APPENDIX D

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

D.1 CORROSION MANAGEMENT PROGRAM OF A NATIONAL OIL COMPANY

A case study is presented of corrosion management practices of a national oil company (NOC). An NOC in the Middle East has developed a mature 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 **Error! Reference source not found.**. The CMP enables proactive and risk based corrosion management, which emphasizes leading proactive actions over lagging reactive actions (i.e., find-it-and-fix-it, repair, etc.) and possible failure.

The CMP framework as described in the manual addresses six essential elements, which are in reasonable agreement with the Management System Elements defined in Section **Error! Reference source not found.** of this report, are as follows:

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

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

Table D-1 shows general agreement of these six essential elements with those developed in the framework, see **Error! Reference source not found.**, with the exception of Resources and Communication. None of the elements in the Company's framework appears to address either Resources or Communication.

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

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

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

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

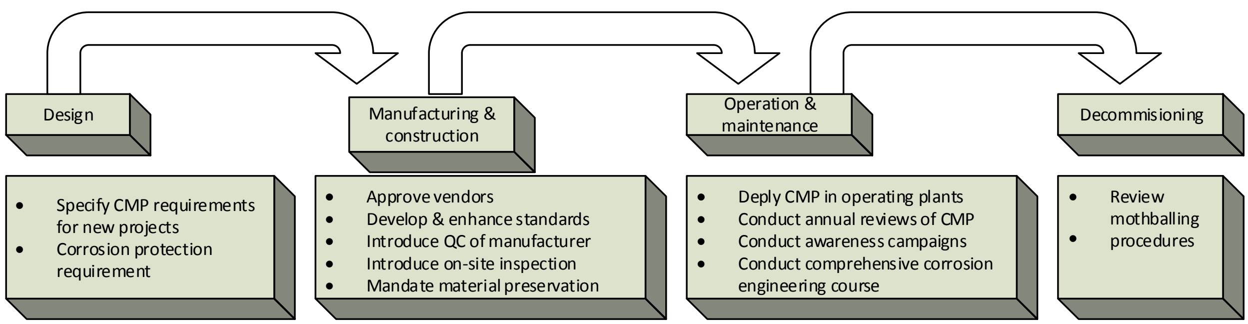


Figure D-1. Corrosion Management Applied to an Asset's Life Cycle

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

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

- Major corrosion challenges.
- Potential damage mechanisms.
- Performance measures.
- Corrosion management strategies.
- New technologies.
- Recommendations.

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

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

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

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

D.2 CASE STUDY OF MAINTENANCE OPTIMIZATION

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

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

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

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

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

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

Example Case Study of Pipeline Internal Corrosion

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

The pipeline of interest is 24-inch I.D. carbon steel with 0.4-inch wall thickness and is divided into four segments named alpha, beta, gamma, and delta. In segments alpha, beta, and gamma, the operating pressure is 500psi and the pressure drops to 100psi in segment delta. The transported fluids contain gas and water phases. At 500psi, CO2 partial pressure is 10psi, H2S 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 CO2 and 0.02psi H2S) 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 D-2.

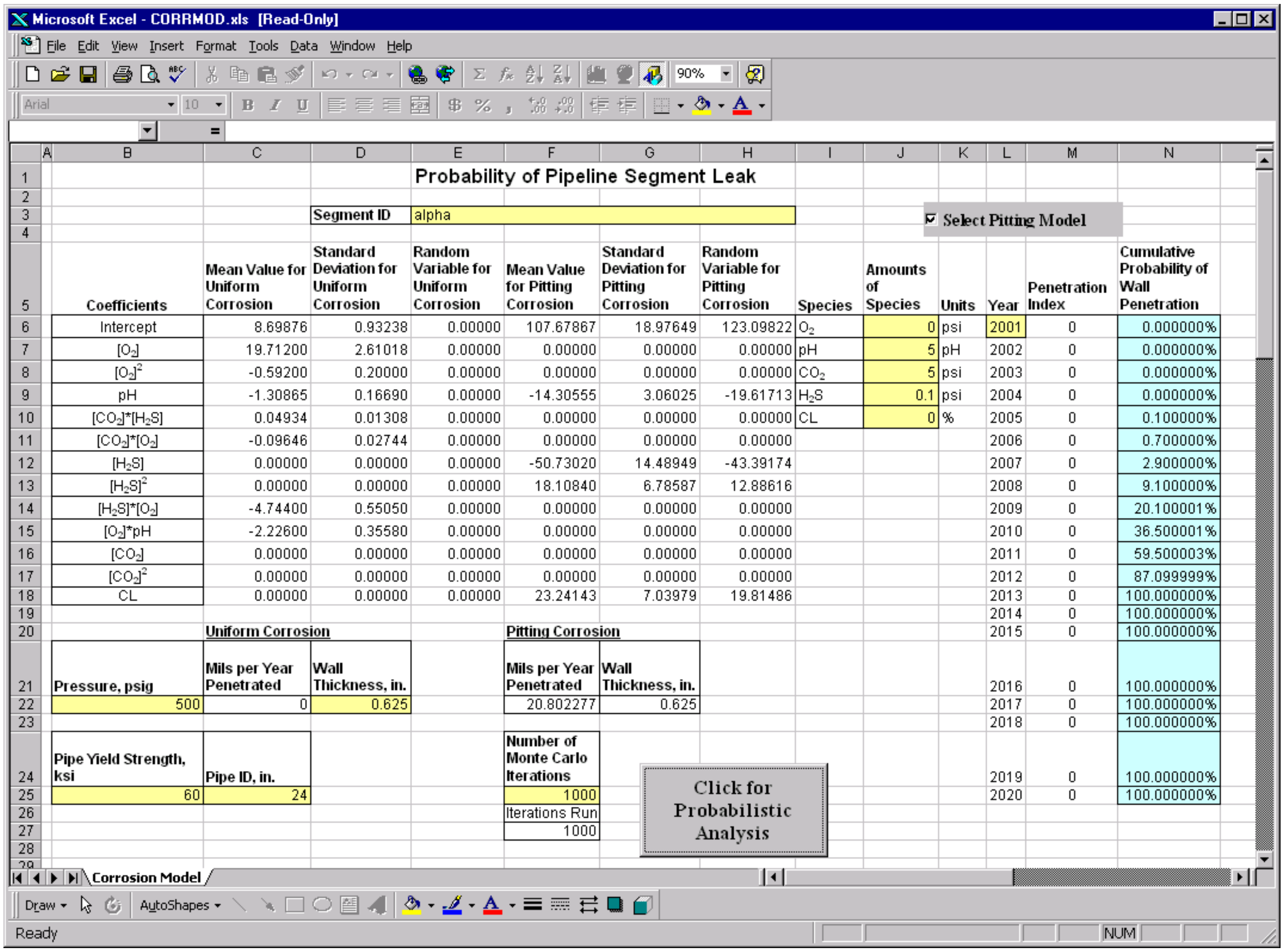
- For segments alpha, beta, and gamma, the following data was entered
  - Concentrations of corrosive species; O2 is zero, pH is 5, CO2 is 5psi, H2S is 0.1psi, Cl- is 0%
  - Year 2001 was used to start prediction
  - Line pressure and wall thickness is 500psi and 0.625 inches
  - Pipe Yield Strength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

Risk Assessment and Maintenance Optimization

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

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

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



Microsoft Excel - CORRMOD.xls [Read-Only]

Probability of Pipeline Segment Leak

Segment ID: alpha

☑ Select Pitting Model

Coefficients	Mean Value for Uniform Corrosion	Standard Deviation for Uniform Corrosion	Random Variable for Uniform Corrosion	Mean Value for Pitting Corrosion	Standard Deviation for Pitting Corrosion	Random Variable for Pitting Corrosion	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 D-2. Screen capture of Corrmod.xls software.

