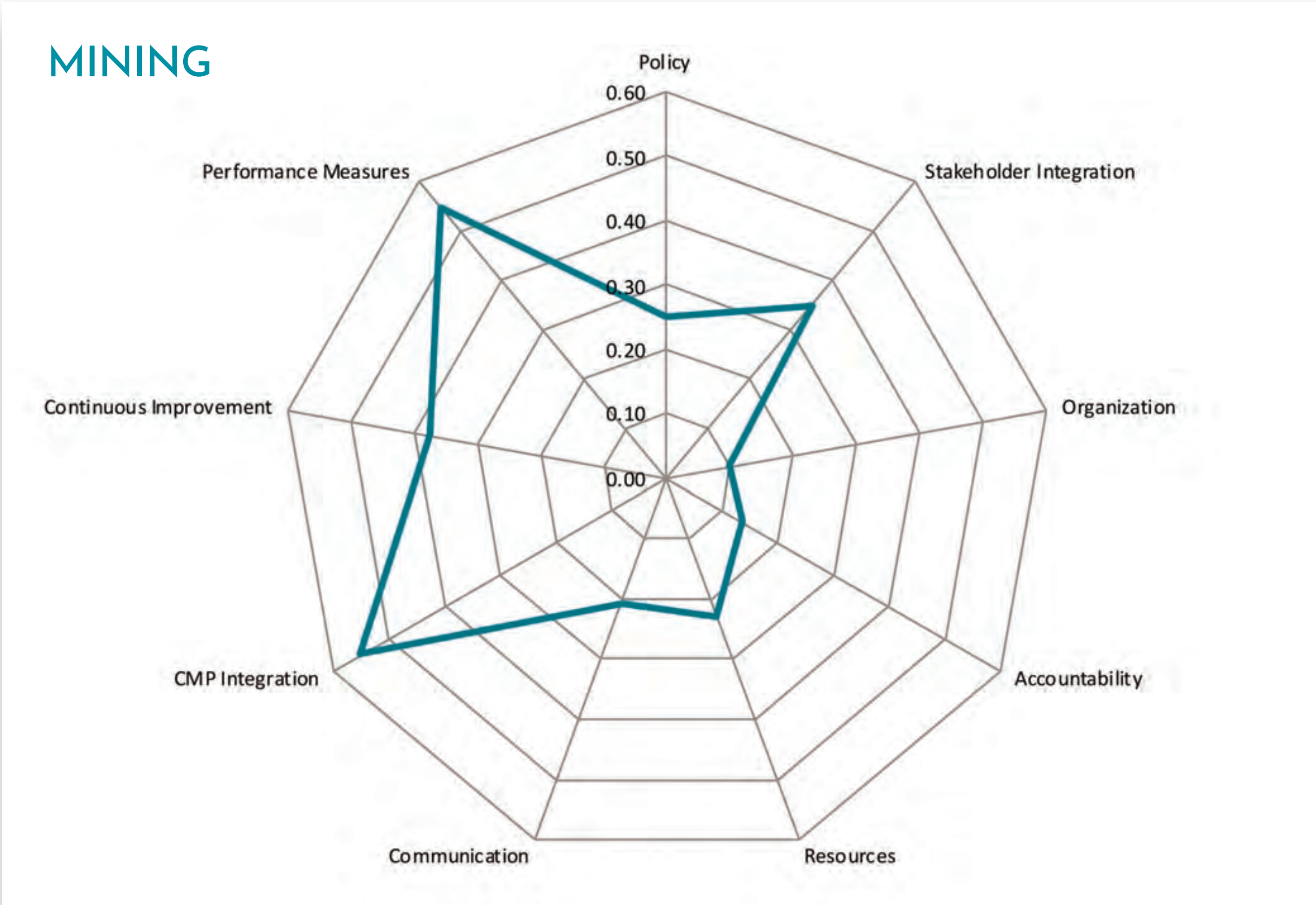
> "MINING EQUIPMENT, INCLUDING MINE SHAFTS, WIRE ROPE, ROCK BOLTS, AND PUMP AND PIPING SYSTEMS, IS VULNERABLE TO MYRIAD TYPES OF CORROSION.

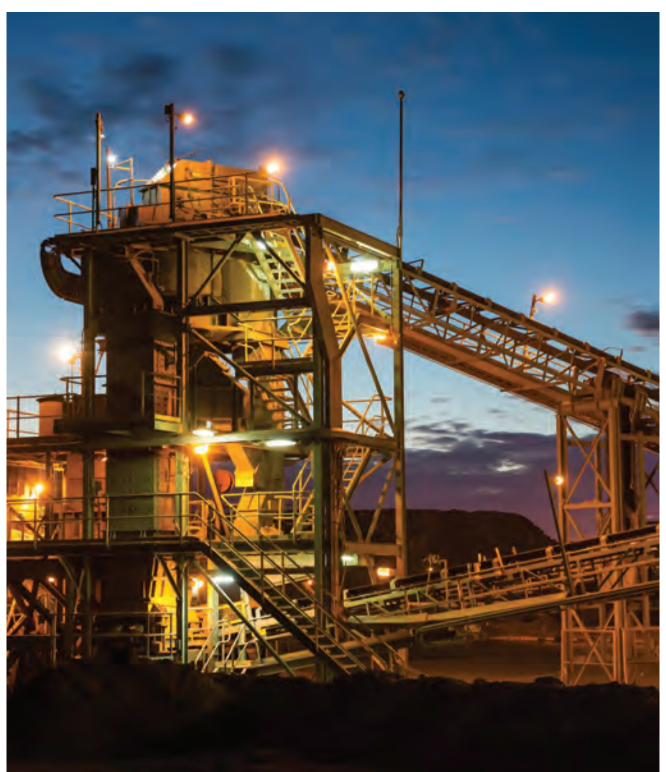
According to The Mining Association of Canada, in 2018 Canada's mining industry "contributed $97 billion, or 5 percent, to Canada's total nominal gross domestic product." Canada's plentiful natural resources within a large land mass comprising 13 provinces allow for the mining of everything from copper, gold, diamonds, nickel, lead, zinc, and molybdenum to potash, uranium, iron, zinc, aluminum and other metals and minerals. Canada ranks alongside the top five countries globally who produce 15 minerals and metals.[vi] Canada's mining industry produces more potash than any other country, according to The Canadian Minerals and Metals Plan. It ranks second in the production of uranium and niobium; third in the production of nickel, cobalt, aluminum, and platinum group metals; and fifth in gold and diamonds.[vii]

Mining equipment, including mine shafts, wire rope, rock bolts, and pump and piping systems, is vulnerable to myriad types of corrosion. Mining facility owners and operators contend with "uniform corrosion, pitting corrosion, crevice corrosion, erosion-corrosion, and intergranular corrosion." Owners and operators also must prevent and control corrosion in "tanks, reactor vessels, cyclic loading machinery, and pressure-leaching equipment."[viii]

IMPACT Canada Study analysts recognized two areas of strength among participants from the Mining sector: *Performance Measures* and *CMP Integration*. Across the lifecycle of asset preservation, study analysts noted that in the domain of *Performance Measures*, participants indicated that their corrosion management systems resulted in the lowest total corrosion cost over the intended life of the asset. "It is possible that this result can be explained by the fact that Mining industry business leaders have no meaningful key performance indicators that would link risks to specific business cases," said Hernandez. According to Zoe Coull and Mario Moreno, "relevant corrosion KPIs are not being identified, measured, or tracked" by high-level Mining industry leaders.[ix]

In the realm of *CMP Integration*, researchers found that Mining sector participants included risk management as one of their corrosion management





processes, a significant strength. In addition, participants reported that corrosion control practices are designed into their systems and solutions, another exhibition of strength.

Whereas the domain of *Organization* posed a significant challenge across the entire lifecycle of asset preservation among Mining industry participants, the study team found that corrosion professionals did interact with colleagues in the design organization, with operations and maintenance groups, and among asset abandonment experts. "In fact, our study team found that Canadian participants scored higher than their global counterparts in organizational interaction as they sought to preserve their assets during the Design, Operations and Maintenance, Manufacturing, and Abandonment phases," said Hernandez.

Two other challenge areas for Mining sector participants fell within the domains of *Accountability* and *Resources* across the entire lifecycle of asset preservation. However, in these and other areas, Canadian participants scored similarly to global participants in the 2016 NACE IMPACT study.

TRANSPORTATION SECTOR

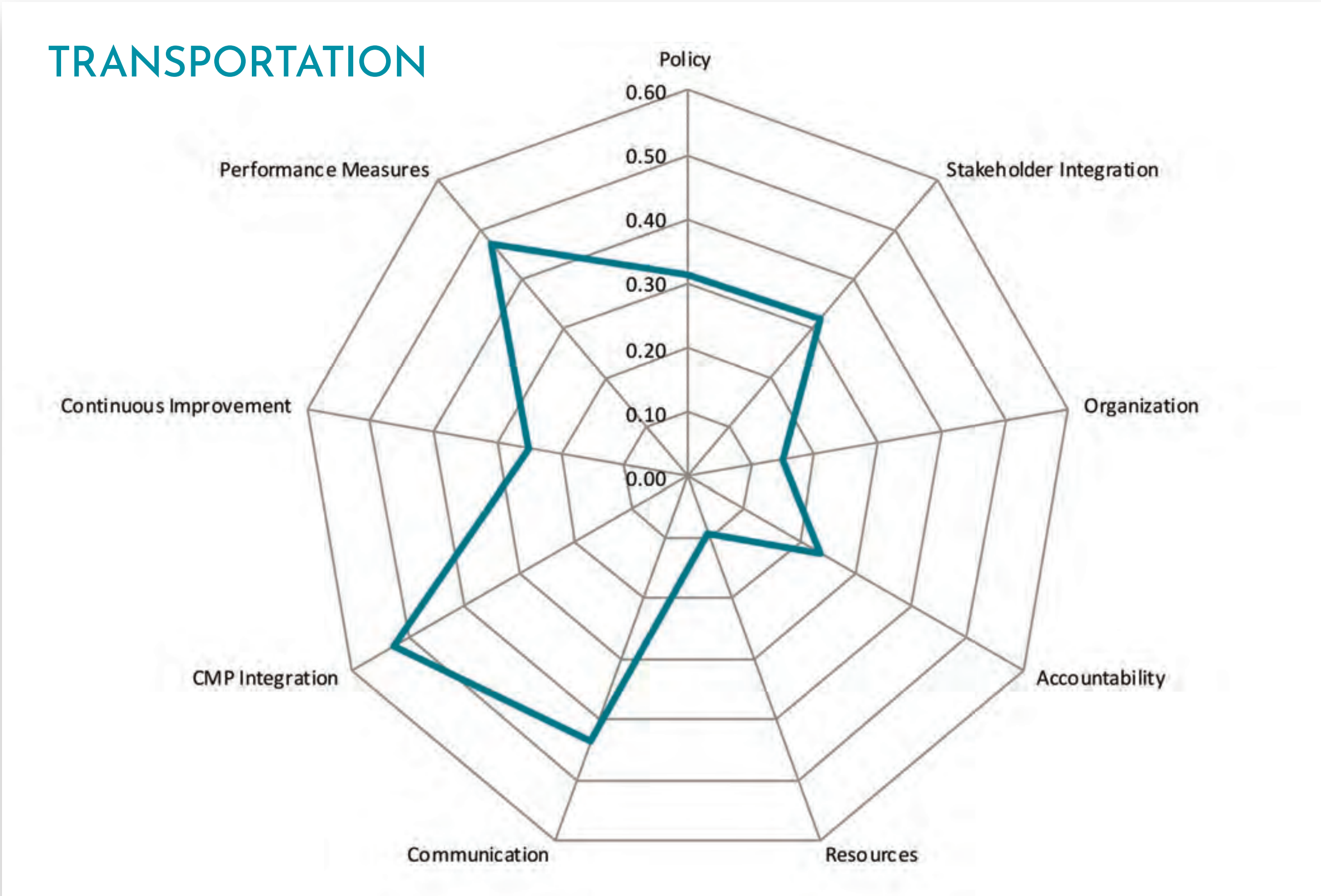
"WHEN MEASURED AGAINST THEIR GLOBAL TRANSPORTATION SECTOR COUNTERPARTS, CANADIAN PARTICIPANTS WERE ESPECIALLY CHALLENGED IN ALL MANAGEMENT SYSTEM ELEMENTS OF CORROSION PREVENTION AT THE DESIGN STAGE OF ASSET PRESERVATION."

The Transportation Sector addressed in this study consists of government ministries, municipalities, and companies who oversee the maintenance and repair of Canada's vast road and bridge infrastructure. "Under Canada's Constitution Act, the provinces and territories have exclusive jurisdiction over the building and maintenance of national highways. Local and municipal roads are under the jurisdiction of municipal governments," according to a U.S. Library of Congress source exploring the funding of Canada's road infrastructure.[x]

A *Statistics Canada* report revealed in 2018 that Canada's publicly owned roads comprised 1,066,180 kilometres, and the majority of this road length consisted of local roads equivalent to two lanes. Non-rural highways —making up the majority of road systems in Yukon and the Northwest Territories —comprised only 51,093 kilometres (or 4.8 percent) of all roads. The report emphasized that municipalities own the majority of Canada's bridges.[xi] The report also offered the following conclusions about the management and physical condition of Canada's roads and bridges:[xii]

- In 2018, nearly 57 percent of "all road owners had an asset management plan," compared with 44 percent in 2016.
- In 2018, 50.3 percent of all public bridge and tunnel owners had an asset management plan, up from 41.9 percent in 2016.
- Among those owners surveyed, non-rural highway bridges were "in the best condition" of all bridge types—nearly 71 percent were reported to be "in good or very good condition." By contrast, about 42 percent of rural highway bridges were "in good or very good condition."
- The percentage of local roads reported to be in "poor or very poor" physical condition decreased, from 16.3 percent in 2016 to 14.7 percent in 2018.

Policies focused on the design, construction, maintenance, and corrosion protection of roads and bridges in Canada fall under the aegis of provincial



transportation ministries and local municipalities. The Ministry of Transportation in Ontario, for example, maintains a set of bridge construction standards and specifications designed to maximize bridge life, as well as standard corrosion protection policy requirements for the optimal use of materials, testing, inspection, and other quality control and safety processes for bridge construction and rehabilitation. (See Case Study: "*Bridge Coating Operation and Maintenance Planning.*")

IMPACT Canada Study analysts found two areas of strength among Canadian companies practicing corrosion management within the Transportation sector: *CMP Integration* and *Performance Measures*. Throughout the lifecycle of asset preservation, researchers noted that within the domain of *CMP Integration*, survey participants feel that their corrosion management processes are well-communicated. Moreover, participants also included risk management as one of their corrosion management processes, a notable strength. As regards *Performance Measures*, participants excelled in that their corrosion management systems resulted in the lowest corrosion cost over the intended life of the asset. These companies also excelled in the monitoring and reporting of their corrosion management performance.

"When our study team compared Canadian companies with global participants in the 2016 NACE IMPACT Study, the Canadian Transportation sector scored higher in the *Performance Measures* domain, specifically with respect to how systems translate into the lowest corrosion cost, the monitoring and reporting of corrosion management performance, and the organizational tracking of performance measures," Hernandez explained.

Transportation sector participants revealed that the domains in which they had room for significant improvement included *Resources*, *Continuous Improvement*, *Organization*, and *Accountability*. "When measured against their global Transportation sector counterparts, Canadian participants were especially challenged in all management system elements of corrosion prevention at the design stage of asset preservation," noted Hernandez.

BY RUSSELL DRAPER, FRANCES WEE, AND MEKDAM NIMA (STANTEC CONSULTING LTD.)

BRIDGE COATING OPERATION AND MAINTENANCE PLANNING[1]

A bridge coating operation and maintenance manual was developed for the City of Vancouver in 2016. The maintenance manual provides guidance to Vancouver's operations personnel to support consistent work standards, encourage use of industry best practices, and track work accomplishment. As such, the manual contributes to the optimal use of Vancouver's resources. Vancouver's coatings maintenance manual offers a superlative example of how other municipalities can improve their corrosion management systems, according to the recommendations set forth in the Corrosion Management System pyramid provided at the end of this case study.

The City of Vancouver's (City) inventory of structures lists 33 vehicular and pedestrian bridges that contain coated steel elements. Included in the inventory are three major steel structures, including Granville St. Bridge, Burrard St. Bridge, and Grandview Viaduct. These structures were constructed circa 1954, 1932, and 1938 respectively. The City has employed in-house bridge crews to complete ongoing maintenance painting for structures within their inventory. However, due to limited operations staffing, the City typically performs minor maintenance painting only, with larger repairs requiring contractor services. In 2016, the City retained the services of a consultant to develop a coatings operations and maintenance manual for its bridge inventory.

The City engaged coating specialists to assess the condition of the coatings on the three major steel structures. They determined that the steel substrate is covered with mill scale and the existing coatings may contain lead. They also found that in-house maintenance crews performed spot repainting and overcoating. Previous maintenance painting practices have been largely successful and have prevented steel section loss over the many years the bridges have been in service. However, because of many overcoating cycles, the existing coating on some of the bridges is excessively thick, brittle, peeling, and flaking, making it unsuitable for overcoating.

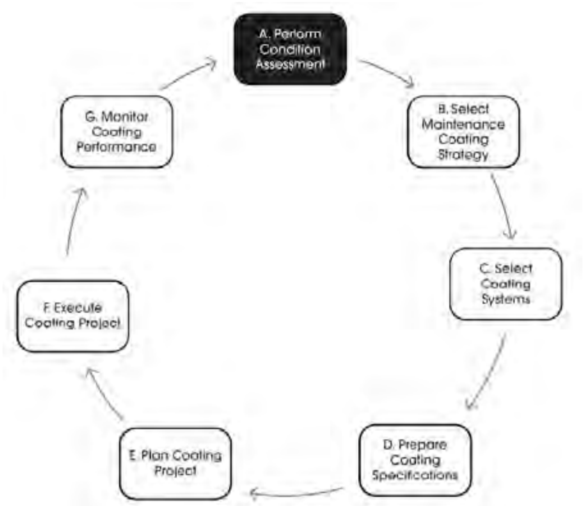
In light of these and other findings, a city wide, bridge coating maintenance plan was developed, supplemented by individualized plans for each of the City's three major bridge structures. The plan was intended to achieve the following objectives: structural integrity of bridge elements; safety and serviceability; regulatory compliance; preservation of aesthetic requirements; and the optimization of maintenance budgets. The plan outlined the consequences of uncontrolled corrosion and the primary and secondary objectives driving regular coating maintenance.

The plan addressed the major phases in a coating maintenance program. As shown in Figure 1, a cyclic program was envisioned. Data generated by periodic coating condition monitoring is used to decide when to perform a detailed condition assessment. Results and recommendations of this assessment become inputs into the subsequent phases of identification, preparation, and execution of planned maintenance work.

Each of the major stages of the bridge coating maintenance program, shown in Figure 1, was broken down into several activities, described below:

Coating condition assessments are required to determine the extent of coating failure and corrosion. The bridges, or elements to be assessed, can be selected by referring to the City's bridge coating database, developed as part of the bridge coating manual. This database contains summarized information about the coating extent and condition based on previous inspections. Also, available as a reference, are the structure nomenclature sketches developed for each bridge that identify coated sub-components along the bridge. Minor bridges or

FIGURE 1. *Major Stages in Coating Maintenance*



small elements, such as railings, can be assessed by means of a brief visual survey. A thorough detailed assessment is required for major bridges. (Further detail about coating condition assessments is provided in the original NACE International paper.[1])

In selecting a **maintenance coating strategy**, the manual recommends the user consider selecting one of five coating strategies: a) no maintenance, b) spot repair only, c) spot repair and overcoating, d) complete recoat, and e) zone painting. The selection of a strategy will depend on the objectives of the coating program, structural condition, coating condition, budgets, presence of lead-containing paints, and other relevant factors. A maintenance coating strategy decision tree is explored in detail, as well as how to address lead-containing paints and coatings. Once a coating strategy has been selected, the next step is to select the coating systems to use. A list of recommended bridge coating systems based on the BC MoTI Recognized Product List is included in the manual, along with a coating system selection procedure.

The coating maintenance manual also contains guidance on how to prepare a coating project or job specification. Bridge maintenance coating procedures are also included. In addition, the manual contains guidance on how to plan and execute a coating project, including typical requirements for equipment, worker training, procurement, quality management, occupational health and safety, environmental management, and records. Important guidelines on the procedures for monitoring each bridge's coating systems' performance are also outlined in the manual, and include the parameters that are rated during monitoring over the short- and long-term.

An **Environmental Management Plan** was developed to address the potential environmental considerations that may arise during coating maintenance works. The plan's purpose is to allow the City to conduct Project activities in an environmentally responsible manner by mitigating or eliminating identified environmental effects. The plan also discusses environmental regulatory permit processes and requirements. Several bridges in the City's inventory are located in unique environmental areas, including some river and coastal areas. Environmental concerns for freshwater fish and fish habitats, marine fish and their habitats, and marine birds are explored, and the appropriate regulatory requirements and recommended protection measures are defined.

An **Occupational Health and Safety** risk assessment and exposure control plan was prepared to address known hazards due to guano- and lead-containing coatings during coating removal, surface preparation, and waste management operations. By identifying, assessing and providing control measures for these occupational hazards, the City will be equipped to plan and execute bridge coating maintenance work in compliance with current health and safety regulatory requirements. The safety plan considers the protection of the workers and the public.

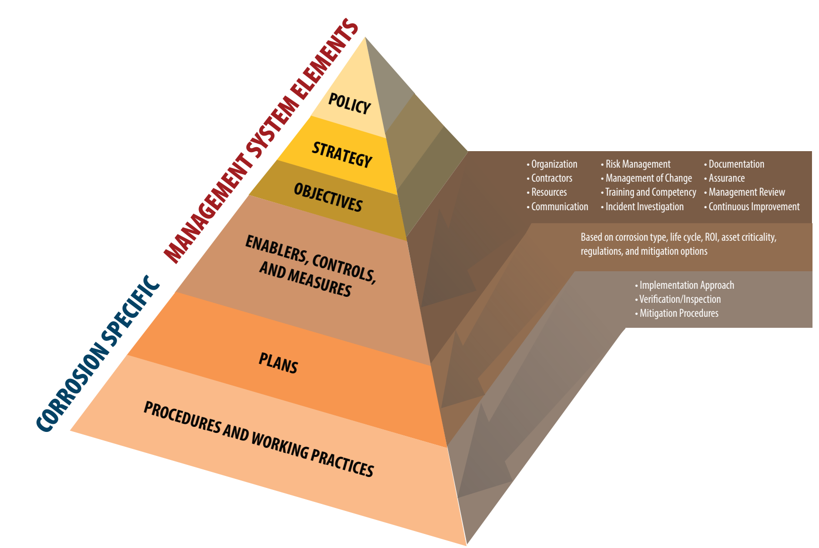
The **bridge coating inventory** was updated to summarize key coating information pertinent to each bridge structure in the inventory based on the as-built drawings, inspection reports, and other coating assessment reports provided by the City. It contains general information on the structure configuration, current coating type and condition, and associated inspection and maintenance items. The preliminary coating system

recommendations and maintenance coating planning documents that form this Bridge Coating Operation and Maintenance Plan are based on the inventory information above. This inventory is intended to be maintained continuously to update any obsolete information and add new information based on recently completed inspections. This will provide the City with an accurate snapshot of the current state of its inventory, and facilitate planning for future maintenance and operation activities.

DISCUSSION AND CONCLUSIONS

There are multiple elements to a bridge coating maintenance system, covering a wide range of topics, including structural integrity, traffic management, coating and corrosion related technologies, work planning, budgeting and tracking, worker training, and environmental, health, and safety considerations. The coatings maintenance manual brings these elements together into a single integrated set of documents. The manual fulfills many of the recommendations contained in the 2016 NACE IMPACT study[2] for a corrosion management system. However, the study states that realizing the maximum benefit in reducing corrosion costs (both direct and consequential) requires that the documentation must be viewed within the context of the broader organizational management system, illustrated in Figure 2.

FIGURE 2. *Hierarchy of Elements of a Corrosion Maintenance Management System[2]*



The initial response to the manual from City personnel involved in its development has been positive. A two-day training workshop was also developed and presented to the bridge crew to familiarize personnel with the procedures and working practices. The feedback subsequently received resulted in a manual tailored to fit the City's resources and capabilities, while meeting the objectives of a viable coating maintenance program. The next stage of this process will require the City to integrate the information contained in this manual into standard operating procedures.

This case study is an edited excerpt of longer article (cited below) that was presented at the NACE CORROSION Conference in 2018.

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SUSTAINABILITY

"CANADIAN BUSINESSES SUGGESTED THAT THEIR CORROSION MANAGEMENT PROCESSES WOULD GREATLY BENEFIT FROM MORE ROBUST SUSTAINABILITY POLICIES AND STRATEGIES AT ALL ORGANIZATIONAL LEVELS AND THROUGHOUT AN ASSET'S LIFECYCLE."

Canadian industry thought leaders behind the IMPACT Canada study have emphasized that a strong corrosion management system should include a commitment to material sustainability and material stewardship. *Material Sustainability* refers to "the way materials are sourced, processed, manufactured into products, and maintained through the product lifecycle and redirected at their end of life," said A.I. (Sandy) Williamson in "Building a Corrosion Management System through Material Sustainability and Material Stewardship."[xiii] *Material Stewardship* is the practice of "managing the flow of materials into society to improve its sustainability by mitigating environmental, economic, and societal impacts and maximizing its efficiency and durability." Municipalities and industries that embrace material stewardship "investigate the maintenance and preservation of a material during . . . its design, product ownership, and reuse (through remanufacture, reuse, or recycling)." (See Appendix C for Williamson's complete article.)

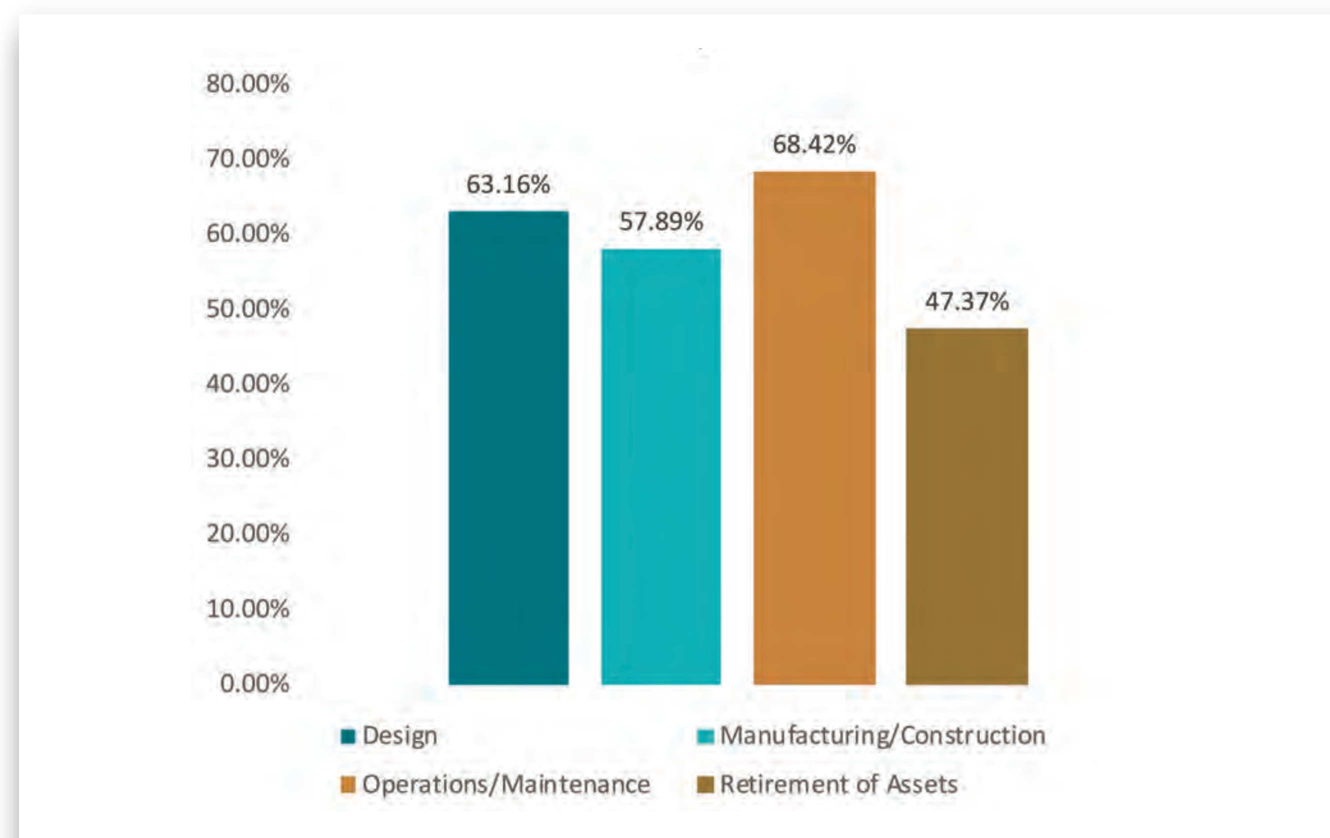
To help organizations strengthen their commitment to both practices, strategists have proposed that they discard the traditional economic model that pursues a "take, make, use, and waste" business process in favour of a "circular model" in which products and materials are used productively "for as long as possible, [suggesting that] "when they reach the end of their use, they are effectively cycled back into the system," Williamson explained. (See Appendix C.)

In their survey of participants for the IMPACT Canada Study, analysts included 10 questions designed to measure a company's commitment to *Material Sustainability* policy and planning. Table 2 shows that close to 70 percent of study participants considered *Material Sustainability* during the operations and maintenance phase of asset preservation, a noteworthy strength. "The fact that more than 60 percent of participants considered Sustainability during an asset's design phase is also quite commendable," said Hernandez. "During the process of retiring assets, however, Canadian companies are somewhat challenged, because fewer than 48 percent cite this domain as a corrosion management priority."

The study team found that Canadian participants excelled at promoting *Sustainability* during the design phase of an asset's lifecycle—more than 60 percent of those surveyed reported that they either "*frequently* or *always*" or "*sometimes*" promoted *Sustainability* during this phase. More than 70 percent of participants reported that material sustainability practices included the design for economics and cost effectiveness—another indicator of strength across this domain. In addition, whereas a larger percentage of participants said they had no process for communicating the importance of *Sustainability* externally, an impressive majority of those surveyed (over 59 percent across three discrete areas of concern) promoted *Sustainability's* importance internally.

"Notwithstanding these strengths, Canadian businesses suggested that their corrosion management processes would greatly benefit from more robust *Sustainability* policies and strategies at all organizational levels and throughout an asset's lifecycle," said Hernandez.

TABLE 2. *Material Sustainability Considered Across Four Lifecycle Stages*



IMPACT CANADA STUDY IMPLICATIONS: STRATEGIES FOR EFFECTIVE CORROSION MANAGEMENT

Throughout the IMPACT Canada self-assessment survey, participants displayed a keen awareness of how their companies excelled and fell short of an ideal vision for managing corrosion across the asset lifecycle. However, Canada has persisted in embracing a host of strategies to strengthen corrosion management and corrosion prevention awareness through strong regulations, standards creation, and university training for practitioners.

Under Canada's strong pipeline regulatory regime, Canada's 98 pipeline companies are regulated by an independent federal agency, known as the National Energy Board, which ensures that cross-border pipelines meet strict requirements to keep Canadians and the environment safe. Pipelines and equipment regulated by the National Energy Board are required to meet specifications set forth by the Canadian Standards Association. *CSA Standard Z662 – Oil and Gas Pipeline Systems* includes technical standards for the design, construction, operation, maintenance, and decommissioning of Canada's oil and gas pipelines.

Standards are promulgated throughout Canada's federal and provincial sectors through rules and regulations governing the nation's building codes and safety requirements for the aviation and transport industries, as well as a vast infrastructure of roads, bridges, railroads, pipelines, and water and wastewater systems.

Canadian standards organizations are working to keep pace with the demand for new standards based on evolving best corrosion prevention practices. In December 2019, the National Research Council (NRC) published updates to 27 specification sections of the National Masters Specification (NMS)—the primary resource for writing project specifications for construction work by the Government of Canada. The NMS is used for all large federal government projects, as well as by other levels of government, and remains a key resource for private sector specifications.

"The results of the IMPACT Canada survey suggest that all participating industry sectors can improve in their adoption of new corrosion-related standards based on leading-edge practices," Hernandez said. Compared to Australia, New Zealand, and Europe, Canadian municipalities have been slow to embrace or adopt certain ISO (International Organization for Standardization) standards such as ISO 55000, which provides an overview of asset management, its principles and terminology, and the expected benefits from adopting asset management.

In Canada there is more work to do to tackle the challenge of ensuring that pressure vessel and piping equipment used in oil and gas refining, chemical processing, and other industries is regulated in a standardized way at the federal level. Provincial authorities such as ABSA (Alberta Boilers Safety Association), for example, are empowered to administer and enforce Alberta's pressure equipment safety programs under the law. However, if an operator owns assets in Alberta and other provinces, it must comply with divergent regulatory requirements set forth in each province.

Business leaders across Canada, the United States, Europe, and India recognize the importance of creating a pool of certified corrosion engineers to assist industry in tackling corrosion. In general, Canada is already poised to provide systems that allow for the education, training, and certification of subject matter experts, technicians, and professionally trained workers who maintain asset integrity. In addition, both Canada and the U.S. benefit significantly from societies who educate craft workers under the employment of contractors, who, in turn, are committed to training such workers as part of their own mission and culture.

Canadian universities and colleges have partnered with corrosion experts to incorporate strong theoretical and practical curricula in chemistry, material engineering, mechanical engineering, civil engineering, and aerospace engineering, disciplines that provide the fundamentals of corrosion management expertise for future generations. Materials engineering programs for undergraduates exist at the University of Alberta, University of Calgary, University of British Columbia, and University of Regina. In particular, the University of Calgary actively partners with industry experts for Pipeline Engineering course curricula content, and it plans to rely on these experts to expand its integrity management content in 2012. Other robust programs can be found at the University of Toronto, Western Ontario University, McMaster University, University of Ottawa, Laval University, McGill University, and University of Manitoba.

Notable government-industry partnerships that advance cathodic protection (CP) training include the Government of Alberta's Apprentice and Industry Training program, which allows NACE-certified CP technicians of all levels to receive an Alberta Occupational Certificate.

Advancing corrosion training through Canada's educational network has helped—and will continue to help—companies integrate CMS frameworks within their organizations. Most important, thought leaders should continue to maximize their exposure to technical societies such as AMPP, IUPAT, and NACE International Northern Area, who excel at raising global awareness of corrosion through annual conferences, technical symposia, certification and training programs, reports, and papers.

Shifting the Culture: A Company-Centric Strategy for Successful Corrosion Management

As discussed at the outset, when asset owners adopt a corrosion management system framework, Canadian business leaders with budget authority are free to directly compare corrosion control measures with all kinds of expenditures. They can maximize the potential of an ROI based upon a reduction of consequential expenses arising from the failure to protect personnel or public safety, the environment, or the integrity of their assets.

The culture of corrosion management must be accepted as the norm in the way that the safety management culture has been adopted within the oil and gas and refining and petrochemical industries. Just as all levels of myriad corporations now have

TABLE 3. *Different Purposes for the Buy-In of a Corrosion Management System*

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 same goal to improve both occupational and process safety, all Canadian companies should embrace the goal of embracing the corrosion management model at every organizational level. 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. Such a shift necessitates a cultural change that must flow from the top to the bottom. Policymakers and regulators must set forth the expectations that would guide this cultural shift.

Companies throughout Canada are poised to reduce their corrosion costs by integrating a corrosion management system that embraces corrosion-specific procedures and practices as well as organizational policy and strategy— that is, at all levels of the CMS Pyramid. (See the Corrosion Management System pyramid on page 9 of this report.)

It is essential to Canada's companies 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. Put simply, the corrosion practices need to be translated into the language of the broader organization. The business as a whole must commit to ownership of the CMS activities and processes at all levels of the company. Table 3 outlines some purposes given for commitment toward a Corrosion Management System at different levels within an organization. (See Appendices A and B for further guidance.)

NACE IMPACT PLUS is a useful instrument that provides tools and examples to help companies in Canada facilitate communication between corrosion professionals and senior management. One of these tools is an audit system that helps accounting departments reduce corrosion costs. IMPACT PLUS can help decision makers build a corrosion management system and integrate it throughout the organization's existing management system. Using IMPACT PLUS, companies can develop a business case that clearly states 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 the decrease in risk (i.e., environmental, safety, business interruption, public relations, etc.). Without buy-in from the top, initiatives have little chance of getting off the ground.