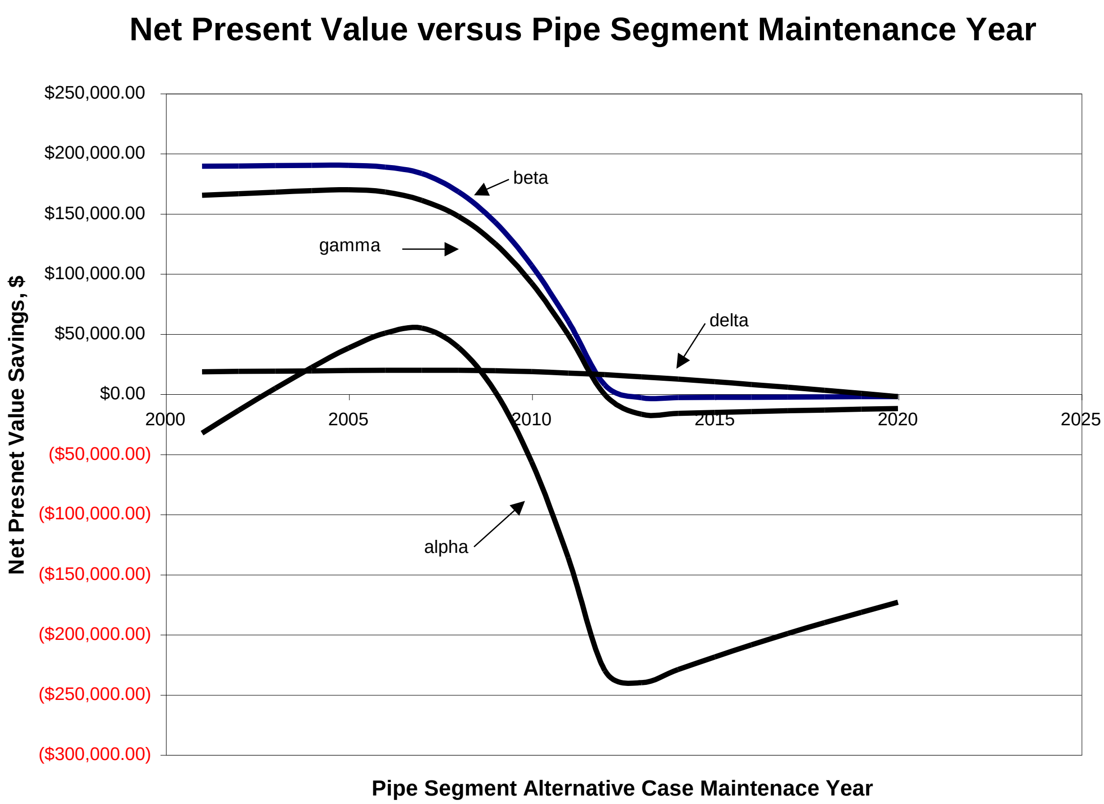


Figure D-3. Results of example problem to determine cost effectiveness of liner installation

D.3 PREDICTING THE IMPACT OF CORROSION UNDER INSULATION FOR AGING PLANTS: A BAYESIAN NETWORK APPROACH

Introduction

Thermal insulation is used refineries, chemical plants, oil and gas production systems, pipelines, and many other applications. Unfortunately, Corrosion under Insulation (CUI) is a common and costly problem in industry. In the case of carbon steel, CUI takes the form of general and localized corrosion. Although the resulting corrosion rate is somewhat low (0.1 to 0.8 mm/y), the corrosion is hidden for long periods of time leading to unanticipated failures. In the case of stainless steel, stress corrosion cracking, often called external stress corrosion cracking (ESCC), can occur under the insulation. Since the rate of cracking can be quite high, ESCC is of great concern to operators. Despite much effort devoted to managing CUI[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 Tntonio, TX, ASTM International.

[2] ASTM (2007). Standard Guide for Laboratory Simulation of Corrosion Under Insulation. 100 Barr Harbor Dr., W. Conshohocken, PA, ASTM International. **G 189-07**.

[3] NACE (2010). Control of Corrosion Under Thermal Insulation and Fireproofing MaterialsA Systems Approach. Houston, TX, NACE International. **SP0198-2010:** 42.

[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 D-4. All the factors that can lead to CUI of carbon steel and stainless steel can be lumped into three major categories: Insulation System, Design, and Environment (shown as color coded sets of bubbles). These factors affect other causative factors, such as time of wetness, that then affect corrosion or ESCC. The corrosion rates are in the range observed by Kurihara et al.[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 D-5.

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[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.

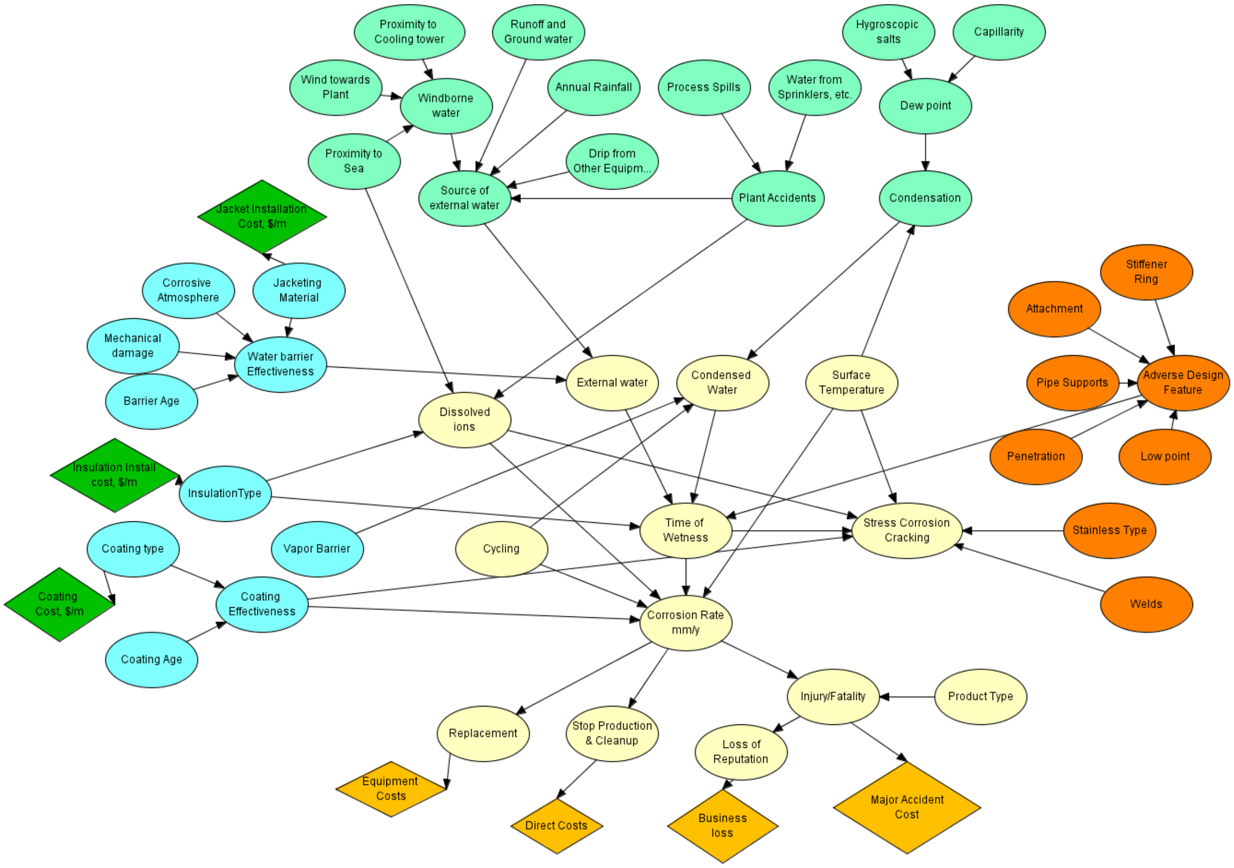


Figure D-4. A BN representation of CUI of carbon steel and stainless steel.