Financial Tools for Managing Corrosion Across Canada's Businesses

Corrosion management includes all activities that are performed through the lifetime of a structure to prevent corrosion, repair its damage, and replace the asset itself. Specifically, these include maintenance, inspection, repair, and removal. Maintenance is considered a regular activity, characterized by annual cost. Inspections are scheduled as periodic activities, and repair is done as warranted. Rehabilitation may be carried out once or twice during the structure's lifetime, and the cost is usually high. Applying different corrosion management methods may positively affect the lifetime of a structure without increasing the cost. (See Appendix F for more detail.)

So that a company can meet its corrosion management objectives, there are methodologies available for calculating the cost of corrosion over all or part of an asset's lifetime. These methods include assessing cost-adding methodology, life-cycle costing, ROI, constraint optimization, maintenance optimization, and lifecycle costing. (See Appendix F for more detail.)

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AMPP

IMPACT PLUS

LIST OF APPENDICES

APPENDIX A

CORROSION MANAGEMENT SYSTEM FRAMEWORK

A Corrosion Management System (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 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 a return on investment (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 ALARP (As Low As Reasonably Practicable).

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 defence 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 Figure 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.

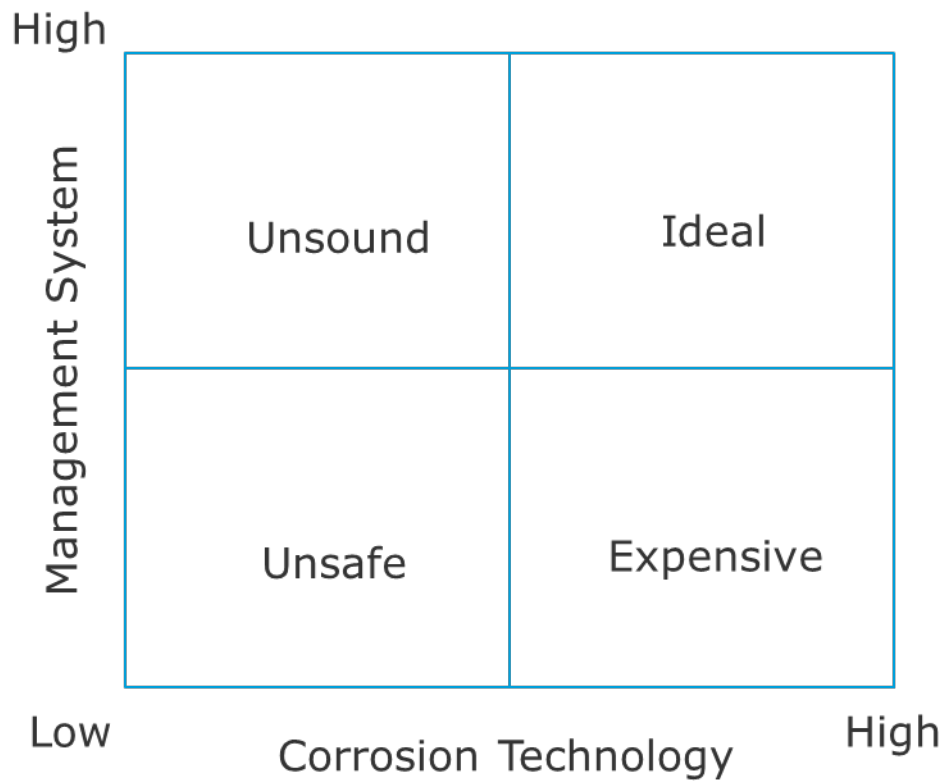

Figure 1. A Two-by-Two Matrix Illustrating the Benefit of Combining Sound Corrosion Technology with a Mature Management System

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.

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 stand-alone 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 2 illustrates the inter-relation 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 stand-alone CMS. The applicable standards and recommended practices, which apply to the various management systems, are included in parentheses in the diagram.

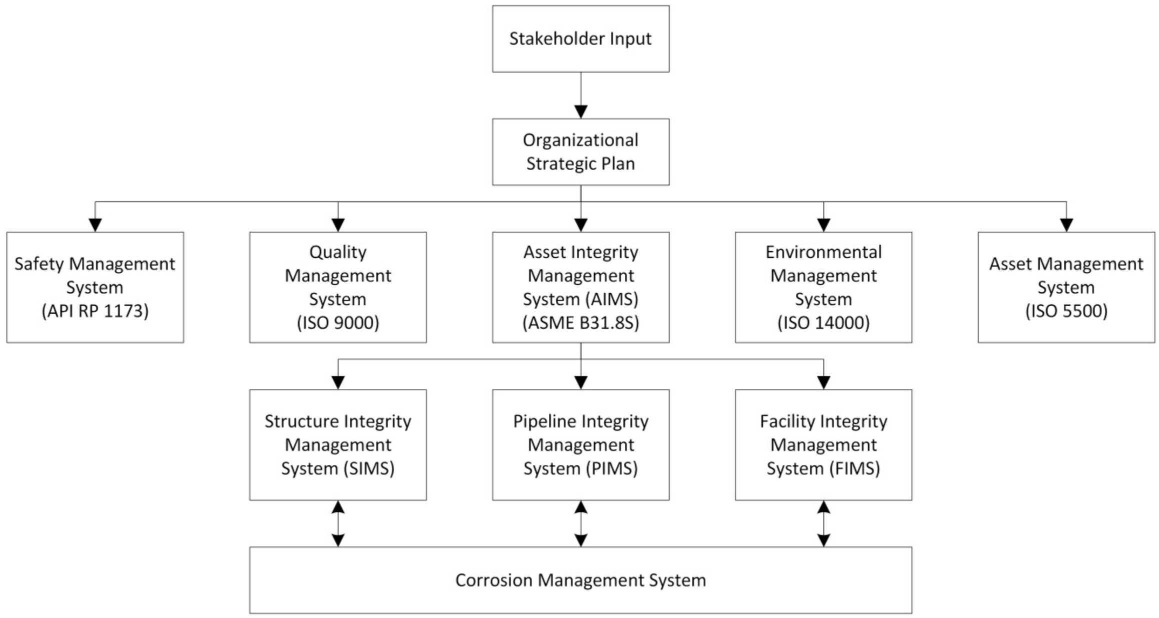

Figure 2. Inter-relation of Organizational Management Systems - Pipeline Example

Figure 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.

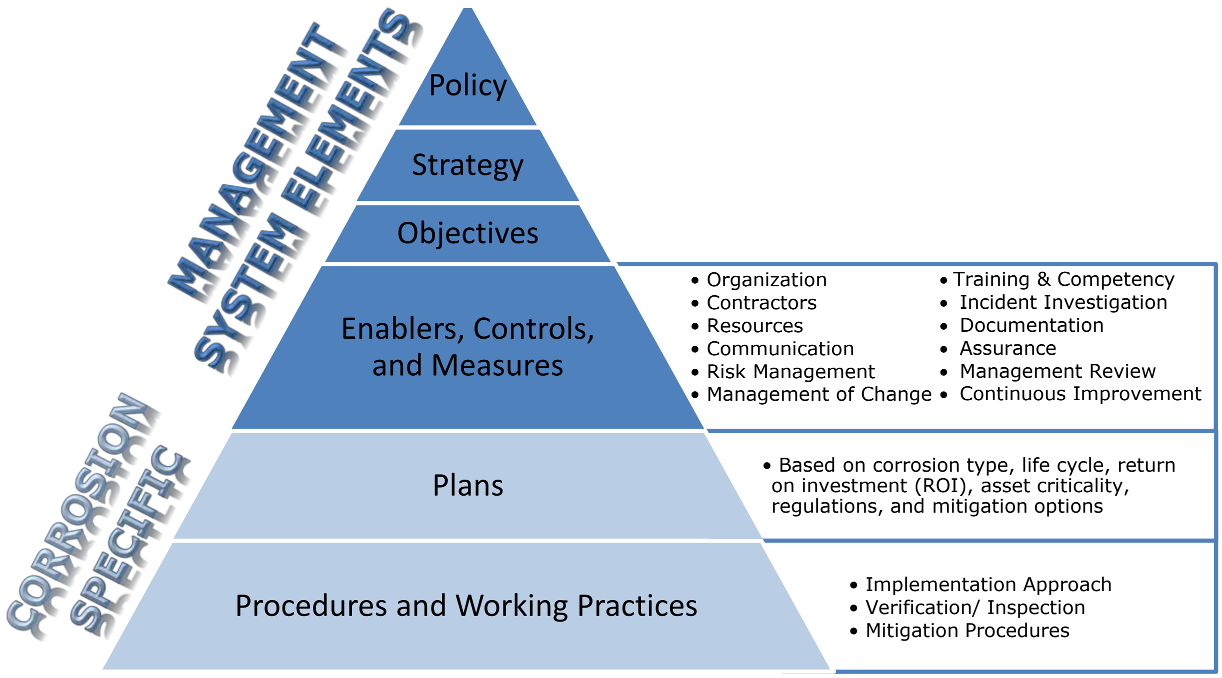

Figure 3. Hierarchy of General and Corrosion Specific Management Elements

Figure 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 0. 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 corrosion management system 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.

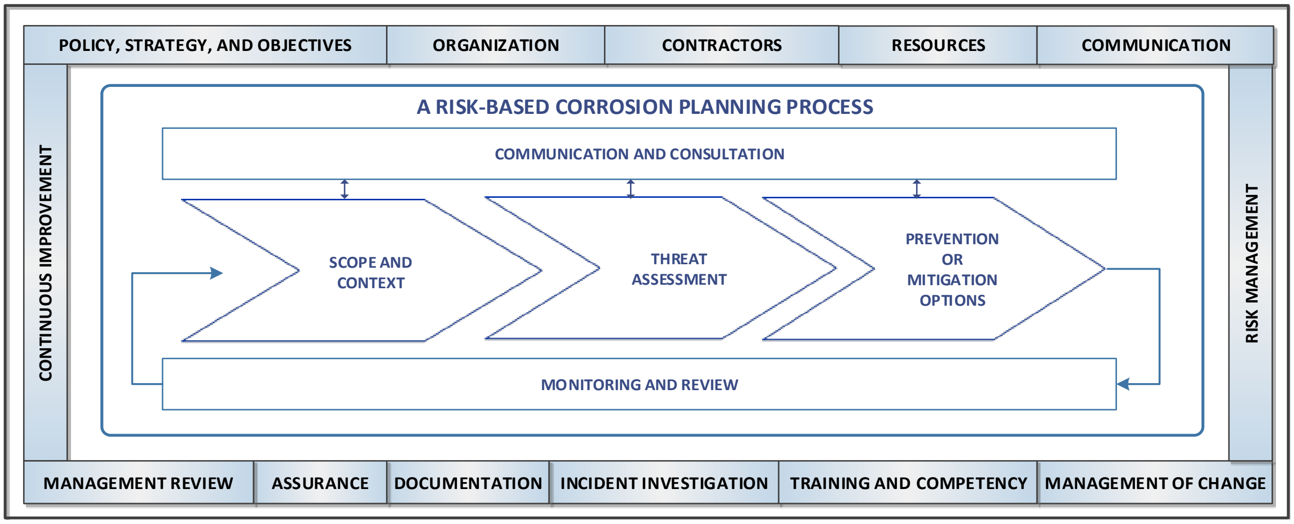

Figure 4. CMS Framework (Based on ISO 31000)

- 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.
- The return on investment (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), 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 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.

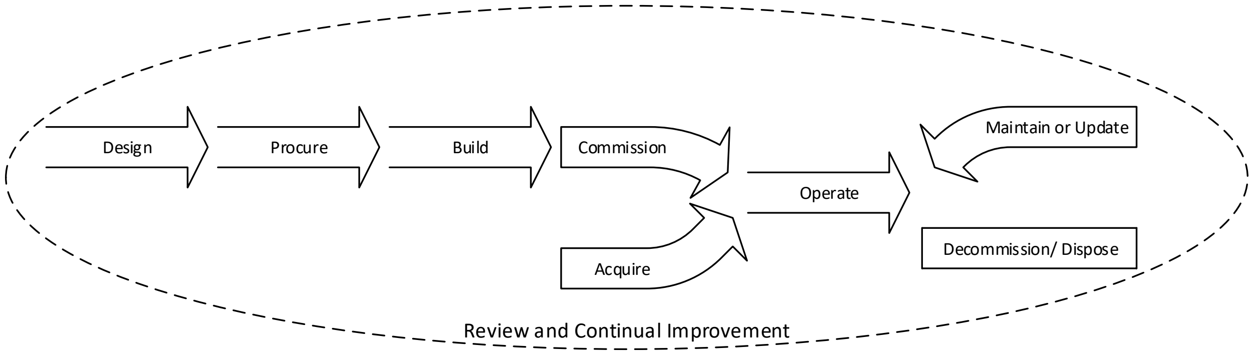

Figure 5. Corrosion Management over the Life Cycle of the Asset

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.

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 stand-alone 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 commitment of upper management. A National Oil Company participant in one of the Middle East focus group meetings 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 says:

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

Enablers, Controls, and Measures

Organization

An optimized CMS requires defined and documented role 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.

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 as 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) – roll out to facilities and contractors is not being done."*

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 system and processes.

Allocation of appropriate resources to deliver programs, which are consistent with the CMS, must be ensured. This is accomplished by allocating proper budgets, by setting achievable staffing levels, and by 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."*

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 National Oil Company:

> *"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."*

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 of 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 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 result of this corrosion mechanism needs 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. The 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.

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.

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 have indeed 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."*
>
> *"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 National Oil Company:

> *"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 favour 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 with senior staff leaving the company. 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 been in the business for 30 years. There's no one being trained to replace me, and I am concerned about that."*

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.

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.

Assurance

The corrosion management plans 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.

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.

Continuous Improvement

In addition to formal processes which 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.

Implementation of the CMS Framework

The previous sections describe the general approach towards 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 stand-alone 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.

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, 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 SCC, 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).

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.

APPENDIX B

CORROSION MANAGEMENT SYSTEM FRAMEWORK AND GUIDANCE

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 detail 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 non-compliances 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.

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.

TERMS AND DEFINITIONS

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

1. <u>Audit</u> - 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 is fulfilled.
2. <u>Corrective Measure</u> – an action taken to respond to the corrosion situation thereby limiting adverse consequences (i.e., actions taken to rectify an existing situation).
3. <u>Inspection</u> - 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-fulfilment 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.

ABBREVIATIONS

CMS	Corrosion management system
MOC	Management of change
AMPP	Association for Materials Protection and Performance, formerly NACE International

GENERAL

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.

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 0, below.

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.

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 1 for a selection of the CMS and asset-level processes. This table is not all-inclusive.

Table 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 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.*

	<u>Learning from Events</u>:
	• *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*

	<u>Monitoring and Measurement</u>: • *Define, document, and track performance indicators for the written CMS and associated critical activities.*

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.

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.*

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 the Section titled "Continual Improvement," 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.

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 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.*

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.*

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 the Section titled “Management of Change,” above, 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.

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 meet or exceed 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.*

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.

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.

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.

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.

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.

Organization

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 the Section titled "Human Resources," below.

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.

Management Review of CMS

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.

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.*

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.

RESOURCE MANAGEMENT

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.

Human Resources

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.

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.

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.*

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.*
- *Labour/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 labour.*
- *Access to emergency response resources (medical, fire, hazardous material release, etc.).*
- *Security of asset, materials, and equipment against theft and damage.*

CMS ASSET IMPLEMENTATION

This section 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 corrosion management plans 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.

Life Cycle Considerations

The organization shall establish, implement, and maintain processes and procedures for the implementation of its corrosion management plans 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.

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.

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.

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 corrosion management plan 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 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 ground beds* • *Installation of CP cables with damaged electrical insulation* • *Creation of stray current interference due to improper anode ground bed 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 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.*

CONTINUAL IMPROVEMENT

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 analysing 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.*

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.

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 analysed 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.

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 understands 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.

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 0, above.

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.

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.

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.

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.

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.

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 0 above for details regarding the requirements for MOC.

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 that 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

BUILDING A CORROSION MANAGEMENT SYSTEM THROUGH MATERIAL SUSTAINABILITY AND MATERIAL STEWARDSHIP

By A.I. (Sandy) Williamson, P.Eng., Williamson Integrity Services Ltd.

Introduction

In 2016 the former NACE International (now the Association for Materials Protection and Performance or AMPP) released the IMPACT Study[1] which underlined the importance of a properly designed Corrosion Management system for organizations. The study also estimated that the annual global cost of corrosion was around 2.5 trillion USD, but more importantly showed that between 15 and 35% of this cost could be saved through properly applying current corrosion mitigation and technology. Since the release of the IMPACT Study, the IMPACT PLUS program has been used by a number of organizations to improve their Corrosion Management systems.

A well designed and implemented Corrosion Management system is and should be a key part of an organization’s sustainable business practices. Within AMPP, Technical Exchange Group (TEG) 531X was formed three years ago to discuss the concepts of Material Sustainability and Material Stewardship, including how these concepts related to Corrosion Management. A number of presentations regarding Material Sustainability and Material Stewardship have since been made at annual and regional conferences. More recently, the AMPP Board of Directors has incorporated these concepts as part of their current 3-year Strategic Plan for the Association.

This article illustrates how Corrosion Management, Material Sustainability, and Material Stewardship principles can be incorporated into an organization’s strategic plan. When successfully adopted such a strategic plan can lead to not only a more profitable organization but also an organization that better uses the earth’s resources and ultimately reduces the impact of greenhouse gas emissions on the earth’s climate.

WHAT IS A CORROSION MANAGEMENT SYSTEM?

A Corrosion Management system is a means of improving the implementation of corrosion control knowledge and tools within an organization. Furthermore, effective Corrosion Management has been shown to contribute to:

- Extension of asset operating life
- Reduction of risks to society and the environment
- Improved efficiency and effectiveness of corrosion control efforts

The IMPACT PLUS Corrosion Management Maturity Model, which is used to assess an organization’s Corrosion Management system provides:

- A platform for corrosion management professionals who desire to move their company to higher levels of performance
- A common language and structure needed to ensure communication throughout all levels of an organization
- An easy way for organizations to identify gaps in processes that could lead to the reduced lifecycle of assets
- A foundation to an organization's goals for a more sustainable approach to Corrosion Management

The IMPACT PLUS program is administered by AMPP, who have certified "navigators" to work with organizations in implementing the program.

WHAT IS MATERIAL SUSTAINABILITY?

Sustainability has a broad definition and can therefore mean different things to different people. In 1987, The United Nations Brundtland Commission Report defined Sustainability as *"Development that meets the needs of the present without compromising the ability of future generations to meet their own needs."* The United Nations developed 17 Sustainable Development Goals (SDGs) in 2015 as a blueprint to achieve a better and more sustainable future for all. The role of the corrosion professional in contributing towards the UN SDGs was studied and presented in 2020.[2]

Figure 1. World production of several industrially critical materials as estimated from United States Geological Survey data

Material Sustainability can be defined as the way materials are sourced, processed, manufactured into products, and maintained through the product lifecycle and redirected at their end of life. Current production and consumption models globally are unsustainable. (See Figure 1.) Total demand for limited resource stocks could reach 400 per cent of the Earth's total capacity by 2050. Meanwhile, the safe boundaries for four of the nine key ecological processes and systems that regulate the stability and resilience of the Earth system have already been exceeded. The corresponding economic impacts of these current trends will be severe, with global price volatilities and supply chain interruptions leading to as much as US$4.5 trillion in lost global economic growth by 2030, or US$25 trillion by 2050.

Predictions of materials' supply constraints using reserve to demand ratios suggest that, within decades, we will be running up against planetary boundaries for several materials of industrial importance such as nickel, copper, and precious metals. Material Stewardship strategies in the 21st century should focus on decreasing this pace of consumption through the 4D strategies outlined in the next section.

WHAT IS MATERIAL STEWARDSHIP?

Material Stewardship is concerned with managing the flow of materials into society to improve its sustainability by mitigating environmental, economic, and societal impacts and maximizing its efficiency and durability.

In more detail, Material Stewardship investigates the maintenance and preservation of a material during its life span, including design, product ownership, and second life use (remanufacture, reuse, recycle).

Four key strategies have been defined to pursue Material Stewardship in what is known as the 4 D's approach[3]:

1. Dematerialization
2. Durability
3. Design for multiple lifecycles
4. Diversion of waste streams through industrial symbiosis

Material Stewardship provides corporations, government organizations, and their stakeholders a model for preserving and extending the lifetime of materials, thus reducing the rate of materials throughput, cutting waste, and preventing the social, environmental, and economic costs due to materials failure.

An example of material stewardship where waste streams are diverted can be illustrated by a process developed by the Canadian company Enerkem[4]. Enerkem manufactures biofuels and renewable chemical products from non-recyclable waste. Their process initially tested and validated several different feedstocks from solid waste coming from several municipalities to dozens of other types of residues. Their technology was then scaled up from pilot to demonstration to commercial-stage over 10 years.

The Enerkem Alberta Biofuels plant in Edmonton, Alberta, is currently taking household waste and producing biomethanol and cellulosic ethanol. The plant has a 25-year agreement with the City of Edmonton for 100,000 dry tonnes of waste per year. Enerkem announced in 2020 that it will be building a $875 million biofuel plant in Varennes, Quebec. This plant will be capable of converting over 200,000 tonnes of non-recyclable waste and wood waste into an annual production of nearly 125 million litres of biofuels. It has been estimated that the plant's contribution to greenhouse gas reduction is equivalent to taking close to 50,000 vehicles off the road annually. Furthermore, the plant will use green hydrogen and oxygen produced through electrolysis, using excess hydroelectricity from Quebec's power grid.

THE LINEAR ECONOMY VS. THE CIRCULAR ECONOMY

A new economic system and business strategy has been proposed that moves industry from the traditional model that follows a "take, make, use, and waste" process into a circular model where products and materials are kept within productive use for as long as possible, and when they reach the end of their use, they are effectively cycled back into the system.

By using the same principles that exist within nature, where biological materials are used over and over, we can design better systems for the use of technical materials. (See Figure 2). Moving to a circular economy will not only support a more sustainable future but will help businesses identify new opportunities with innovative products and services while optimizing their operations and supply chains. Altogether adoption of more circular thinking will lead to more profitable and long-term businesses.

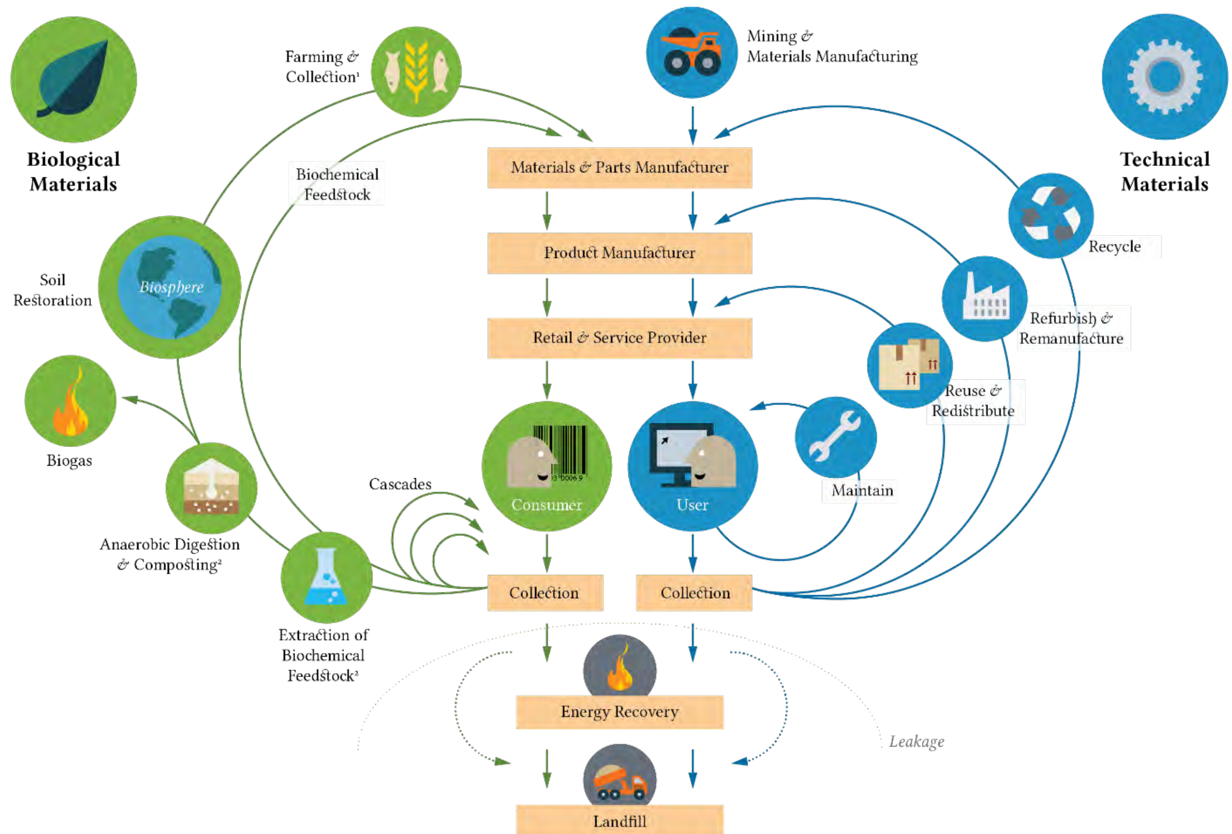

Figure 2. Circular Economy Systems Diagram (Source: Ellen MacArthur Foundation[5])

A number of areas requiring investigation for moving ahead with a circular approach are identified in the recently published Circular Economy Handbook[6]. The four areas are:

1. **Operations**: Addressing the value lost through Operations and by-products of business processes with respect to energy, emissions, water, and waste.
2. **Products and Services**: Rethinking the design, lifecycle, and end of use of a product or service to optimize its usage, eliminate waste, and close product loops.
3. **Culture and Organization**: Embedding circular principles into the fabric of an organization through redefined working practices, policies, and procedures.
4. **Ecosystem**: Collaborating and partnering with public and private sector actors to create and enabling environment for collective transformation. This includes examining the essential role of Investment and Policy.

The Circular Economy Handbook builds on a previous publication (2015), "Waste to Wealth"[7] where a $4.5 trillion opportunity was identified by simply redefining the concept of "waste" as a valuable resource. The following four categories of waste were identified:

1. **Wasted resources**: Use of materials and energy that cannot be effectively regenerated over time, such as fossil energy and non-recyclable material.
2. **Wasted capacity**: Products and assets that are not fully utilized throughout their useful life.
3. **Wasted lifecycles**: Products reaching end of use prematurely due to poor design or lack of second-use options.
4. **Wasted embedded value**: Components, material, and energy not recovered from waste streams.

Five business models (Circular Inputs, Sharing Platforms, Product as a Service, Product Use Extension, and Resource Recovery) were introduced by the authors in order to capture the value of redefining waste. A number of organizations have used these business models over the past five years in order to adopt a more circular approach. In order to help organizations transition from their current business to a more circular model, a number of learnings for particular industries have been included in the Circular Economy Handbook.

As one example, the objective of better product recovery can be illustrated by designing for end of use disassembly, refurbishment, and remanufacture. In addition, materials can be chosen that are recyclable or compostable at the end of use.

DEVELOPING A STRATEGIC PLAN FOR SUSTAINABILITY

The Natural Step Canada organization[8] has written a guidebook with the intent of helping organizations develop a strategic plan that embeds key sustainability principles within the plan. Based on input from experts, business professionals, and community leaders from across Canada and around the world, the guidebook provides the necessary tools and references to put together a strategic plan that considers the following four sustainability principles:

1. The organization will reduce and eventually eliminate its contribution to the systematic accumulation of materials from the earth's crust, by favoring:
    a. Energy efficiency and power from renewable sources
    b. Metals that are plentiful in nature e.g., aluminum and iron
    c. Reusable, recyclable, and recycled-content materials
2. The organization will reduce and eliminate its contribution to the systematic accumulation of substances produced by society, by favoring:
    a. Natural, biodegradable materials (glass, wood, cotton, water-based etc.)
    b. Materials that are managed in tight technical cycles
    c. Organically grown, untreated
    d. Reusable, recyclable, and recycled-content materials

3. The organization will reduce and eliminate its contribution to the ongoing physical degradation of nature by favoring:
    a. Materials from well-managed ecosystems
    b. Fast-growing crops (hemp, bamboo etc.)
    c. Use of previously developed lands
    d. Reusable, recyclable, and recycled-content materials
4. The organization will reduce and eliminate its contribution to conditions that systematically undermine people’s ability to meet their needs by favoring:
    a. Safe working and living conditions
    b. Inclusive and transparent decision making
    c. Affordable products and services, sufficient resources for livelihood
    d. Political freedom

While the above four sustainability principles guide an organization in moving in a more sustainable direction, it is important that the plan also provides a good return on investment for the organization. Each step or action of the plan should be evaluated for its strategic value.

A number of useful case studies are provided within the Natural Step guidebook. One of these case studies highlighted The Whistler 2020 team which was faced with the prospect of increasing energy usage resulting from the Whistler community growth and preparation for the 2010 Winter Olympic Games. The team worked with the local natural gas distributor, Terasen Gas, to come up with a plan that involved transitioning from propane to natural gas, which releases 15% less carbon dioxide than propane. Rather than using propane that arrived by truck or train, a natural gas pipeline was built to supply the community. Furthermore, the natural gas pipeline was seen by the team as only a temporary solution and an investment in the transition towards renewable energy. The renewable energy solution was to use ground source heating and cooling (geothermal) for new developments, including the 2010 Olympic Athletes’ Village.

The Whistler 2020 team worked with Terasen’s renewable energy division and came up with the following actions:

- The cost of the natural gas pipeline was reduced from $50 million to $30 million due to the reduction in throughput of the pipeline. The lower cost and shorter amortization period ensured that the Whistler community would not be locked into a certain form of energy for 50 years but would allow Whistler to transition to geothermal energy.
- Terasen and the Regional Municipality of Whistler (RMOW) explored the potential for geothermal heating and cooling for new developments, including the 2010 Olympic Athletes’ Village, as well as existing developments in the main village of Whistler.
- RMOW set up a new utility to provide district-based thermal energy.

- The rate target for the thermal energy was set to 10% below electricity rates to encourage usage in new developments.
- Other alternative energy technologies and fuels such as gas created through gasifying solid waste and landfill gas were explored.
- New infrastructure was encouraged to use geothermal heating for the future
- Natural gas is to be used where alternatives are not feasible and to provide fuel during heavy energy load periods when it is uneconomical to use ground source systems.

SUMMARY

The NACE IMPACT study has played a great role since its introduction in 2016 by showing the global importance of Corrosion Management across many industries and organizations. A well designed and implemented Corrosion Management System needs to incorporate Material Sustainability and Material Stewardship to become a key part of an organization's sustainable business practices and strategic plan. When successfully adopted such a strategic plan can lead to not only a more profitable organization but also an organization that sustainably uses the earth's resources and ultimately reduces the impact of greenhouse gas emissions on the earth's climate.
Associations like the Association for Materials Protection and Performance can help guide industries into a new era of sustainable policies and practices. Material Sustainability and Material Stewardship initiatives provide AMPP an opportunity to foster a technical society of forward-looking, proactive professionals equipped to support sustainability in tangible, meaningful ways through knowledge, standards, and vision for future generations.

Editor's Note: A version of this article originally appeared in in the June 2020 issue of Materials Performance*.*

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APPENDIX D

NACE CORROSION MANAGEMENT PRACTICES SURVEY 2020

INSTRUCTIONS

This survey is being conducted by APQC on behalf of NACE International, the Worldwide Corrosion Management Authority. The purpose of this survey is to gather corrosion management practice data across industries in Canada to better understand opportunities for improvement and cost reduction. The survey is structured into the following sections: participant demographics, followed by questions about the entire asset lifecycle (the heaviest question set), design, manufacturing and construction, operations and maintenance, retirement, and sustainability.

The survey may take some time to complete. Please take as much time as you need. You may save your responses by selecting 'File' then 'Save as' from the tool bar and come back to it another time.

If you do not know the answer to a question, please leave it blank. Please complete at least 70% of the survey, as a submission less than 70% complete is not usable for comparison purposes.

Do not forget to review the IMPACT survey terms & conditions and press the "SUBMIT" button in order to submit your completed, online response to APQC. Thank you for your participation!

If you have any questions about the survey, please do not hesitate to contact Monica Hernandez at monica@infinitygrowth.ca or 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, NACE Corrosion Management glossary. It will open in a separate web browser, allowing you to reference these definitions while you complete the survey. It is recommended you open the Glossary now.
NACE Corrosion Management Practices Survey
NACE Impact Survey

ORGANIZATION INFORMATION

Name

Corrosion Management Role

Phone

Email

Organization Name

Industry

What province is your organization located?

1 | 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

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

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

2 | 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
- ☐ Societal
- ☐ Design for manufacture/construction
- ☐ The intended life of the asset
- ☐ Functional requirements
- ☐ Other
- ☐ No asset design strategy exists

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

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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

3 | 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

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

4 | 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

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

5 | 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

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

6 | SUSTAINABILITY

77. Does your organization have a material sustainability policy?
- No
- Yes, for part of the asset lifecycle
- Yes, for part of the organization
- Yes, for the entire organization and asset lifecycle

78. Does your organization have a material sustainability strategy?
- No
- Yes, for part of the asset lifecycle
- Yes, for part of the organization
- Yes, for the entire organization and asset lifecycle

79. Is there an organizational understanding of material sustainability?
- There is no organizational understanding of corrosion management roles and responsibilities
- There is an understanding of corrosion management roles and responsibilities mostly in the corrosion management organization
- There is an understanding of corrosion management roles and responsibilities only locally
- There is an understanding of corrosion management roles and responsibilities across the organization (horizontally and vertically)

80. Does your organization's leadership take ownership and engage in material sustainability? (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

81. Is material sustainability considered during a) Design, b) Manufacturing and Construction, c) Operations and Maintenance, and d) Retirement of assets (check all that apply)?
- Design
- Manufacturing/Construction
- Operations/Maintenance
- Retirement of assets

82. How is material sustainability monitored, measured, and reported?
- Locally, by a corrosion technical professional
- Locally, by corrosion management and organizational management
- Within the general/corportate management organization
- At all management levels

83. Do communications within the organization promote the importance of material sustainability?
- 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

84. Do material sustainability practices include design for economics and 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

85. Are supplier/vendor material sustainability practices audited and overseen?
- Supplier/vendor corrosion practices are not audited and/or overseen
- Supplier/vendor corrosion practices are sometimes audited and/or overseen
- Supplier/vendor corrosion practices are frequently or always audited and/or overseen

86. Do you have a material sustainability plan for asset retirement?
- 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

87. 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

APPENDIX E

Case Studies of 1) A National Oil Company, 2) Pipeline Maintenance Optimization, 3) Use of Bayesian Networks for Corrosion under Insulation, and 4) Understanding the Total Cost of a Corrosion Issue in the Oil and Gas Industry

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 corrosion management program (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 Appendix A, Figure 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 Corrosion Management System Elements defined in Appendix A 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 1 shows general agreement of these six essential elements with those developed in the framework, see 0, with the exception of Resources and Communication. None of the elements in the Company's framework appears to address either Resources or Communication.

Table 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

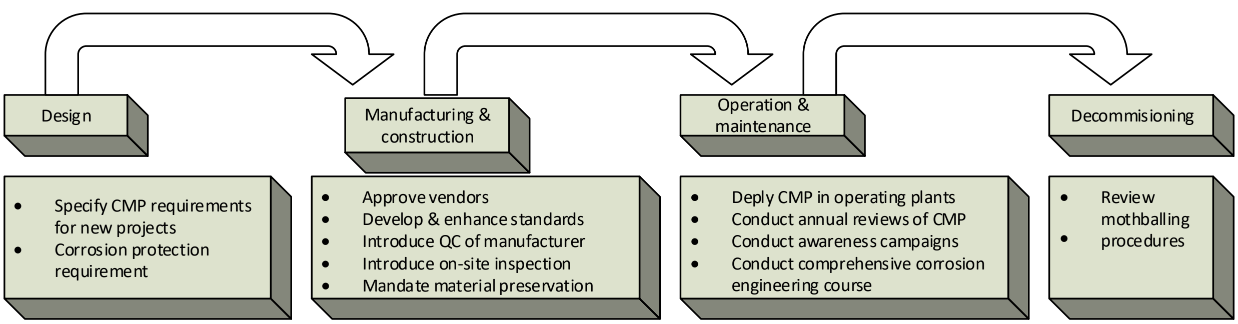


Figure 1. Corrosion Management Applied to an Asset's Life Cycle

Figure 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 database 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.

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:

$$
\begin{aligned}
CR(mpy) &= a + b(O_2) + c(O_2)^2 + d(pH) + e(CO_2)(H_2S) + f(CO_2)(O_2) + g(H_2S) \\
&+ h(H_2S)^2 + i(H_2S)(O_2) + j(O_2)(pH) + k(Cl) + l(CO_2) + m(CO_2)^2
\end{aligned}
$$

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

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

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 2.