Prediction of the business impact of CUI

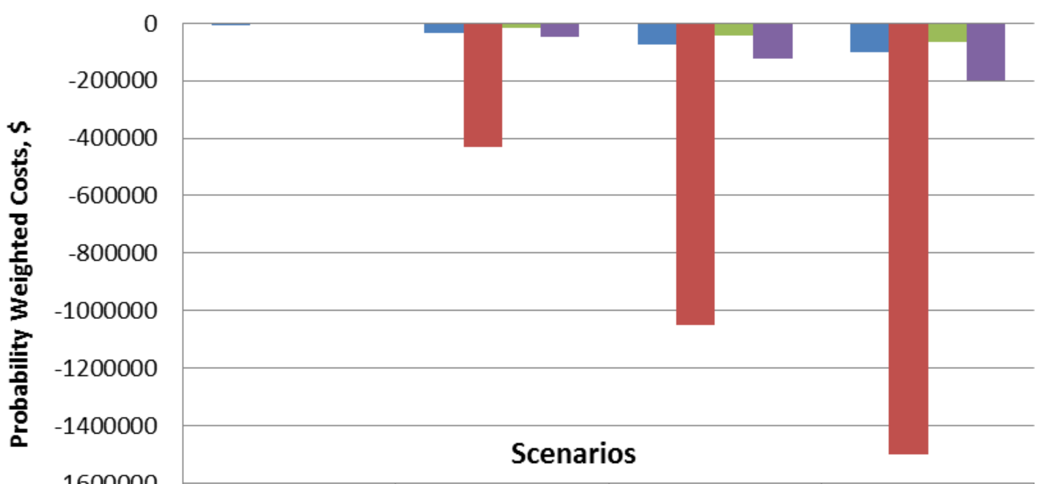
The predicted business impact could be a valuable KPI for operational leaders to make risk-informed decisions, based on their risk appetite and internal decision criteria. The business impact criteria are defined as follows:

- 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 labor 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 D-4 through utility nodes (diamond-shaped nodes). By connecting the failure consequence nodes to the corrosion node, the business impact can be calculated in a probabilistic manner. Furthermore, by assigning utility nodes to various maintenance activities such as, improved coating and insulation, the BN enables risk informed maintenance decisions.

A number of scenarios can be constructed on the basis of inputs to BN as illustrated in Figure D-5 and the corresponding business impacts can be estimated (costs are shown as negative numbers). For example, in Scenario 1, the surface temperature is low and therefore the corrosion rate is likely to be low leading to a low probability of failure and injury/fatality. Therefore, most business costs (other than maintenance costs) are low. On the other hand, if the surface temperature is 60° 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 D-5. Examples of Estimated Business Costs for a Number of Scenarios Calculated by BN Shown in Figure D-4. Note: the cost numbers are mainly illustrative and do not represent actual values.

Uses and Limitations of Bayesian Networks

BN allows us to combine expert opinions, data, and analytical models in a single framework.

1. Since many aging plants have missing historical and design data, we can initially assume that the probability of data attaining a certain value is the same (called uniform probability) and proceed with the analysis. Of course, the resulting probability calculations may have significant uncertainty, and have to be updated with suitable data.

In order to obtain more data cost-effectively, BN's can provide analyses of the value of information on the resulting calculation of a variable of interest (e.g., probability of corrosion rate). This permits the user to allocate resources to factors that most impact risk. An example of such a calculation is shown in Figure D-6. The importance essentially reflects the effect of reducing the uncertainty of a factor (e.g., surface temperature) on narrowing the probability distribution of the variable of interest (corrosion rate in this case).

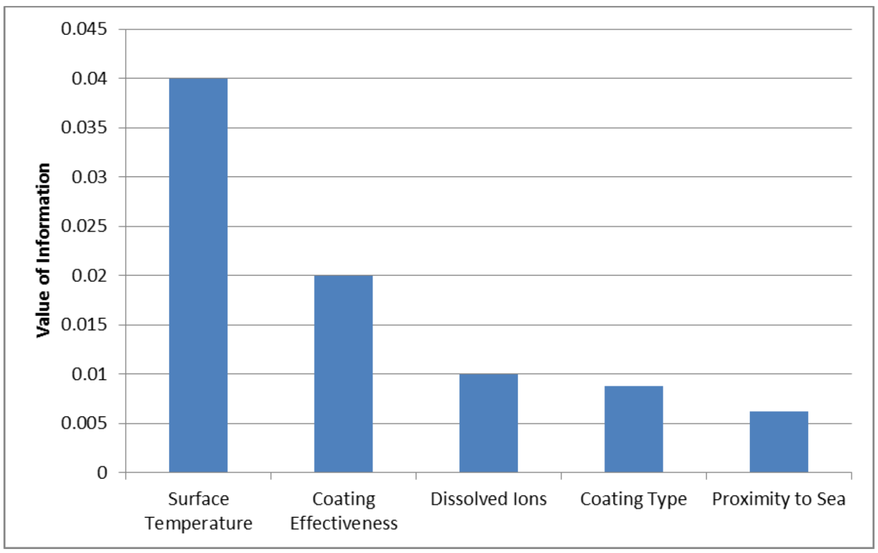
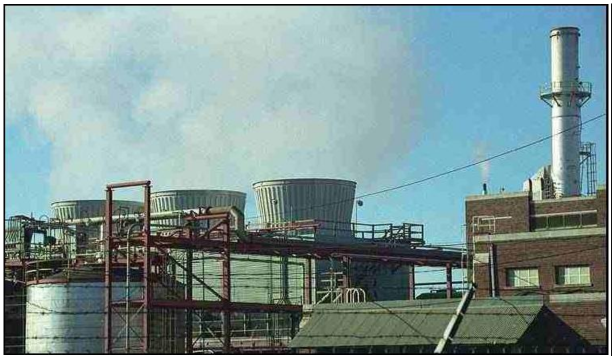


Figure D-6. Value of information analysis of Bayesian network for CUI

D.4 DEPARTMENT OF DEFENSE CORROSION PROJECT CASE STUDIES WITH CALCULATED ROI

FAR03: Green Water Treatment

Project Number	FAR03
Project Title: Green Water Treatment	



The MIOX mixed oxide disinfectant system has been installed in cooling towers at Corpus Christi Army Depot

Purchase, transportation, and storage of corrosive and hazardous chlorine compounds are eliminated