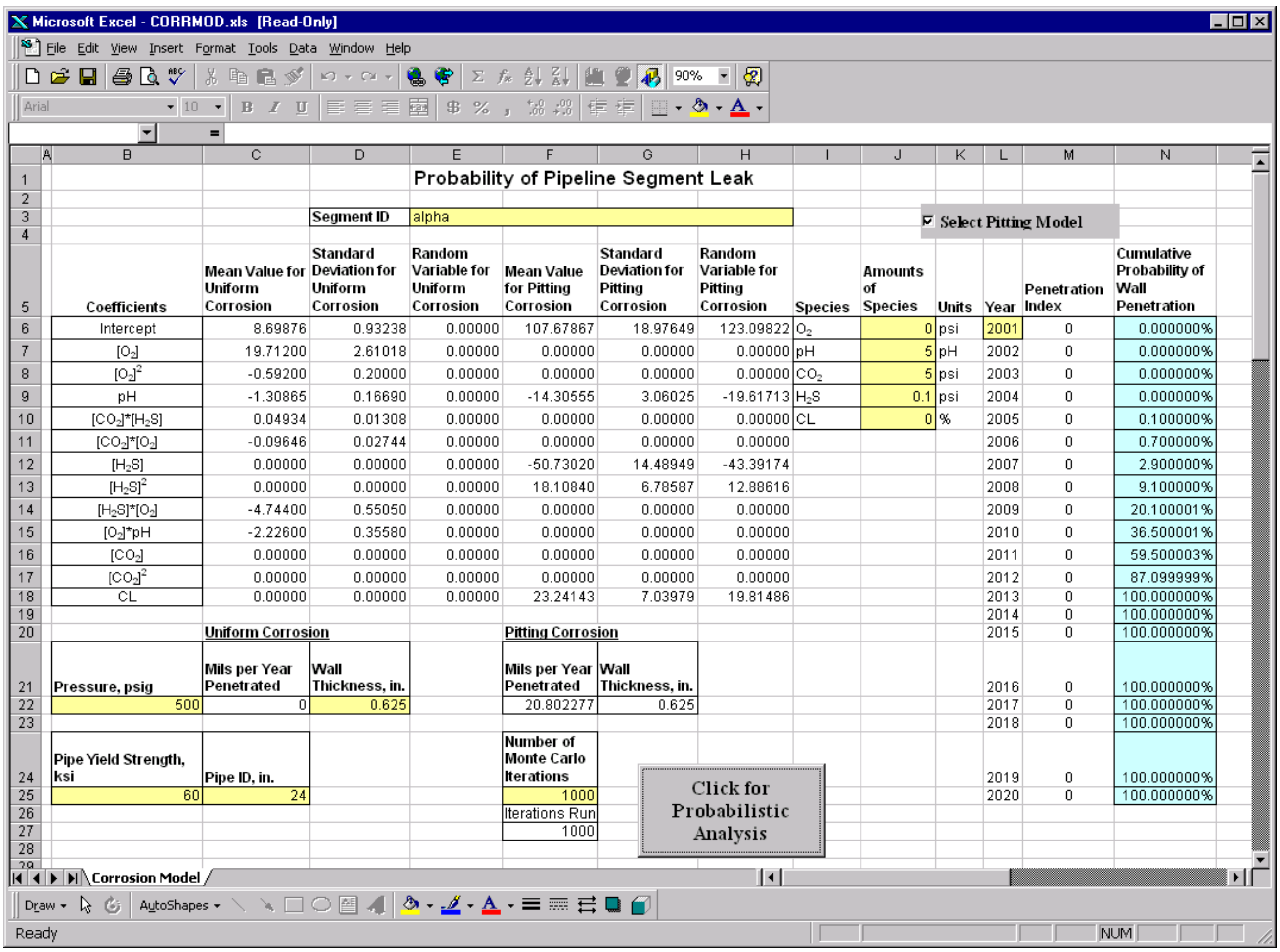
- For segments alpha, beta, and gamma, the following data was entered
  - Concentrations of corrosive species; O2 is zero, pH is 5, CO2 is 5psi, H2S is 0.1psi, Cl- is 0%
  - Year 2001 was used to start prediction
  - Line pressure and wall thickness is 500psi and 0.625 inches
  - Pipe Yield Strength 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 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	Species	Amounts of Species	Units	Year	Penetration Index	Cumulative Probability of Wall Penetration
Intercept	8.69876	0.93238	0.00000	107.67867	18.97649	123.09822	O_2	0	psi	2001	0	0.000000%
$[O_2]$	19.71200	2.61018	0.00000	0.00000	0.00000	0.00000	pH	5	pH	2002	0	0.000000%
$[O_2]^2$	-0.59200	0.20000	0.00000	0.00000	0.00000	0.00000	CO_2	5	psi	2003	0	0.000000%
pH	-1.30865	0.16690	0.00000	-14.30555	3.06025	-19.61713	H_2S	0.1	psi	2004	0	0.000000%
$[CO_2]*[H_2S]$	0.04934	0.01308	0.00000	0.00000	0.00000	0.00000	CL	0	%	2005	0	0.100000%
$[CO_2]*[O_2]$	-0.09646	0.02744	0.00000	0.00000	0.00000	0.00000				2006	0	0.700000%
$[H_2S]$	0.00000	0.00000	0.00000	-50.73020	14.48949	-43.39174				2007	0	2.900000%
$[H_2S]^2$	0.00000	0.00000	0.00000	18.10840	6.78587	12.88616				2008	0	9.100000%
$[H_2S]*[O_2]$	-4.74400	0.55050	0.00000	0.00000	0.00000	0.00000				2009	0	20.100001%
$[O_2]*pH$	-2.22600	0.35580	0.00000	0.00000	0.00000	0.00000				2010	0	36.500001%
$[CO_2]$	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000				2011	0	59.500003%
$[CO_2]^2$	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000				2012	0	87.099999%
CL	0.00000	0.00000	0.00000	23.24143	7.03979	19.81486				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%

Uniform Corrosion

Pressure, psig	Mils per Year Penetrated	Wall Thickness, in.
500	0	0.625

Pipe Yield Strength, ksi	Pipe ID, in.
60	24

Pitting Corrosion

Mils per Year Penetrated	Wall Thickness, in.
20.802277	0.625

Number of Monte Carlo Iterations: 1000

Iterations Run: 1000

Click for Probabilistic Analysis

Corrosion Model

Ready NUM

Figure 2. Screen capture of Corrmod.xls software.

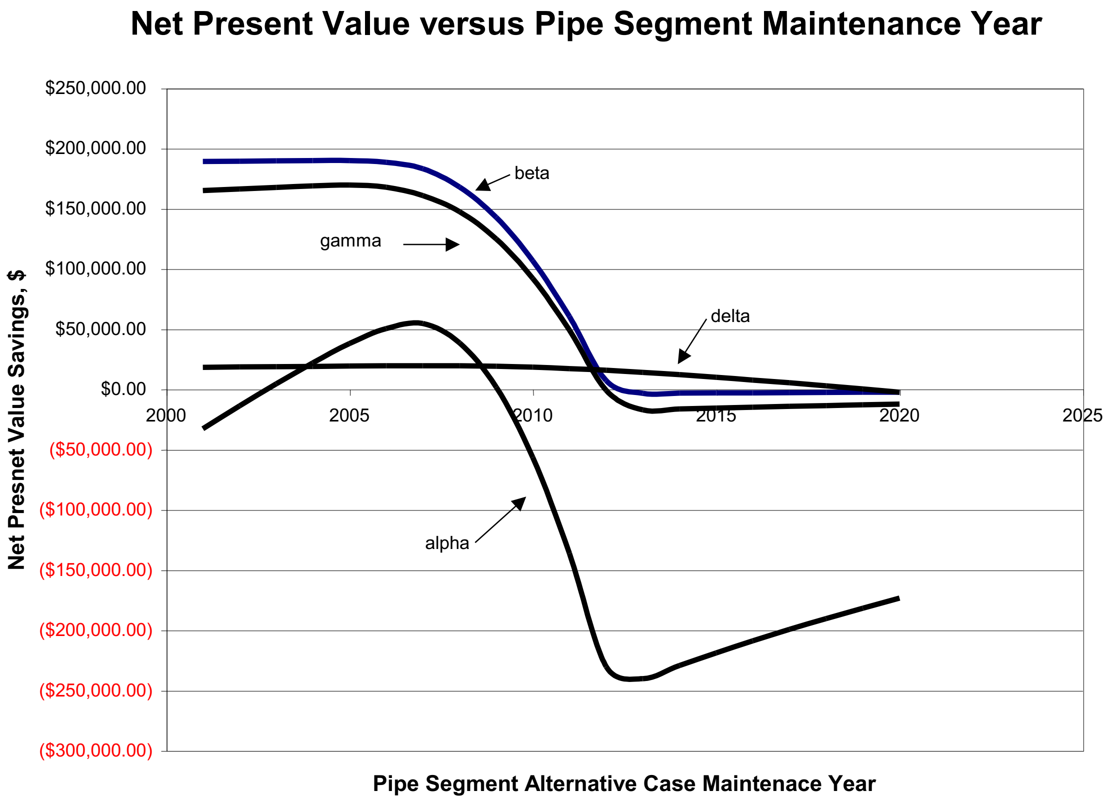


Figure 3. Results of example problem to determine cost effectiveness of liner installation

CASE STUDY: HEAT EXCHANGER FAILURE - UNDERSTANDING THE TOTAL COST OF A CORROSION ISSUE IN THE OIL AND GAS INDUSTRY

Reference: A.I. Williamson, L. Cardenas. "Heat Exchanger Failure Case Study: Understanding the Total Cost of a Corrosion Issue in the Oil and Gas Industry," CORROSION 2017, paper no. 9286, Houston, TX: NACE International, 2017.

Abstract

The total cost of corrosion in the oil and gas industry is an often overlooked subject when evaluating the impact of an upset or failure due to corrosion. Costly issues can arise when as little as a single piece of equipment is not designed to properly mitigate corrosion. Not only is there a need to replace the failed piece of equipment but there are many other costs to consider, including, but not limited to:

environmental and cleanup costs, safety related costs, unnecessary corrosion inhibition costs, and costs associated with potential future failures at other projects that have utilized similar designs and processes.

In this case study, a Steam Assisted Gravity Drainage (SAGD) facility in northern Alberta, Canada, is examined as it experienced two very similar failures in heat exchanger tubes within 2 years of each other due to a boiler feedwater (BFW) tank without a nitrogen blanket and a low flow condition. High amounts of oxygen were able to dissolve into the BFW, which led to several problems downstream of the BFW tank, particularly in the tubes of the heat exchangers. The low flow conditions present in the system led to a buildup of solids, which also aided in an accelerated corrosion rate.

Introduction

The total cost of a corrosion problem or failure is widely overlooked in the oil and gas industry. Not only does the affected equipment need to be serviced or replaced, but there are a number of other costs that may need to be addressed including, but not limited to:

- Equipment replacement
- Additional chemical programs
    - Wasted or unused oxygen scavenger, corrosion inhibitor
- Environmental clean-up
- Near misses, accidents and fatalities
- Economic losses due to plant operation interruptions i.e., shutdown
- Installation of other preventative measures

Many of these costs can be avoided by taking the time to design for corrosion control by looking at a processing facility as a whole, rather than in separate pieces. This is crucial because operations in all facilities are integrated, and changes in one area can have consequences in another. This includes upstream and downstream operations such as drilling, well completions, gathering systems, brackish water, water disposal, and sales oil pipelines. Furthermore, operational experience needs to be considered during the construction of new facilities because this can provide further insight into optimal design of these new facilities.

In this case study, multiple heat exchanger failures occurred as a result of a BFW tank that was not protected by a gas blanket. The lack of gas blanket resulted in higher than normal levels of dissolved oxygen in the boiler feedwater. This paper examines the failures, the conditions that led to the failures, and the repercussions of the failures from a monetary standpoint.

PLANT OVERVIEW

Steam assisted gravity drainage (SAGD) is a thermal in-situ oil recovery process used to produce heavy crude oil from an oil sands formation. Pairs of stacked horizontal wells are drilled parallel to each other into the formation. The top well functions as the injection well, and it injects high pressure, high temperature steam into the surrounding reservoir to heat it up thereby reducing the bitumen's viscosity, causing the bitumen to flow downward. The lower well is the production well which collects the heated production fluids (bitumen, connate water, and condensed steam) from the reservoir and transports them to the surface where they are delivered via aboveground pipelines to a central processing facility.

The steam-to-oil ratio, or SOR, is an indicator of the efficiency of a SAGD operation. A typical SAGD production schematic can be seen in Figure 1 below.

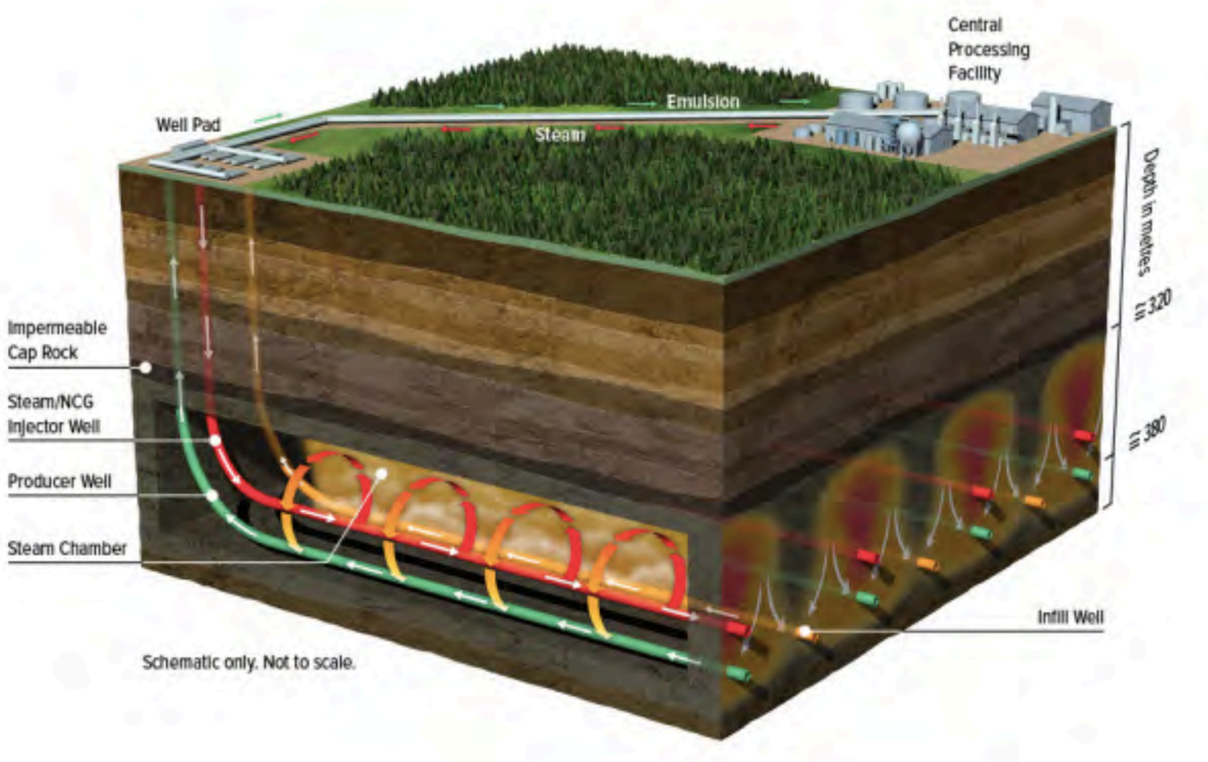


Figure 1: Typical SAGD Production Schematic (Ref. 1)

A typical SAGD central processing facility (Figure 2) consists of an inlet separation unit, oil treatment unit, produced water treatment unit, and a steam generation unit. The produced bitumen, gas and water stream (emulsion) is transferred from the field to the inlet separation unit. Here the gas vapor is separated from the mixture and the remaining products of oil and water are sent to the oil treatment unit. Diluent is added to the oil and water so that it can flow easier.

The mixture of oil, produced water, and diluent is sent to the oil treatment unit where the oil and diluent are separated from the produced water through a series of chemical and mechanical processes. The oil and diluent, called dilbit, is stored and sent via pipeline for sale.

The produced water is sent to the water treatment unit where it is treated and recycled back into the process as steam. Make-up water is added to the produced water stream to provide sufficient volume for steam generation. This make-up water is often brackish in nature and therefore adds salinity to the boiler feed water. Once through steam generators (OTSGs) typically yield 80% steam and 20% water. The steam is transferred to the well pads and injected into the reservoir.

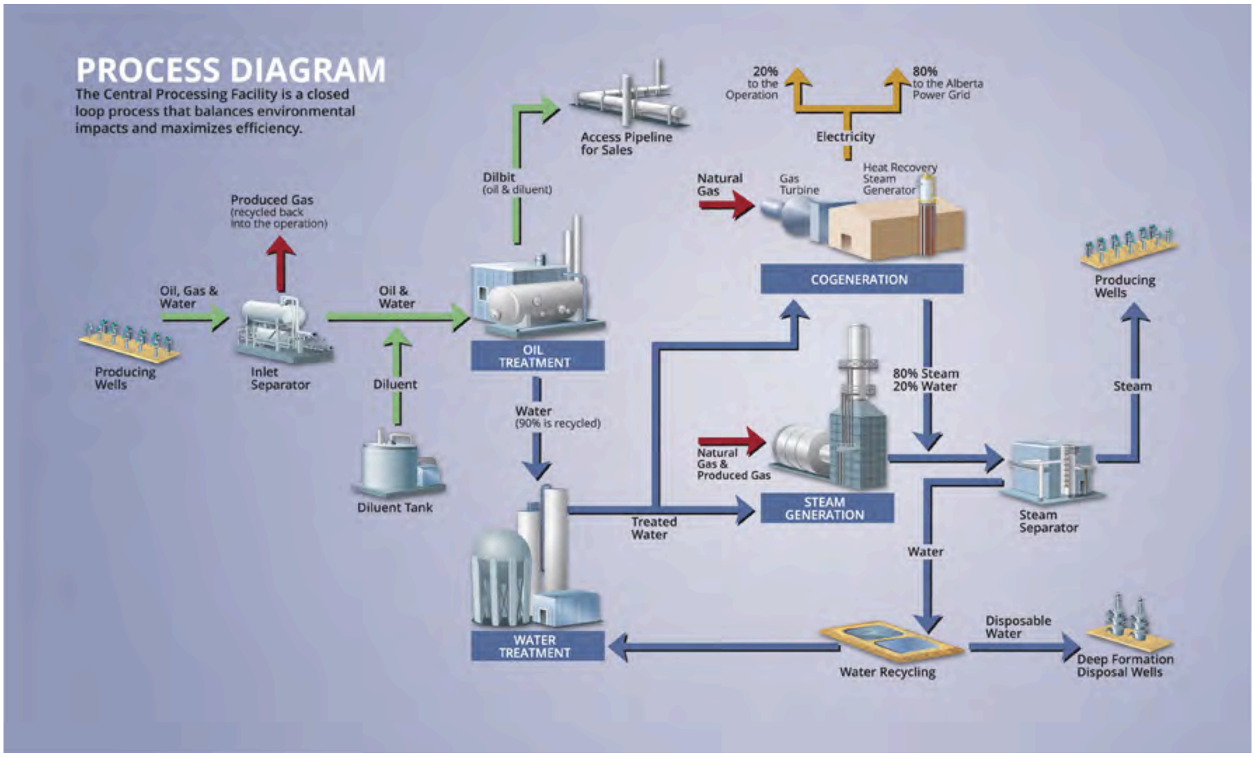


Figure 2: Typical SAGD Central Processing Facility – Process Diagram (Ref. 1)

The subject SAGD central processing facility was commissioned in 2006. The sections of the facility that this paper focuses on are the BFW system and the steam generation unit. In this case study, the BFW system is of particular interest.

TIMELINE

In 2006 the subject SAGD processing facility began operations. The BFW system was designed and constructed without a gas blanket on the BFW tank, which allowed oxygen ingress into the BFW system as levels changed in the BFW tank. Furthermore, the BFW system initially was operated at lower than design flow conditions. These low flow conditions were due to lower than design production volumes and therefore lower than design steam requirements at the time. This low flow condition meant that the system equipment and piping were more prone to a buildup of suspended solids. These two conditions, one design (no gas blanket) and one operational (low flow conditions), were the major corrosion inducing factors which ultimately led to the failures of several heat exchangers.

Blowdown/BFW Exchanger "A" Bundle

During September and early October of 2009 it was observed that a trend of increased pH, silica, and conductivity was occurring through the Boiler Blowdown/BFW exchangers. With this information, the "A" bundle was taken out of service and inspected. The inspection revealed signs of corrosion and significant wall loss. The failure occurred on the outer diameter (OD) of the tubes. The exchanger had been in continuous operation since start up in 2006. It was in contact with boiler feedwater on the shell side and boiler blowdown water on the tube side. Both the shell and tubes of this exchanger were made of carbon steel. X-ray diffraction analysis revealed that the main components of the scale on the tube sample consisted of iron oxides (approx. 64% magnetite and 9% hematite) and iron oxide hydroxide (approx. 27% goethite).The cause of failure was found to be a result of shell side corrosion, caused by tuberculation.

Blowdown/BFW Exchanger "B" Bundle

This tube failure occurred in April 2010. The exchanger was in service since start-up in 2006. It was also in contact with boiler blowdown on the tube side and boiler feed water on the shell side. Both the shell and tubes of this exchanger were made of carbon steel. Once again, a trend of increased pH, silica, and conductivity was detected across the exchanger. X-ray diffraction analysis revealed that the main components of the scale on the tube sample consisted of iron oxides (approx. 32% magnetite and 6% hematite) and iron oxide hydroxide (approx. 31% goethite and 15% lepidocrocite). The cause of failure was found to be the same as the cause of failure of the exchanger "A" bundle. The failure analysis also proposed that the presence of chlorides may have further accelerated the corrosion rate (see Damage Mechanism section below).

Interim Chemical Program

The tube failures of both the "A" and "B" bundles resulted in the addition of a more robust chemical program to mitigate corrosion. In May 2010 an interim chemical program was put in place to mitigate corrosion as a result of dissolved oxygen in the BFW system. The original chemical program from 2006 included an oxygen scavenger to reduce dissolved oxygen levels. The oxygen scavenger was being injected directly downstream of the BFW tank. The interim chemical program also added a polymeric dispersant to minimize particulate iron laydown in the heat exchangers thereby allowing the iron to carry through both heat exchangers and OTSGs. A strong reducing agent was also added to promote passivation of the metal surfaces in the presence of dissolved oxygen and protect against pitting/localized damage. The chemical injection locations were modified based on the failure analysis from the exchangers. The metal passivator was injected upstream of the BFW tank and both the oxygen scavenger and polymeric dispersant were injected downstream of the BFW tank. The intent of the interim chemical program was to maintain sulfite residuals, thus inferring dissolved oxygen levels in the BFW were maintained at or near zero. Figure 3 shows a simplified schematic of the interim chemical program.

Nitrogen Blanket Installed on BFW Tank

A recommendation to install a gas blanket on the BFW tank was made in July 2010. In September 2011 a nitrogen blanket was installed on the BFW tank. A nitrogen blanket fills the vapor space in the tank with inert gas so that air and gases from the atmosphere (including oxygen) cannot enter the tank and dissolve into the water, when levels in the tank fluctuate. The BFW tank was constructed of internally coated carbon steel. Corrosion rates gradually decreased at corrosion probes and coupons installed downstream of the BFW tank, shortly after the gas blanket was installed.

Corrosion Monitoring Optimization

In November 2011 the corrosion monitoring system in the facility was updated. The facility did have a corrosion monitoring program in place since start up; however a number of the locations and methods were found to be inappropriate. For example, linear polarization resistance (LPR) probes were being used and these probes have been found to be susceptible to fouling in SAGD produced water systems, resulting in unreliable data. Furthermore, the probes were placed in suboptimal locations, and the 4 orientation was also ineffective for detecting increased metal loss. The LPR probes were replaced with electrical resistance (ER) probes which have been found to be more reliable in SAGD produced water service. The various ER probes in the subject BFW system are now collecting data and are continuously trended alongside operating parameters and BFW stream composition. Figure 3 shows the general locations of the corrosion monitoring probes and coupons.

In addition, accurate dissolved oxygen measurement tools were purchased and used for direct online measurements. A plant-wide survey of dissolved oxygen levels was completed in the various water streams within the produced water treatment unit, and the steam generation unit. This provided solid data for chemical program review and possible optimization.

Emulsion/BFW Exchanger Bay 1 “B” Bundle

In October 2012 extensive damage was found in this exchanger. This exchanger had been in service for 6 years at the time of inspection. It was in contact with boiler feedwater on the tube side and emulsion on the shell side. Both the shell and tubes of this exchanger were made of carbon steel. X-ray diffraction analysis revealed that the main components of the scale on the tube sample consisted of iron oxides (approx. 55-65% magnetite) and iron oxide hydroxide (approx. 5-10% goethite and 10-20% lepidocrocite). An oxygen driven pitting mechanism was found to be the culprit for the corrosion seen on the tube side of the exchanger and underdeposit corrosion was found to be responsible for the damage seen on the shell side of the exchanger.

The tube damage occurred before the nitrogen blanket was installed, but did not become apparent until after the installation of the blanket. It is known that the corrosion damage occurred before the installation of the blanket because an internal inspection before the installation of the nitrogen blanket revealed concerns with some of the tubes leaking and requiring plugging. Also, the morphology of the damage is indicative of an oxygen driven mechanism, yet there had been no oxygen present in the water since the installation of the nitrogen blanket and chemical program update.

Emulsion/BFW Exchanger Bay 2 “B” Bundle

In October 2014, an internal inspection of this exchanger revealed signs of corrosion and significant wall loss. Replacement of the bundle was not necessary, but several tubes needed to be plugged. It was also in contact with boiler feedwater on the tube side and emulsion on the shell side. Both the shell and tubes of this exchanger were made of carbon steel. X-ray diffraction analysis revealed that the main components of the scale on the tube sample consisted of iron oxides (approx. 90% magnetite) and iron oxide hydroxide (approx. 10% goethite and lepidocrocite). Once again, an oxygen driven pitting mechanism was found to be the culprit for the corrosion seen on the tube side.

The tube damage occurred before the nitrogen blanket was installed, but did not become apparent until after the installation of the blanket. The reason that it is known that the damage occurred before the installation of the blanket is for the same reasons as explained above for Bay 1 “B” bundle.

Updated Chemical Program

After the nitrogen blanket was installed on the BFW tank to prevent any oxygen ingress, extensive sampling revealed that there was little to no change in the dissolved oxygen levels with or without metal passivator injection. Dissolved oxygen levels increased from 1-2 ppb with oxygen scavenger injection to 4-7 ppb without oxygen scavenger injection.

The updated program therefore included a boiler additive/dispersant and an oxygen scavenger. The oxygen scavenger was moved upstream of the BFW tank, and the additive/dispersant continues to be injected downstream of the BFW tank. Feed rates of the oxygen scavenger were adjusted by measuring residual sulfite levels and also using real-time corrosion rate measurements provided by the ER probes. Surveys of dissolved oxygen levels are completed twice a year in various streams of the produced water treatment unit, the BFW system and the steam generation unit of the facility. Figure 3 shows a simplified schematic of the updated chemical program.

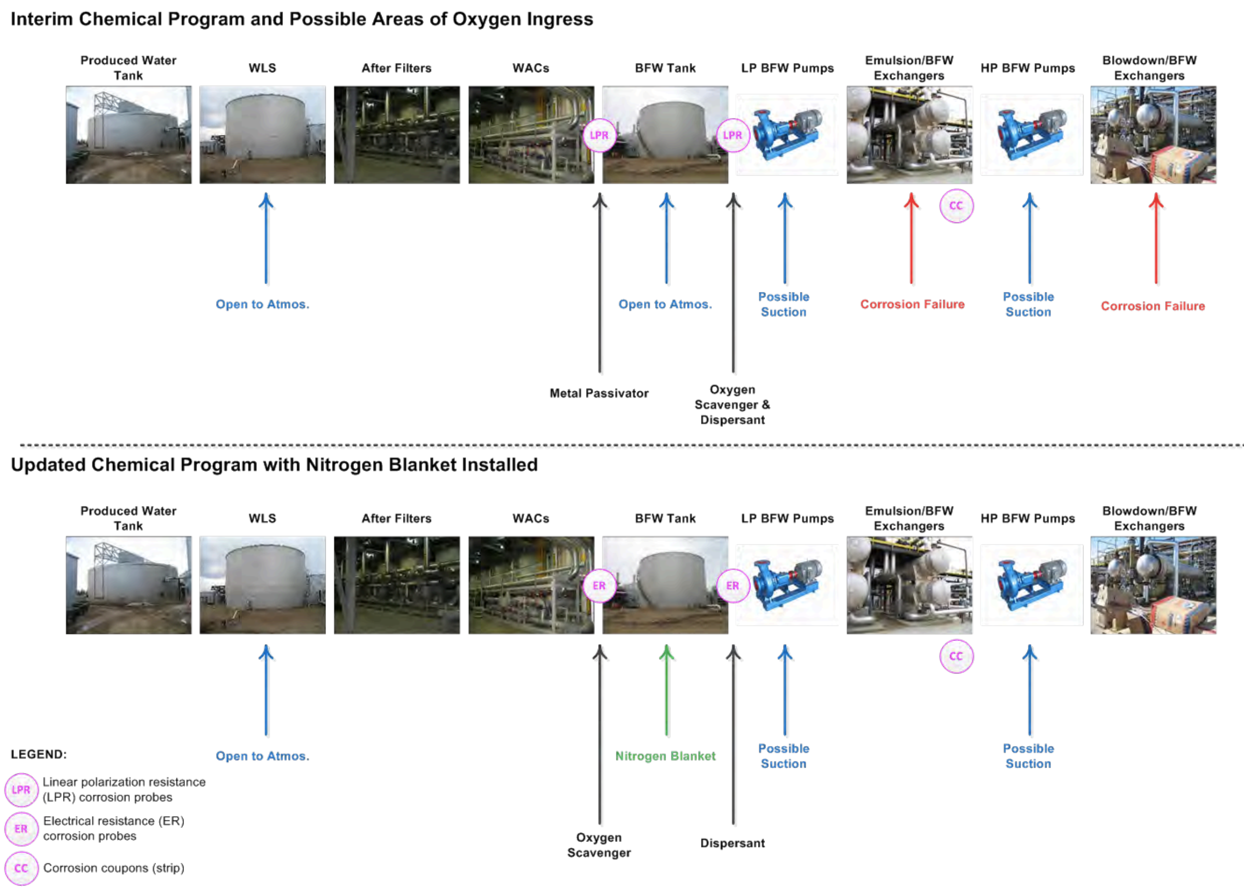


Figure 3: Interim and Updated Chemical Program with Corrosion Monitoring Locations

Timeline and Summary of Events

As can be seen from the events in the above timeline, the configuration of the facility is an integral part of designing for corrosion control. In this case, a series of heat exchanger tube failures occurred within four years of each other due to a poorly designed BFW system. An oxygen scavenging chemical was being injected upstream of the BFW tank. This would be an acceptable corrosion mitigation technique in most cases, however the BFW tank was open to atmosphere and oxygen was able to re-enter the water after the scavenger had been applied, essentially wasting the scavenger.

DAMAGE MECHANISM

X-ray diffraction analysis revealed that the main components of the scale on the tube samples of all four exchanger bundles consisted of iron oxides and iron oxide hydroxides. The detected iron oxides and iron oxide hydroxides form from a reaction between oxygen, water and iron. The presence of relatively small amount of hematite can be indicative of oxygen corrosion, either due to dissolved oxygen in service or air ingress during shutdowns. In all cases, the failures (or corrosion damage) were found to be caused by tuberculation.

Tuberculation is essentially the formation of localized corrosion products scattered over the surface in the form of knoblike mounds called tubercles. The process of tubercule formation is a complex one. The volcano-like structure often starts with a deposit at a point of low flow velocity (Ref. 2). This creates an oxygen concentration cell, thus promoting dissolution of iron as Fe2+ under the deposit. Fe2+ ions are electrochemically oxidized to Fe3+ as they encounter higher oxygen concentrations. The resulting corrosion product, Fe(OH)3 forms the wall of the growing tubercule. The exterior of the tubercule becomes cathodic, while the interior becomes highly anodic. Figure 4 below shows the corrosion reactions taking place during tuberculation. Figure 5 shows the typical appearance or morphology of damage associated with tuberculation.

Anodic reactions:

$$1.\ Fe \rightarrow Fe^{++} + 2e^-$$
$$2.\ Fe^{++} + 2OH^- \rightarrow Fe(OH)_2$$
$$3.\ 4Fe(OH)_2 + O_2 + 2H_2O \rightarrow 4Fe(OH)_3$$

Cathodic reactions:

$$1.\ \tfrac{1}{2}O_2 + H_2O + 2e^- \rightarrow 2OH^-$$
$$2.\ 2H^+ + 2e^- \rightarrow H_2\uparrow$$

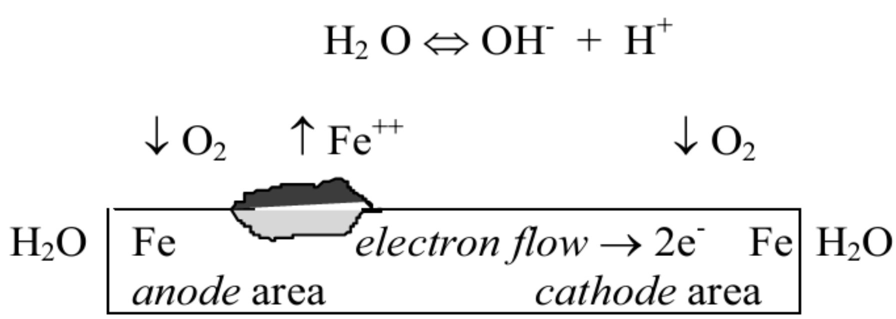


Figure 4: Corrosion Reactions – Tuberculation

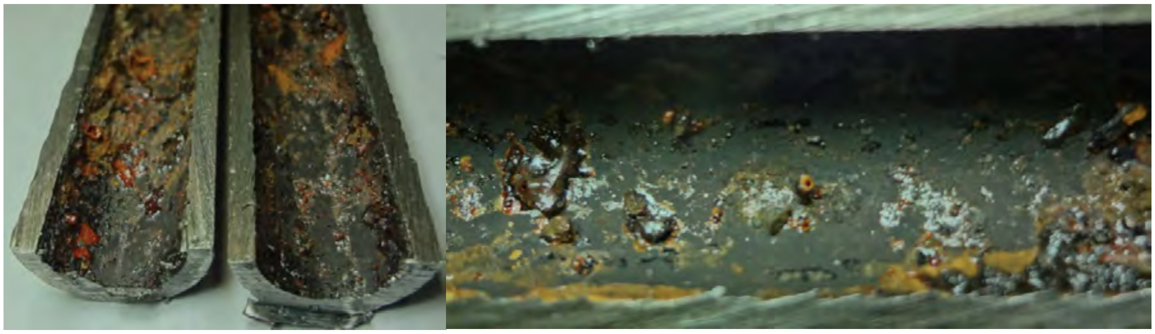


Figure 5: Appearance/Morphology of Damage – Tuberculation.

The presence of chlorides typically accelerates the corrosion reaction within the deposits. Chlorides will preferentially migrate within the deposit due to the build-up of positive charges as iron (as Fe2+) goes into solution. This can also result in the "localized" pH becoming more acidic inside the growing tubercle.

COST ANALYSIS

A difficulty in promoting corrosion management is that cost savings from corrosion control are usually difficult to measure; i.e. maintenance costs slowly decrease, inspection intervals increase, fewer failures save lost production time and/or lost product, decrease in environmental release, improved public relations, etc. (Ref. 3).

In an attempt to quantify the impact of corrosion in this particular case study, the following specific costs were considered:

- Equipment replacement
- Increased chemical program costs
- Optimized corrosion monitoring program
- Production losses due to shutdown
- Installation of other preventative measures (nitrogen blanket)

This is not necessarily a complete list of costs that were incurred by the operator due to the corrosion failures discussed above. Other easily quantifiable costs that could be considered, but were not explored in this case study include for example: inspection costs, equipment installation and delivery costs.

Furthermore environmental damage and injuries/fatalities were not incurred by the operator in this case, however they were possible.

Cost Breakdown

- In order to prevent oxygen ingress, the BFW tank was retrofitted with a nitrogen blanket in September 2011. The installed cost of this blanket was approximately CAD$122,000.

- The interim chemical program was estimated to have cost an additional CAD$144,000 per year, over the period of four years.