Fiscal Year	2006
Service	Army
Major Category	Equipment
Purpose	Across the three implementation sites (Ft Rucker, West Point, Ft. Wainwright), the non-hazardous inhibitor formulations and smart-monitoring and control systems will be implemented in an estimated 10 heating and 10 cooling systems. Additional heating and cooling plants at installations in the region will be inspected to assess the efficacy of installing the smart corrosion control system at these sites (ultimately Corpus Christi Army Depot was selected). Specifications for non-hazardous boiler and cooling tower treatments and the smart control system will be developed, and the systems will be installed. Training on system operation and maintenance will be provided to the installations. The operational efficiency of the heating and cooling systems will be determined, and downtime due to corrosion failure, safety and environmental impact will be assessed.
Technology	A new chemical formulations for heating and cooling systems have recently been introduced, most notably in the areas of environmentally friendly, or “green” chemical formulations such as the MIOX mixed oxidant process and glycol alternatives for treating boiler and cooling systems combined with smart monitoring and control systems that use just enough chemicals, when needed to maintain optimal treatment levels for corrosion, scale, and microbiological growth.
Application	This technology was developed in the 1980’s in response to the Army’s solicitation for a simple, portable alternative water purification system. In addition to cooling towers, the technology can be scaled for use in swimming pools, wastewater treatment, and hand-held units for field disinfection of potable water.
Benefits	The goals of the project are: improving the reliability and reducing the cost of operating and maintaining boilers and cooling towers by using non-hazardous corrosion inhibitors and a smart control system. The objective is proper design and installation of the chemical feed and control system, and continuous operation and chemical feed.

Lessons Learned	The type of salt selected for developing the brine may negatively impact system performance. If food-grade table salt is used, it must be mixed in a brine tank containing a settling bed of quartz rocks. The quartz remains chemically inert in the carrier fluid, but the gravel allows suspended salt crystals to settle to the bottom of the tank, where the salt can dissolve quiescently at the intended rate, undisturbed by water turbulence. With-out the settling bed, salt sediment may flow through the system and clog downstream filters. In order to avoid the need for a quartz settling bed in the brine tank, the use of pelletized forms of salt is recommended.
Transition Status: Ongoing ROI: 9.4	ROI Validation states that it is recommended that the managers of U.S. military installations fully utilize a system of MIOX for reduction of microbiological growth in cooling towers. It also states that changes were recommended to UFGS 23 64 26 to incorporate the mixed oxidants process of chemical treatment for cooling tower systems. The revised criteria documents listed above will be submitted to HQ USACE (CECW-CE) for inclusion in the criteria update cycle. Recommended changes to current UFGSs and UFCs will be submitted on line through the Whole Building Design Guide website.

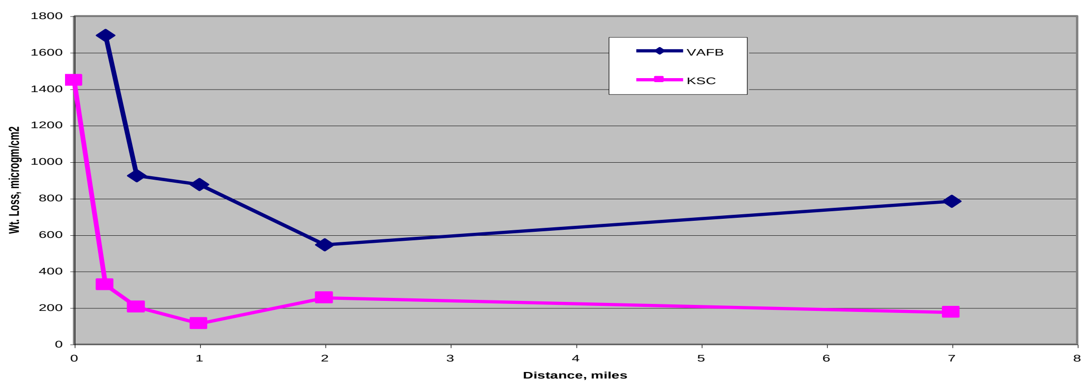
FAR13: Coating System for CP and Fire Resistance for metal Structures

<table>
<tr><td>Project Number</td><td>FAR13</td></tr>
<tr><td colspan="2">Project Title:
Coating System for CP and Fire Resistance for metal Structures

Purchase, transportation, and storage of corrosive and hazardous chlorine compounds are eliminated
</td></tr>
<tr><td>Fiscal Year</td><td>2006</td></tr>
<tr><td>Service</td><td>Army</td></tr>
<tr><td>Major Category</td><td>Coating</td></tr>
<tr><td>Purpose</td><td>The goals of the project are: Reducing the corrosion rate of the structural steel and increasing fire safety for the structures at Rock Island Arsenal, as well as validating the technology for other uses across the DoD.</td></tr>
<tr><td>Technology</td><td>Intumescent coatings are based on traditional paint resins, such as solution vinyl, latex, and epoxy, and are applied as thin films like traditional paints. The resins allow the coatings to form tight bonds to structural surfaces. When exposed to fire, the intumescent coating reacts by expanding. It is transformed to a thick, ceramic-like, insulating char that provides thermal protection for the substrate.</td></tr>
<tr><td>Application</td><td>Candidate structures at Rock Island Arsenal will be assessed for application of the intumescent epoxy system. The coating system will be applied to one hangar and one additional structure selected by the installation.</td></tr>
<tr><td>Benefits</td><td>Because the Pitt Char XP Fire Protective Coating is an epoxy, it resists solvents, acids, alkalis, salts and abrasion while retaining its fire protective properties. The coating bonds tightly and cures to form a dense, impervious barrier that blocks corrosives such as salt spray and moisture. It is a tough coating that withstands damage from impact. The coating is unique in that it is flexible, with elongation over 19%. It will adhere to structural steel and other metals, and fiberglass reinforced composites.</td></tr>
</table>

Lessons Learned	Bid / Contract Scope language needs to be very specific. All parties need to agree in writing on the scope of the project. A coating system test panel should be approved by all parties and be retained to serve as a reference for all work on the structures. Plans for movement of material and equipment must be coordinated among all parties. Planned start date should take into consideration the time of year and normal temperatures ranges typically encountered. Placement of waste receptacles onsite and timely pick-up of waste such as spent abrasive media and paint and solvent wastes should be coordinated in advance with an approved local waste disposal company.
Transition Status: Ongoing ROI: 8.8	ROI Validation states that the following impacted criteria documents were identified: UFGS 07 81 00 Spray-Applied Fireproofing and UFC 3-600-1 Fire Protection Engineering for Facilities. Changes were recommended to the UFGS to incorporate epoxy intumescent fireproof coatings. Recommended changes were incorporated into the February 2011 release. It is recommended that a product specification be adopted by The Society for Protective Coatings (SSPC) or the Master Painter's Institute so that the product specification can be referenced as a system. Revisions to UFC 3-600-1 will be submitted to HQ USACE (CECW-CE) for inclusion in the criteria update cycle. An analysis was performed with Army IMA (now IMCOM) to determine the important factors for Army

FAR15: Development of Corrosion Indices and Life Cycle Protection

Project Number	FAR15
Project Title: Development of Corrosion Indices and Life Cycle Protection  The MIOX mixed oxide disinfectant system has been installed in cooling towers at Corpus Christi Army Depot	
Fiscal Year	2006
Service	Army
Major Category	Other
Purpose	The proposed FY06 work will develop a life cycle predictive tool to optimize preventive maintenance cycles based on region and material, for weapons and facilities. The predictive tool will be a location based corrosivity software model that will draw on the data acquired in the FY05 project. The downloadable software package which will assign a corrosion index to a site based on environmental data.
Technology	Corrosion growth can be projected with the use of appropriate models. The mechanical impacts of this damage can then be ascertained using structural models. This approach requires the development of multiple technologies and extensive amounts of data. Not only is extensive corrosion and structural modeling required, but also part specific damage definitions must be developed with the associated NDI techniques. This complex effort will determine microclimate environmental severity factors and the associated corrosion growth rates. The prediction and management of corrosion damage requires first that the initial condition of the specific structure with respect to corrosion be defined. Subsequently the severity of the environment to which the structure is exposed must be measured and the time that the structure is exposed to that environment projected. The corrosion growth can then be projected with the use of appropriate models. The mechanical impacts of this damage can then be ascertained using structural models. This approach requires the development of multiple technologies and extensive amounts of data. Not only is extensive corrosion and structural modeling required, but also part specific damage definitions must be developed with the associated NDI techniques. This complex effort will determine microclimate environmental severity factors and the associated corrosion growth rates. This project will build a software based model of corrosion
Application	Material and process selection can be tailored for both equipment and facilities DoD-wide based on the corrosion index. The efficacy of the corrosion index will also be determined for various environments.

Benefits	The corrosion index will allow the user to develop select appropriate corrosion resistant materials, coatings, cathodic protection and water treatment for use in project specifications and maintenance practices.
Lessons Learned	Tests of the models have shown that a major limitation is that location for the predictions must be in proximity to the location where the weather da-ta are collected. This is particularly true in coastal locations adjacent to saline bodies of water. At this time it is estimated that the point of weather data collection is optimum at 0.25 miles or less from the location of interest.
Transition Status: Implemented ROI: 33.1	ROI Validation states that this work resulted in linear models of an atmospheric corrosivity rate model based on geographic location. These models have been incorporated into a software package. The models can be run from a PC and allow the user to display corrosion rates/severity levels for locations in the database along with confidence intervals on the results. In addition, the user can calculate corrosion rates for new locations that have not been previously monitored provided that the appropriate weather data are available. The software is available through the DoD Corrosion Defense (CorrDefense) website, www.corrdefense.org.

FAR16: CP of Rebar in Critical Facilities

Project Number	FAR16
Project Title: CP of Rebar in Critical Facilities	



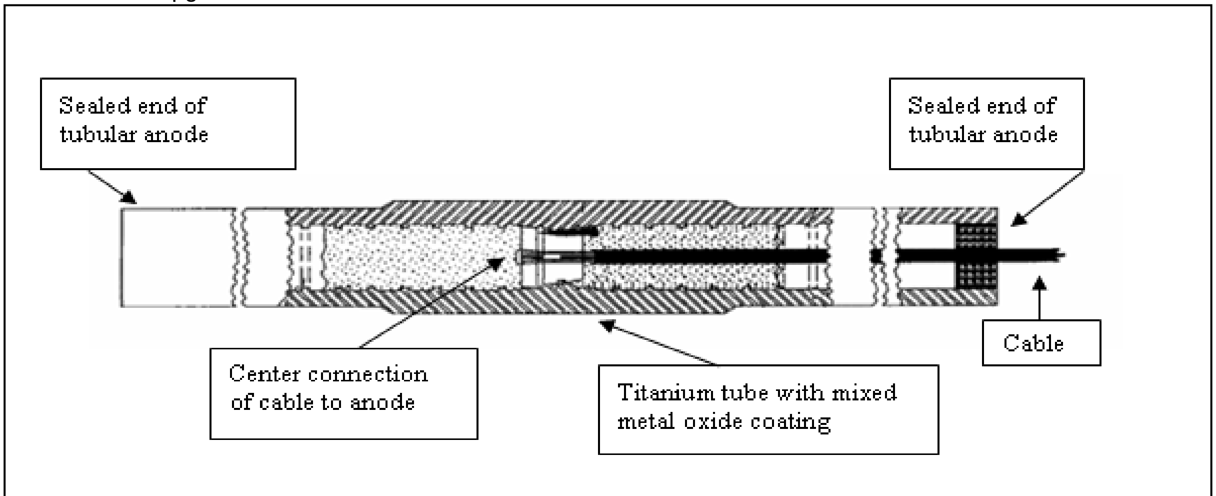

Fiscal Year	2006
Service	Army
Major Category	Coating
Purpose	Corrosion Prevention of Rebar in Concrete in Critical Facilities Located in Coastal Environments at Okinawa.
Technology	Corrosion protection for the rebar can be established through the use of a zinc-rich cathodic protection compound that can be applied to the concrete deck. The phenomenon of “sacrificial” cathodic protection is based on the ability of a more active metal, such as zinc to easily loose electrons when electrically connected to steel rebar, while an ionic current flows via moisture through the pores of the concrete. This establishes an electrochemical reaction that results in the steel rebar becoming the cathode, while the zinc-rich coating becomes the anode, and is “sacrificed,” and slowly oxidizes over many years. In this case, the rebar is said to be cathodically protected.
Application	The cathodic protection compound can be applied to uneven surfaces and to the underside of structures. It is recommended for bridges, parking decks, ramps, garages, concrete piers, offshore platforms, piles, pillars, pipes, buildings, foundations and underside application to structures of many sizes and shapes. One gallon is used for 160 sq. ft. of the concrete structure.

Benefits	The zinc-rich urethane coating contains particles of magnesium and indium, as well as moisture-attracting compounds that facilitate the protection process. It is applied easily by spraying, brushing, or rolling, and is particularly suited to applications such as bridges, decks, ramps, concrete piers, offshore platforms, and foundations. The coating also can be applied to uneven surfaces and to the underside of structures, as well as to vertical, horizontal, and overhead surfaces, and to structures of many shapes.
Lessons Learned	Corrosion inhibitors are generally applied to clean concrete surfaces and allowed to penetrate and dry. The allocated time and rate are usually a function of the ambient environment and manufacturers recommendations for installation of the particular brand or product. Therefore, the climate and environment the application is used in has to be considered prior to application. Repairs need to be scheduled to coincide with application. It was difficult to use the Galvapulse method to determine the corrosion rate on the LGC coating as the titanium mesh distorted readings. Rilem water tubes will not seal well to a coated surface, and it was difficult to perform the water permeability test following treatment of the structures.
Transition Status: Ongoing ROI: 12.9	ROI Validation states that this corrosion prevention technology is not covered in any UFC or UFGS. ERDC-CERL has prepared the draft Unified Facilities Guide Specification for submission to HQ USACE (CECW-CE) for inclusion in the criteria development cycle. An analysis was performed with Army IMA (now IMCOM) to determine the important factors for Army-wide implementation. This analysis also showed potential for DoD-wide application.

FAR20: Ceramic Anode Upgrades at Ft. Jackson

Project Number:
FAR20

Project Title
Ceramic Anode Upgrades at Ft. Jackson



Fiscal Year	2006
Service	Army
Major Category	Material
Purpose	At Ft. Jackson, a new type of ceramic anode will be used to protect underground pipes, which will be installed in deep wells 50-100 feet deep. The deep-well ceramic anodes will be in soil that has a 20-70 ft. water head, and the connection between the anodes and the cable is the weakest link, which must be protected.
Technology	The solution to the problem of natural gas line protection is the installation of a cathodic protection (CP) system consisting of deep well ceramic anodes. Impressed CP systems protect the buried pipe by supplying electrons from the ceramic anodes that are made to assume a negative potential relative to the pipe. The mixed metal oxide ceramic anodes are to be installed in 4 strategic locations in 200 feet deep below the ground. Installation of deep well impressed current ceramic anode beds help to more widely distribute the protection current from ceramic anodes to protect pipelines.
Application	This CPC proposal seeks to demonstrate the efficacy of the CP technology in conjunction with remote monitoring at Ft. Jackson.