• As mentioned in the timeline, the corrosion monitoring program was updated in November 2011. The equipment cost for this update was approximately CAD$20,000.

• The failed heat exchangers in this case study needed to be replaced. They were designed for the correct process conditions; however, those conditions were upset due to the oxygen ingress into the BFW tank and the misplacement of the oxygen scavenger. The total costs of the heat exchangers replacements (including labor) are as follows:

Exchanger Name	Replacement Cost (CAD$)
Blowdown/BFW Exchanger “A” Bundle (2009)	309,530
Blowdown/BFW Exchanger “B” Bundle (2010)	217,667
Emulsion/BFW Exchanger Bay 1 “B” Bundle (2012)	250,000
Emulsion/BFW Exchanger Bay 2 “B” Bundle (2014)	259,877
Total Replacement Cost	**1,037,074**

• During the replacement of the exchangers, steam generation was interrupted. The loss of revenue caused by shutdown time for all the above failures was estimated at CAD$22.4 million.

Net Present Value

In order to accurately compare the financial impact of not considering and installing the proper corrosion mitigation measures during design, construction and commissioning, a net present value (NPV) analysis has been completed for two scenarios.

NPV is a financial tool which calculates the difference between the present value of cash inflows and the present value of cash outflows. Net present value is a commonly used metric in capital budgeting to analyse the profitability of a projected investment or project. NPV accounts for the time value of money, which is the idea that future dollars have less value than presently held dollars (Ref. 5).

In Scenario #1, it is assumed that the nitrogen blanket and chemical program were installed correctly during construction and plant commissioning, and no further mitigation was required up to the end of 2014. A conservative amount of CAD$25,000 per year has been considered as the cost of inspections and maintenance. The estimated NPV of this scenario is CAD$63.4 Million.

In Scenario #2, the actual events that took place as described in this paper are examined and a NPV is calculated using the costs that the operator took on throughout the years to mitigate the corrosion that caused the failures. The estimated NPV of this scenario is CAD$80.2 Million.

The difference in NPV of Scenario #1 and Scenario #2 is of CAD$16.8 Million. The formula used to calculate NPV has been provided in Appendix A.

FURTHER CONSIDERATIONS

In some cases, when a piece of equipment fails in an unreasonable amount of time, a material upgrade may be needed to mitigate against further failures. In many cases, the failure could have been prevented by using an upgraded material in the first place. Although this would mean an increased initial cost during design and construction, it may mean saving significant amounts of capital over the lifetime of the plant. This decision requires foresight from the design team, operator and plant personnel in conjunction with corrosion and materials experts.

There were no personnel safety consequences in this case; however, this is a serious possible consequence of piping and equipment failures in oil and gas processing facilities. Beyond the trauma and grief for the casualty and their family, friends and coworkers, failures, or other situations that lead to injuries can hurt a company's image in the public eye, hurt investor relations, and cause a loss in revenue due to mandatory shut down.

DESIGNING FOR CORROSION CONTROL

The choice (and detailed specification) of a material known to be chemically resistant to a given environment is only one step in the selection process. Another step, of equal importance, is the choice of proper design configurations and principles to permit the material to perform in the desired manner (Ref. 4).

Taking proper design configurations into consideration and implementing appropriate corrosion mitigation techniques is a vital part of the design process. There is another step in assuring good performance, which unfortunately is often given inadequate attention. That is careful inspection and verification that design specifications and recommendations are actually carried out in the installation.

Many corrosion-related failures can be prevented by designing the plant or facility correctly, by selecting corrosion resistant material for the service, setting up corrosion monitoring systems and/or implementing effective inspection plans. The damage mechanism that caused these particular failures are well known and easily preventable.

Furthermore, it is essential that design houses draw on operation's experience from previous projects when planning new construction. It is unfortunate that the same mistakes are continually made from a design and construction standpoint. Many costs related to corrosion damage could be avoided by applying knowledge gained from past operations. This further highlights the need of a close working relationship between design engineering firms, corrosion engineers, and the operator.

CONCLUSIONS AND RECOMMENDATIONS

It is clear from the information presented in this case study, that there are many preventable costs associated with a corrosion failure. In this particular case, had the facility been initially designed properly, the various failures and subsequent costs could have been easily avoided. The NPV analysis proved that it would have been economically favorable to have installed mitigation measures during design and construction, rather than to install them in a reactionary manner post-failure, along with taking on many other associated costs.

It is important to take these experiences and share them with other industry members as these types of failures and the associated economic losses are easily preventable. The damage mechanisms that caused the tube bundles in the exchangers to fail are well understood, and can be readily mitigated.

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. To achieve the full extent of potential savings, it is necessary to implement an all-encompassing corrosion management system and fully integrate it into an organizations' overall management system. This includes a continuous, balanced, and coordinated improvement effort of all aspects of corrosion-related design and processing decisions.

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Acknowledgements

The authors of this paper would like to thank Ryan Wilkes for his contributions.

APPENDIX A: Net Present Value Analysis

Net Present Value (NPV) is the difference between the present value of cash inflows and the present value of cash outflows. NPV is used in capital budgeting to analyze the profitability of a projected investment or project.

NPV is calculated using Equation 1 below:

$$\text{NPV} = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_o \qquad (1)$$

Where:

t = number of time periods
Ct = net cash inflow during the period t
Co = total initial investment costs, and
r = discount rate

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[1,2,3], CUI continues to occur in many industries and is estimated to cost process plants about 10 percent of their total maintenance budgets[4]. Major equipment outages and unexpected maintenance costs stemming from CUI account for more unplanned downtime than all other causes[5]. 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.

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[1] Pollock, W. I. and J. M. Barnhart (1985). Corrosion of metals under thermal insulation. Corrosion of metals under thermal insulation, San Antonio, TX, ASTM International.

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[4] Fitzgerald, B. J., et al. (2003). Strategies To Prevent Corrosion Under Insulation In Petrochemical Industry Piping. Corrosion 2003, Houston, TX, NACE International.

[5] 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.

What is the solution?

Bayesian Network (BN) models are highly suited to assess the performance of complex interactive systems[6] 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.

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[7].

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 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 colour 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.[8] (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 5.

[6] Fenton, N. E. and M. Neil (2012). Risk assessment and decision analysis with Bayesian networks. Boca Raton, Taylor & Francis.

[7] Ayello, F., et al. (2014). "Quantitive Assessment of Corrosion Probability—A Bayesian Network Approach." Corrosion **70** (11): 1128-1147.

[8] 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.

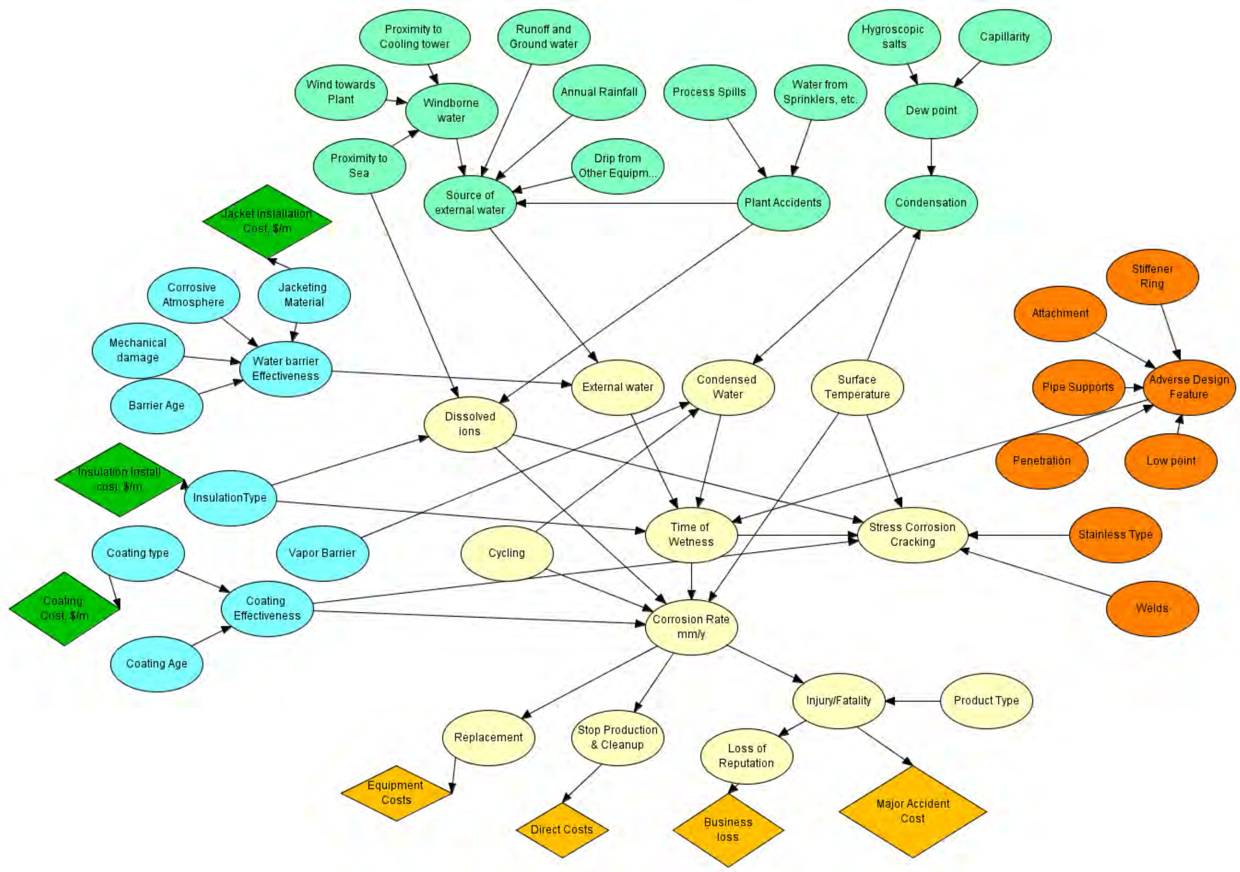


Figure 4. A BN representation of CUI of carbon steel and stainless steel.

Prediction of the business impact of CUI

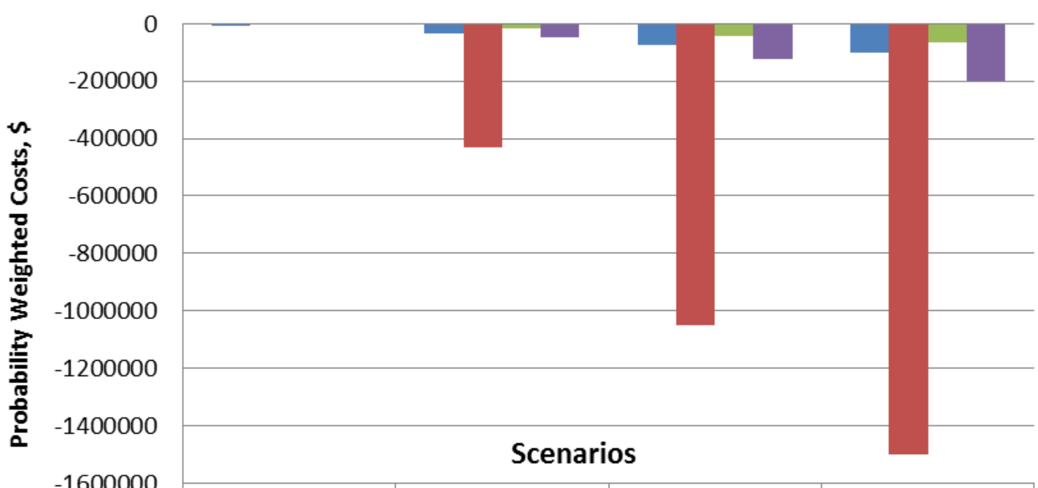
The predicted business impact could be a valuable KPI for operational leaders to make risk-informed decisions, based on their risk appetite and internal decision criteria. The business impact criteria are defined as follows:

- 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 labour for repair/replacement
- Major Accident Potential: defined by the Seveso Directive in Europe[9] (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

[9] 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.

The business impact of CUI is expressed in Figure 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 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° 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.



	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 5. Examples of Estimated Business Costs for a Number of Scenarios Calculated by BN Shown in Figure 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 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).

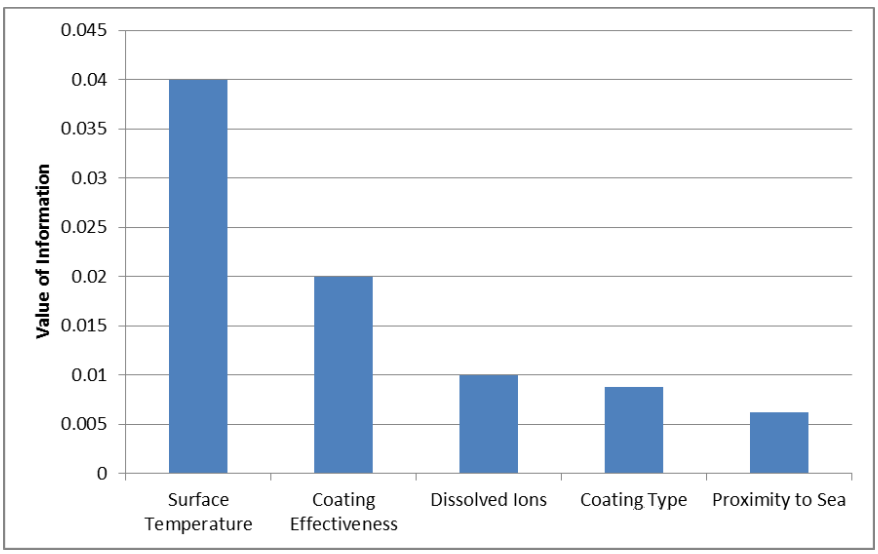


Figure 6. Value of information analysis of Bayesian network for CUI

APPENDIX F

CORROSION MANAGEMENT FINANCIAL TOOLS

Corrosion management includes all activities, through the life time 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 range from cost-adding to life-cycle costing and constraint optimization are summarized below and discussed in in detail in Appendix G.

Return on investment (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. Return on investment 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. Return on investment 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 USD10,000, and state-of-the-art corrosion control is implemented, projected annual savings would be USD3,000 at an annual cost of USD300. 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)

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 or sometimes expressed as a ratio, 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 analyse 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.

Cost-Adding Methodology

The method, which has been developed by the US DoD calculates the cost of corrosion of an asset or a project by looking from the top down Programs, projects and assets are analysed 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 which are filled by looking from the bottom. All corrosion related expenditure are added and compared with the top-down cost assessment. By comparing the top-down and bottom-up corrosion cost assessment, the US 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. For further detail about the DoD's corrosion costing method, see Appendix G.

Life Cycle Costing

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

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 E. A brief overview is provided here. CUI is a problem in refineries[10,11] 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. Bayesian Network (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:

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- People: Injury or fatality leading to legal fees, escalating insurance costs, and fines
- Repair/ Replace: Cost of parts and labour 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 E). 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.

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

[11] 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

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 E 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.

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.[12] 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 life cycle cost (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 probabilistic approach, which 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 these approaches are discussed in detail in Appendix E.

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. Build constrained optimization model.

The constrained optimization model is presented in Appendix E.

[12] 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.

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 E.

APPENDIX G
Corrosion Costing Model

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.

CORROSION COSTING METHOD USED IN THE US DEPARTMENT OF DEFENSE

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 trade-offs 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.

Corrosion Cost Determination

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:

- Labour 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.

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.

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 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.

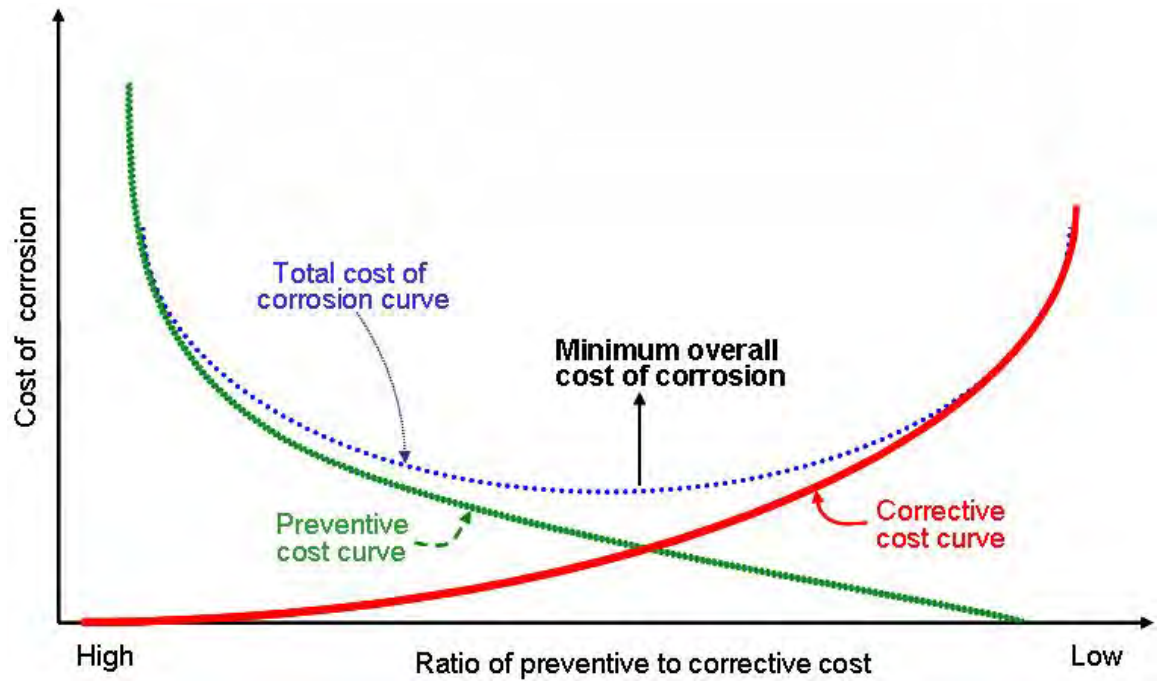

Figure 1. Preventive and Corrective Corrosion Cost Curves

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 1.

Table 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 labour 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 labour 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.

Structure and Parts Costs

DoD characterizes corrosion costs as either structure or parts costs. All direct materials and direct labour 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.

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 analysing 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. checkbook 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.

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 2.

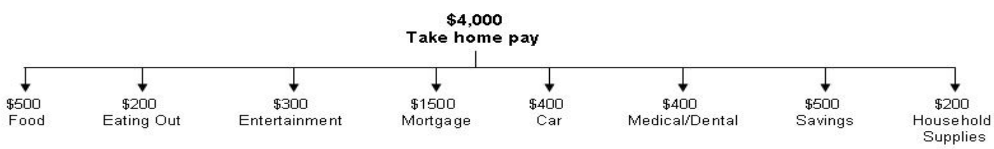

Figure 2. Top-down Analysis using Household Budget Example

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 3 clearly shows that the amount spent on meat cannot exceed $1,000.

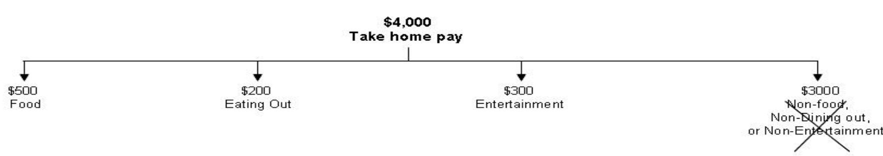

Figure 3. Consolidation of Budget Categories Showing those that Potentially Contain Meat.

The spending within these three categories can be further examined in more detail as shown in Figure 4.

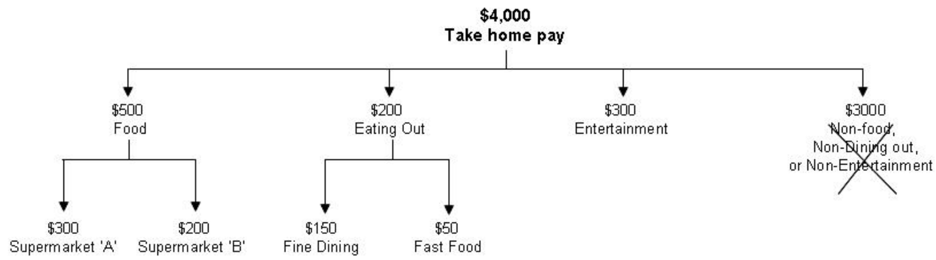

Figure 4. Expansion of Potential Meat Spending in More Detail

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.

Bottom-Up Analysis

Figure 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.

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 5 shows the analysis to this point.

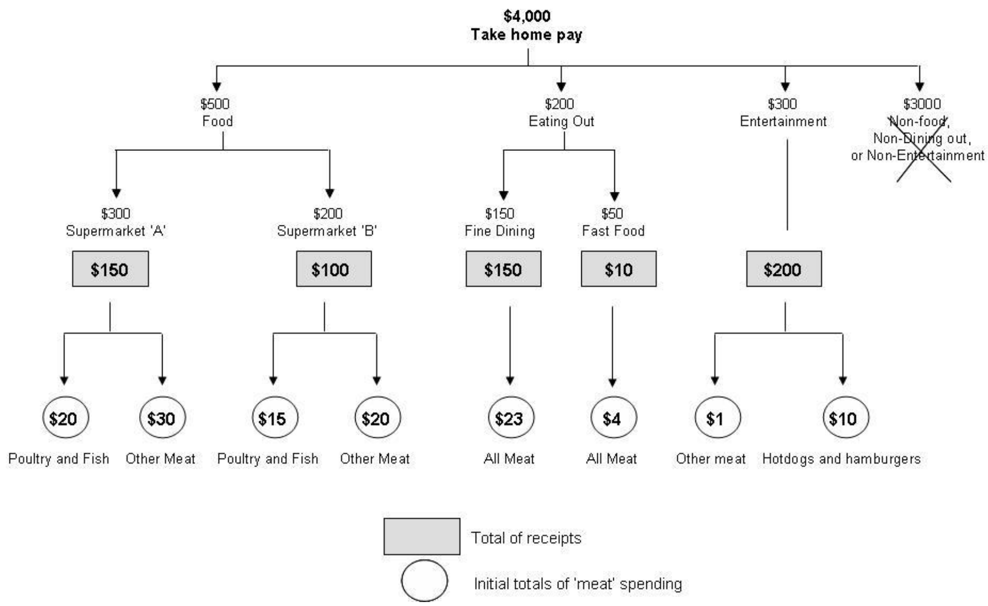

Figure 5. Initial Calculation of Meat Spending

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 6.

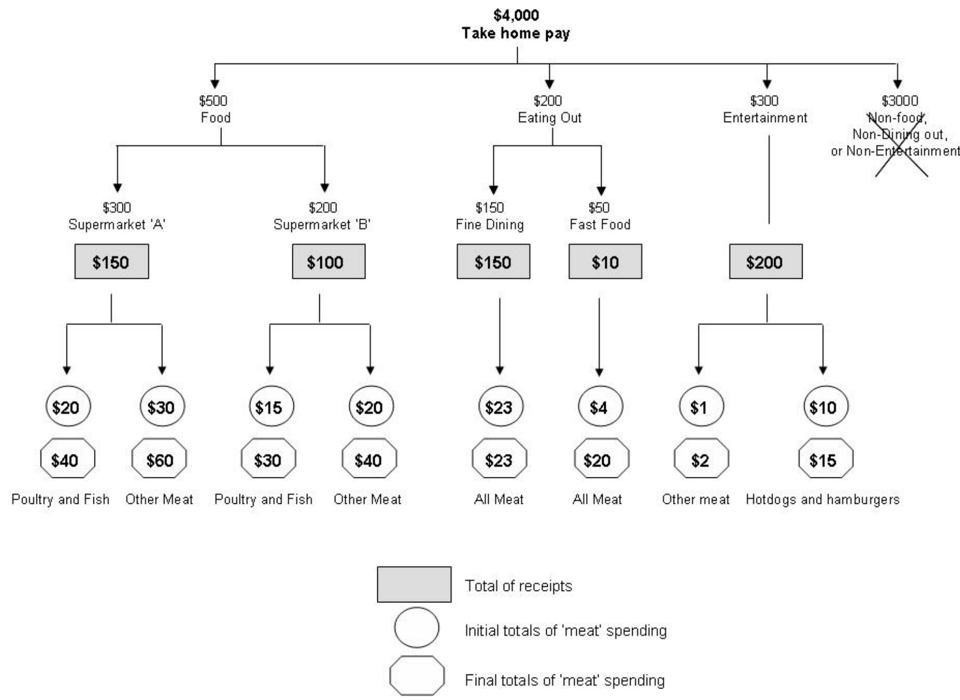

Figure 6. Final Calculation of Meat Spending

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 percent 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 6 and determines the total monthly spending on meat to be $230.

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 7 shows a cost tree from a completed DoD corrosion study.

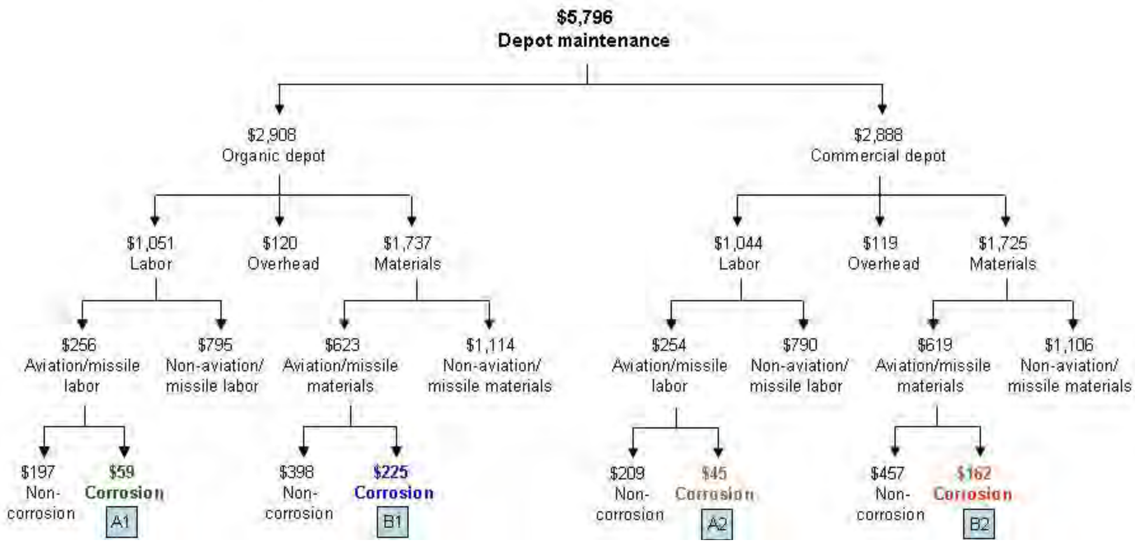

Figure 7. Cost Tree from a DoD Corrosion Cost Study

The cost diagram in Figure 7 outlines the spending on corrosion during depot maintenance of a military aircraft[13]. 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 labour, 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 centre 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 that involve corrosion-related work are flagged.

[13] 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.

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 labour 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 labour and materials costs, identify corrosion-related events, and are used with discipline. If any of these three boundary conditions are 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 centre, 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 also 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 8 below.

Using this data structure, the data can be analysed 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.
- Labour costs.

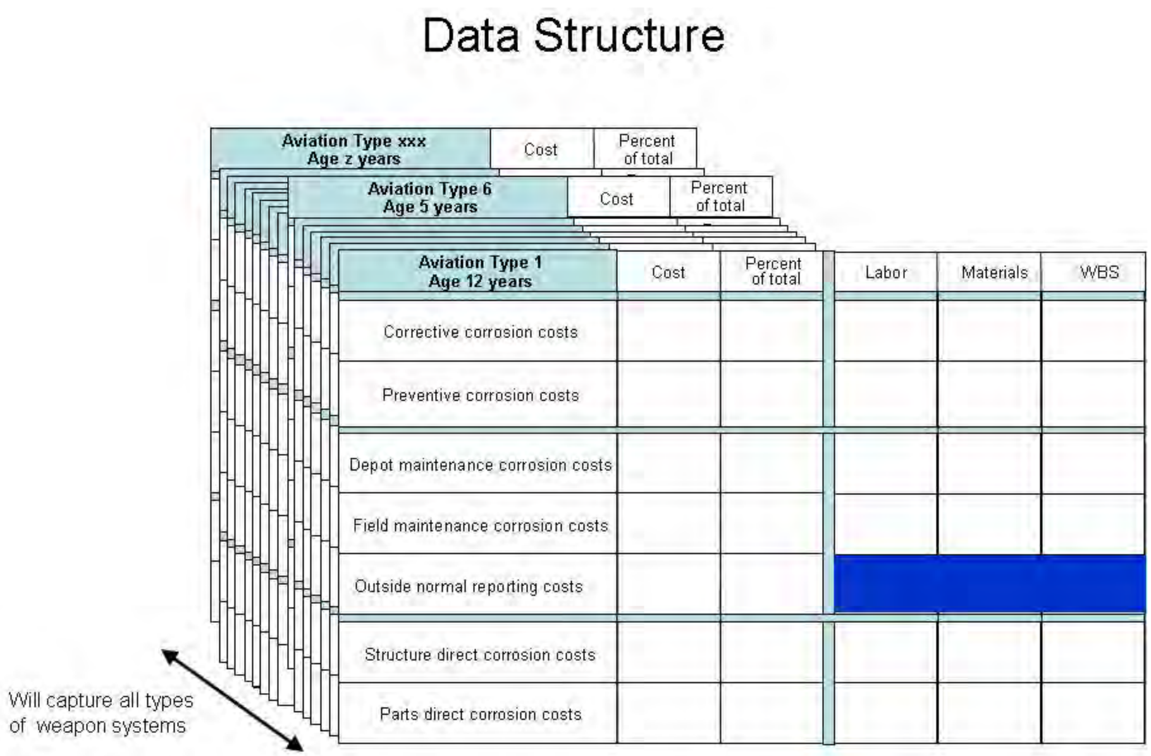

Figure 8. Corrosion Cost Data Structure and Methods of Analysis - Work Breakdown Structure (WBS).14

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[15] level maintenance materials if desired.

[14] 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.

[15] Field level maintenance is more limited in scope than depot maintenance and is normally performed close to the owning units area of operations.

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.

The LLC approach makes it possible to compare alternatives by quantifying a long-term outlook and determining the return on investment (ROI).

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.

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.

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.

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.

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.

Cash Flow

After the corrosion management practices are analysed, 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.

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 IMPACT India report). 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 labour 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.

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:

- <u>Year zero.</u>

  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.

- <u>During service.</u>

  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.

- <u>Last year.</u>

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, labour, 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 labour, 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 <u>initial investment</u> occurs in the "present"; therefore, no discounting is necessary.

<u>Annual maintenance</u> 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:

$PV = I + PV\{AM, P, R, RH, ROS\}$

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.

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 clean-up, litigation)?

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 corrosion management program 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.

RISK-BASED APPROACH TO LIFE CYCLE COSTING

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 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:

$$p(|f(x) - p(x)| > \varepsilon) \rightarrow 0 \text{ as } N \rightarrow \infty \text{ ,}$$

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:

$$p(A) = p(B) \cdot \frac{p(A|B)}{p(B|A)} \text{ , where}$$

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.

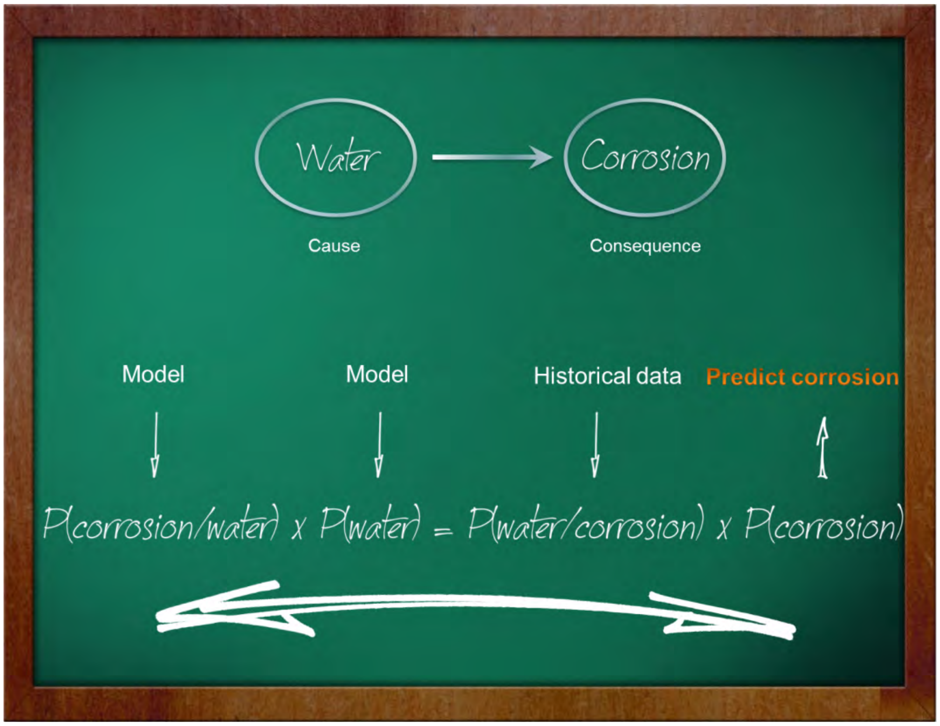

Figure 9. Simplified Bayesian Network

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.

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 E; 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.

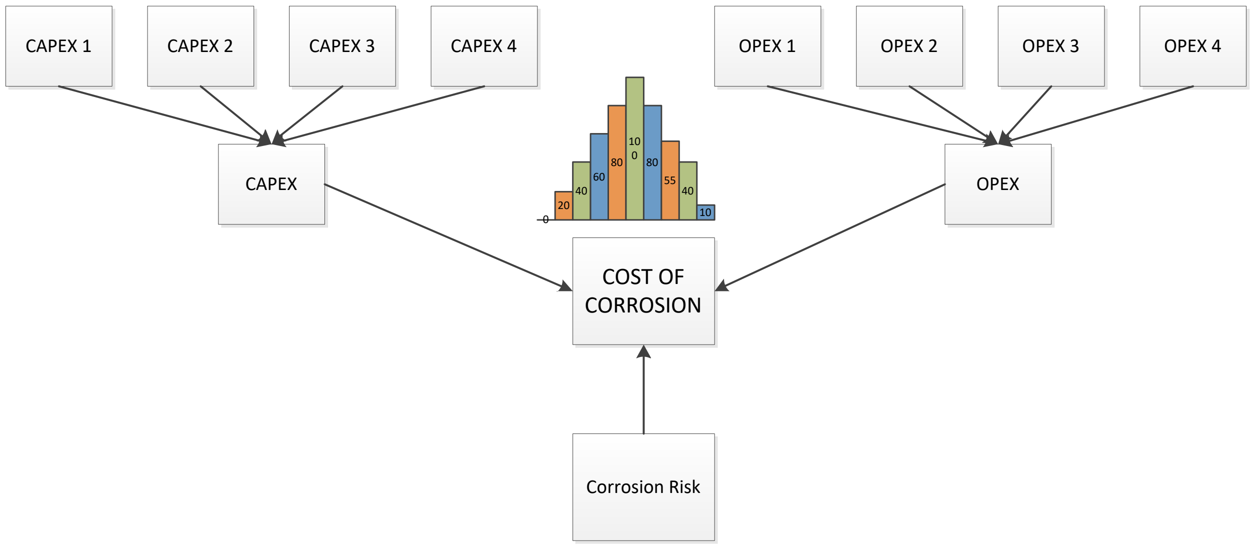

Figure 10. Cost of Corrosion of an Asset Showing the Three Main Contributors

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.

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:

$$\underset{I,\ CM,\ \lambda}{\text{Max } SL} = \text{Max } SL(I, CM) - \lambda\,(I\,P_I + CM\,P_{CM} - B)$$

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.

$$\text{Min } \alpha \;\Big|_{AEV\{I\},\ AEV\{CM\}} = AEV\{I\} + AEV\{CM\} + \lambda\,[\,SL(AEV\{I\}, AEV\{CM\}) - SL_0\,]$$

where SL_0 desired service requirement

or the same equation with Present Values

$$\text{Min } \alpha \;\Big|_{PV\{I\},\ PV\{CM\}} = PV\{I\} + PV\{CM\} + \lambda\,[\,SL(PV\{I\}, PV\{CM\}) - SL_0\,]$$

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 trade-off 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 trade-offs we need to know the time period a structure is expected to be in service.) This equation of marginal trade-off 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.

$$\text{Min } \alpha \;\Big|_{AEV\{I\},\, AEV\{CM\}} = AEV\{I\} + AEV\{CM\} + AEV\{SC\} + \lambda\,(SL[AEV\{I\}, AEV\{CM\}] - SL_0)$$

where: SC indirect cost of the CM practice analysed

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.