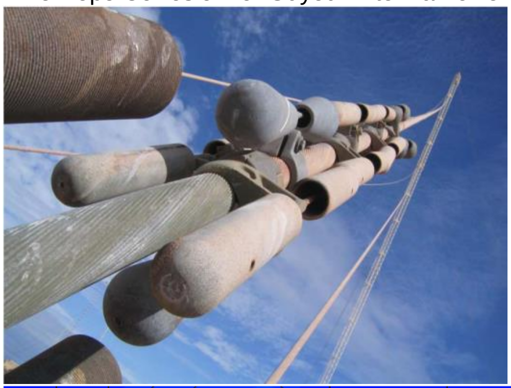
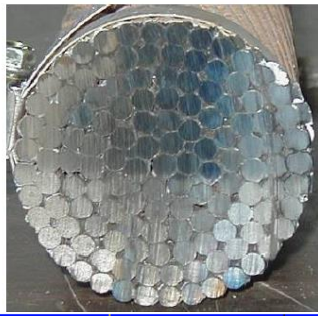
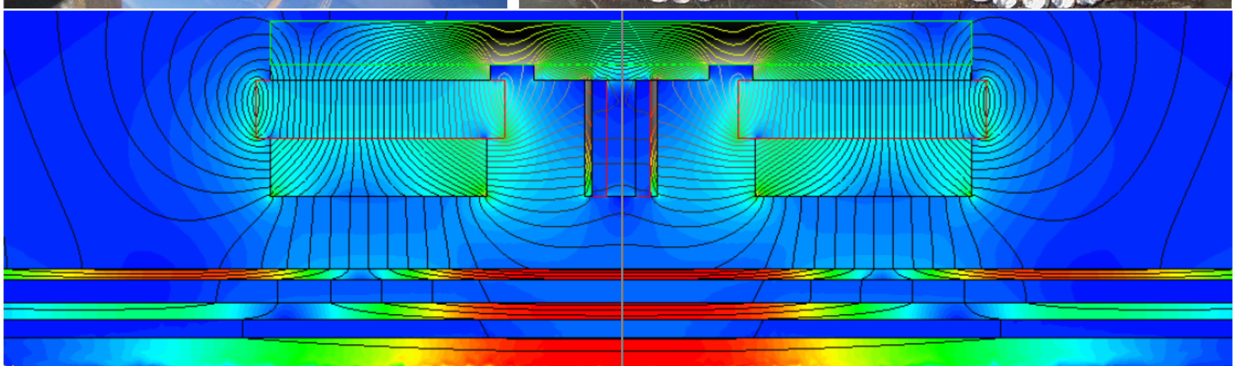
Benefits	It is expected that the implementation of these technologies will bring the natural gas piping system into compliance and extend the lifetime of the water tanks.
Lessons Learned	On many installations piping and other underground systems have been replaced or moved and documentation of these changes have not been consistently recorded in one easy to access place. The many variances in the soil types and depths at Fort Jackson presented another need for having contingency plans as bedrock was encountered at varying depths. If the piping system is not properly isolated, cathodic protection of the sys-tem is much more difficult to achieve.
Transition Status: Ongoing ROI: 14.7	The following impacted criteria documents were identified: UFGS -26 42 15.00 10, Cathodic Protection System (Steel Water Tanks), and UFGS -26 42 17.00 10, Cathodic Protection System (Impressed Current). Changes were made to these documents to incorporate ceramic anode technology for deep bed impressed current CP systems. Suggested changes are contained in the final report (ERDC/CERL TR-09-26). The revised criteria documents listed above will be submitted to HQ USACE (CECW-CE) for inclusion in the criteria update cycle. Recommended changes to current UFGSs and UFCs will be submitted on line through the Whole Building Design Guide website. Transition to American Water Works Association (AWWA) guidance is being explored. An analysis was performed with Army IMA (now IMCOM) to determine the important factors for Army-wide implementation. This analysis also showed potential for DoD-wide application.

FNV01: CP Utilizing IR Drop Free Sensors

Project Number	FNV01
Project Title: CP Utilizing IR Drop Free Sensors 	
Fiscal Year	2006
Service	Navy
Major Category	Sensor
Purpose	Improved corrosion (cathodic) protection (CP) monitoring systems are needed for cross-country pipelines such as the pipeline on Guam that runs from the Navy fuel distribution pipeline manifold at Tiyan to the Andersen Air force Base Tank Farm.
Technology	Potential measurements of underground structures made with portable reference electrodes placed on the surface or buried permanent reference electrodes often contain an error known as IR Drop error. IR Drop error results from the interaction of the cathodic protection current with the soil resistance. One way of accounting for this error is to momentarily interrupt the cathodic protection current and measure the potential immediately after interruption. This so-called instant-off potential can be substantially free of IR Drop error. It is nearly impossible to feasibly interrupt cathodic protection current on structures protected with distributed sacrificial anodes. Even in cases where current interruption is possible, there may be other sources of current at that location such as those from nearby cathodic protection systems, stray currents or telluric currents. Cathodic protection coupons, sometimes called instant off sensors, have been developed as a means to make instant off potential measurements under virtually all conditions.

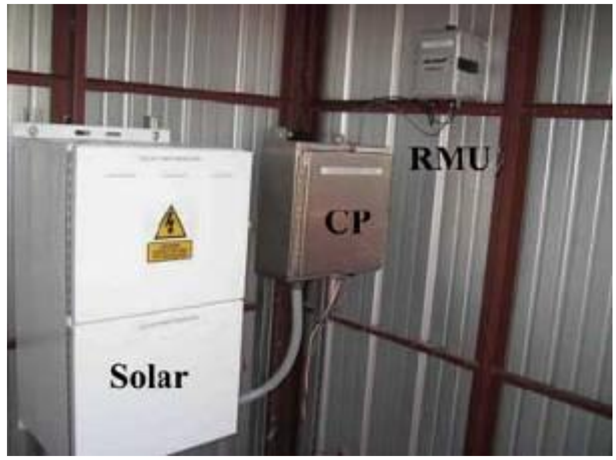
	A transponder/data logger has been implemented in metropolitan street environments where access to cathodic protection system test points is limited by vehicle traffic and pavement. In this project we will be utilizing this technology a step further for novel application in a cross-country environment with severe conditions.
Application	Successful implementation of this technology system on the Tiyan pipeline in Guam will validate its transition for use on other Navy and DOD cross-country pipelines, as well as other critical facilities that utilize cathodic protection systems. These facilities include waterfront structures, potable water tanks, and utility piping.
Benefits	Due to the difficulty in locating the test stations in this severe cross country environment with overgrown brush and constant movement of soil that bury the test stations, IR drop free sensors will be integrated and installed with interrogator transponders and data loggers that will record output over time and will enable identification of location and wireless measurement of desired parameters.
Lessons Learned	.
Transition Status: Implemented ROI: 11.4	ROI Reassessment states that based on the test results to date, we can conclude that the IR free coupons are functioning well, and valid IR drop error free structure to electrolyte potentials are being obtained. This provides valuable data that can assist in the prevention of pipeline leaks and avoid high environmental cleanup costs. The use of the drive by data interrogation system theoretically reduces annual testing costs. Ideally, utilizing such data acquisition system would reduce the man power and survey time. Radio frequency transmission modules, however, have exhibited problems. Even when the units were operating, the time and manpower required to obtain the data exceeded that of the traditional cathodic protection survey. In situations where battery or component failure was encountered, many man-hours were spent mitigating the problems. Therefore, the cost savings associated with reducing annual system testing costs were not realized, and the originally estimated ROI of 13.27 is not considered to be valid. A new calculation without this cost savings yields an ROI of 11.41.

FNV06: Wire Rope Corrosion for Guyed Antenna Towers

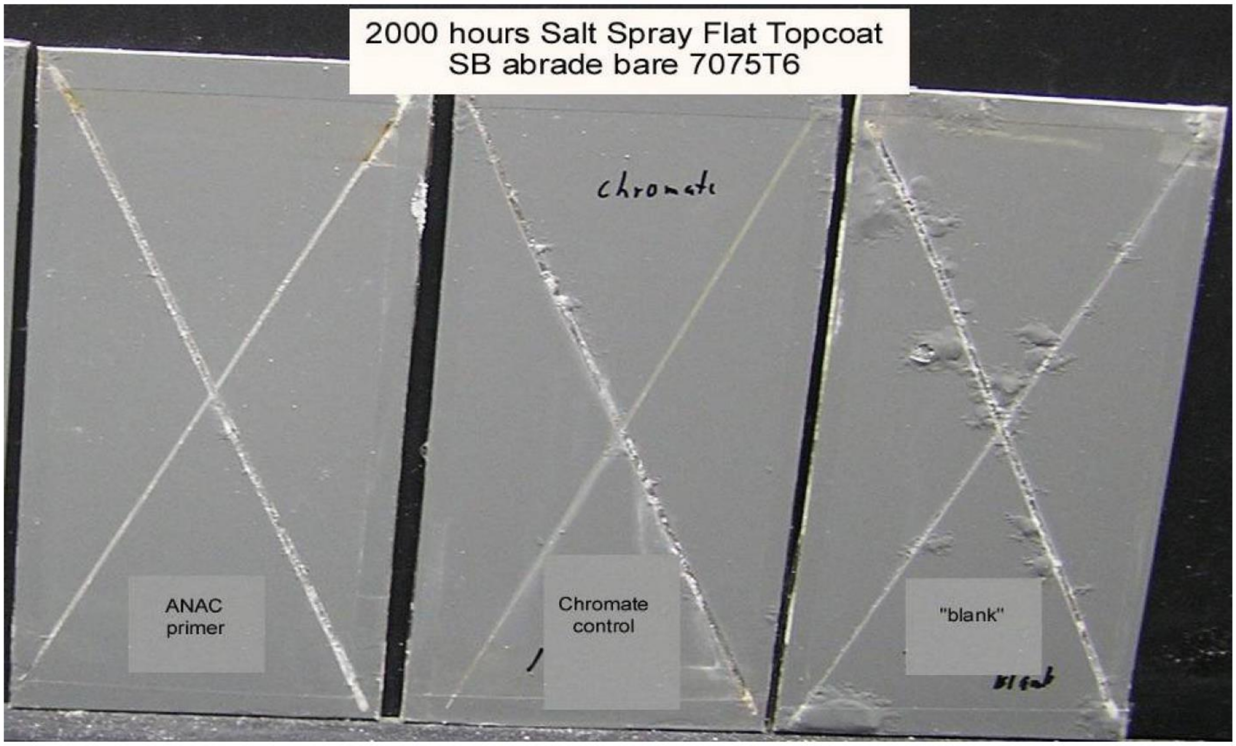
Project Number	FNV06
Project Title: Wire Rope Corrosion for Guyed Antenna Towers    	
Fiscal Year	2006
Service	Army
Major Category	Equipment
Purpose	We propose to develop a corrosion control process that reliably measures and monitors guy wire corrosion over time and space. In particular, we will develop a reliable corrosion inspection tool that will ride remotely along each guy wire and measure the corrosive state along the full length of each and every guy wire.
Technology	We will develop the tools for inspecting each guy wire along its full length. We currently rely on telescopic visual inspection from the ground and the tower. Due to the length of the guy wires there is only a short section of each guy that is accessible for meaningful visual examinations, this being the lower and upper sections of guy wire. Such visual inspections are also incapable of measuring swelling or determining internal corrosion along most of the guy. We will determine which set of techniques work best for our larger diameter (~ 4 inches) guy wires, and then package these methods on a “vehicle” that can travel along each of our guy wires.
Application	After verifying the effectiveness of this wire rope inspection tool in the lab, we will use it in the field to measure the corrosive state of all 357 guy wires that hold up the antenna at Holt, NW Cape, Australia.
Benefits	The primary deliverable will be a guy wire inspection tool and a process for managing corrosion of the guy wires at all VLF/LF antenna sites. As a secondary deliverable, we will generate a timetable for guy wire replacement at our Holt antenna that will help manage guy wire replacement by minimizing cost and maximizing antenna availability.
Lessons Learned	Initially, we had hoped to cover the entire cost of buying and testing the guy inspection Tool with DOD-CPC funds, and then use matching NNWC funds to inspect as many guys as possible at the Holt (Australia) antenna. Unfortunately, the Tool is made of materials (rare earth magnets, copper, etc.) that have recently become very expensive, so the original goal was not achievable. In addition, the large magnets needed for a large-diameter Tool generate very large internal forces, making them difficult to handle safely for development and testing purposes.

Transition Status: Ongoing ROI: 55.6	The ROI Validation states that the project plan was implemented at a smaller diameter prototype than large diameter guy inspection tool needed for full intended fleet use. Implementation became part of second CPCP project for large diameter guy inspection Tool. Fleet implementation is still valid as planned. Since completion of project, guy corrosion has accelerated more rapidly than assumed in original project plan, making implementation of final large diameter guy inspection tool ever more critical. Project is being continued under F09NV09.

FNV07: Solar Powered Cathodic Protection System

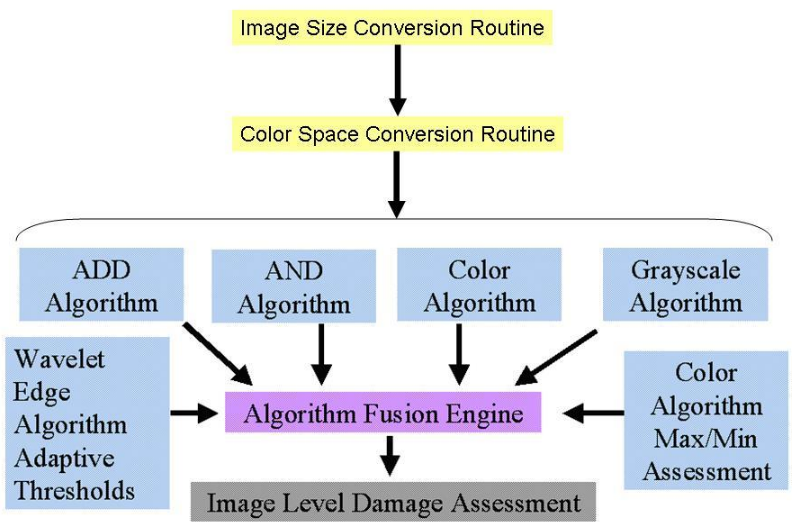
Project Number	FNV07
Project Title: Solar Powered CPS 	
Fiscal Year	2006
Service	Army
Major Category	Equipment
Purpose	This project proposes to demonstrate a solar powered CP system using recently developed high efficiency (96-98%) controls that have flexibility to match the anode ground-bed (and its fluctuating conditions).
Technology	The CP system would be a straightforward impressed current CP system design and installation with the exception of the power supply. Instead of a conventional AC powered rectifier, a solar-power supply and control system would be specified. Design and installation will be accomplished by existing contracts.
Application	Installation of a Solar Powered CPS at Guantanamo bay. Underwater water utility and fuel pipelines traverse Guantanamo Bay, Cuba in service of the Naval Station Guantanamo Bay. Recent studies have indicated that the pipelines are not adequately protected on the eastern side of the bay by the cathodic protection (CP) on the western side of the bay. Installation of an additional conventional impressed current CP system on the eastern side of the bay would be relatively simple if AC power was readily available. However, demolition of obsolete housing units as a result of base realignment caused the deletion of the electrical distribution system in this vicinity of the base. AC power is therefore no longer readily available.
Benefits	The primary deliverable for this project will be a well- controlled solar powered cathodic protection system that will fully and adequately protect water and fuel distribution pipelines from corrosion and result in expected pipeline service lives of 20+ years with little risk of detrimental impacts to personnel safety and environmental damage associated with corrosion caused leaks.
Lessons Learned	Design agency engineers and technical exerts should carefully review the design drawings and specifications. Award for the MACC contract was delayed for three months because the difficulty the contractor encountered in obtaining bid bonds for the Guantanamo Bay area. Construction was delayed for nearly six months due to difficulties in shipping construction materials to Guantanamo Bay. Periodic monitoring of the system operation was difficult due to the remoteness of the site.
Transition Status: Implemented ROI: 3.0	The initial estimated ROI has been revised to reflect estimated power consumption savings, based on current operating status. The original power cost savings was based upon full output of the previously existing CP rectifier. The solar CP system is operating at a lower output. After the three plus years the remote monitoring unit (RMU) battery was found to be depleted. Findings were similar for other RMUs from the same manufacturer. The new system costs have been revised to include the cost of battery replacement every three years. The revised ROI is 3.02. A new type of RMU will likely be installed to eliminate this battery replacement requirement or decrease the frequency of battery replacements.

WAF01: Magnesium Rich Primer for Chrome Free Aircraft Coating Systems

Project Number	WAF01
Project Title: Magnesium Rich Primer for Chrome Free Aircraft Coating Systems  	
Fiscal Year	2006
Service	Air Force
Major Category	Coating
Purpose	A one-year OSD funded project is proposed for corrosion prevention and control that will: 1. Facilitate the refinement of Mg-rich primer prototype formulations to MIL-SPEC qualified commercial products, 2. Evaluate the performance of resultant Mg-rich primers with existing non-chrome surface treatments and topcoats as completely chrome-free coating systems, and 3. Obtain field-level performance evaluation of down-selected Mg-rich based chrome-free coating systems.
Technology	Because Mg is more active (i.e., anodic) in the galvanic series than aluminum and its alloying constituents, it will cathodically protect the substrate until the Mg particles present in the coating film are consumed. Prototype Mg-rich primer formulations that were initially developed and tested at NDSU displayed effective AA 2024-T3 corrosion protection out to 3,500 hours of B-117 salt spray.
Application	Mg-rich based chrome-free coating systems on non-critical Air Force and Navy aircraft components (e.g., hatches, access panels).
Benefits	The reduction and eventual elimination of chromate containing coatings for corrosion inhibition is of utmost importance to ensure the safety of DoD personnel and significantly reduce the financial burden related to hazardous materials handling and disposal.

Lessons Learned	Coatings must be evaluated and qualified on a system level basis rather than individually. Development of new coating formulations is an extremely difficult balance of obtaining desired properties that are often times mutually exclusive. There is a critical need for advanced accelerated corrosion testing methods that accurately predict long-term outdoor performance. When completely new classes of coatings are developed (such as Mg-rich), they may have unique testing idiosyncrasies that are not covered by current state of the art protocols. Hexavalent chromium is a better corrosion inhibitor than most give it credit and sets a very high standard for performance in development of a suitable replacement. In the search for Cr(VI) replacements, some performance trade-offs may need to be considered in order to be successful.
Transition Status: Ongoing ROI: 56.5	ROI Validation states that no organization is using the technology but the C-130 and B-52 program offices have approved field demonstration plans and will field test the technology on operation aircraft within the next year for consideration for implementation. Also, the F-16 is pursuing further testing of the Mg-rich technology for their weapon system. Implementation has not yet occurred but field test plans by two USAF weapon systems for a field test on an operation aircraft has been developed and approved. Aircraft will be coated within the 2011 year. Full implementation on an aircraft has not occurred but testing on aircraft continues.

WNS11: Corrosion Detection Algorithm for Ship's Topside Coatings

Project Number	WNS11
Project Title Corrosion Detection Algorithm for Ship's Topside Coatings  	
Fiscal Year	2006
Service	NAVY
Major Category	Sensor
Purpose	The intention of the Corrosion Detection Algorithm for Ship's Topside Coatings would be to utilize current and future image databases maintained by others as a source and archive for analyses performed by a Topside-CDA (TCDA).
Technology	Remote tank inspection devices have been successfully utilized to perform coating inspections in tank and voids spaces. This work has a tailored computer algorithm called the Corrosion Detection Algorithm (CDA) to quantitatively determine from video imagery the corrosion damage in tanks from 0.0-20% damage. The primary objective of the work in this proposal is to deliver a modified CDA which could be used to conduct damage assessments and to analyze images taken with a variety of hand-held digital cameras that meet minimal requirements.
Application	For tank and void spaces, conventional inspection practices were comprised principally of trained human inspectors. More recently, video inspection technology has allowed for the creation and implementation of image based analysis of corrosion and coatings damage. The Naval Research Laboratory (NRL) has designed and demonstrated such a system called the Insert able Stalk Imaging System (ISIS) and the adjoining software analysis package called the Corrosion Detection Algorithm (CDA). The current document proposes to leverage this technology for topside spaces in order to allow condition-based maintenance.
Benefits	This would allow for the routine inspection, imaging and analysis of topside spaces.
Lessons Learned	It is recommended that the Navy institutionalize a single Fleet wide "Topside Maintenance Protocol" for assessing topside coatings and defining where preservation is required. The methods that have been developed and demonstrated under this program should be capable of being directly applied, today in support of this type of Protocol when it is developed.
Transition Status: Ongoing ROI: 16.2	ROI Validation states that NRL has performed several full scale demonstrations of this technology on active Navy vessels which has aided in the development of a detailed inspection protocol for performing AFTCAT Inspections. This effort was supported by a NAVSEA PCoE program in 2011 and 2012. This protocol will be incorporated into the Topside and Freeboard Assessment Guide requirements owned by the Carrier Planning Activity (PMS312) during the

	next revision. Updated ROIs include additional funding received to support project transition and a plan for Fleet transition and implementation. NRL is currently working with the Carrier Planning Activity to update their topside and freeboard inspection requirements to include AFTCAT as the primary method for collecting coating and corrosion data of exterior surfaces.