Alternative Technologies for Corrosion Prevention – An Analytical Toolkit

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At the same time as we are attempting to improve corrosion protection in military systems we are faced with increasingly stringent environmental and health restrictions on our primary corrosion inhibitors – cadmium and hexavalent chromium. This has sparked a search for alternatives, but there tends to be an expectation that the alternatives will never match the high performance or low cost of the originals. However, our experience with corrosion and wear resistant technologies has been the opposite – that it is possible for new technologies to improve upon the performance of the old, and to do so at substantially lower life cycle cost. This is the case because the old standbys are often not as reliable as they are assumed to be, and newer technologies are frequently far superior. The process or materials costs of the new technologies tend to be higher, but often pale in comparison with the savings that accrue from improved performance.

In looking for better alternatives it is important to think outside the box, and consider technologies that at first may not seem to be the obvious options. And when evaluating the costs and benefits it is equally important to understand how the weapons system is made and maintained, and what drives its major life cycle costs, since the most important costs may not be at all the items that come up in a typical cost-benefit analysis.

There is no one, simple way to decide on the best alternative technologies. During the course of various projects for the US DoD we have developed a suite of analytical tools that we use in assessing clean alternative technologies for corrosion and wear reduction. Technology Analysis locates the best alternative clean technologies; two new cost-benefit decision tools help us understand the most important costs and cost savings; a new Implementation Assessment approach helps us evaluate the full costs, benefits and risks of adopting new technologies, while determining the most cost-effective way of going about implementing them; while an interactive roadmapping tool shows the best route to success in complex weapons systems.

This presentation will focus on the use of these various tools, with examples of some of the more interesting and surprising conclusions that have come out of our analyses of corrosion and wear alternatives.

1. Introduction

All military systems deteriorate over time due to wear, corrosion, and fatigue. But by far the most serious and costly problem is corrosion. Unlike wear, which we can usually detect by fluid leakage or fatigue, which can be predicted, corrosion is often difficult both to predict and to detect. It tends to be worst in the least accessible areas and often beneath paints. In its most insidious form – stress corrosion cracking – it is unpredictable and often undetectable until it causes catastrophic failure.

At the same time as we are recognizing the enormous cost of corrosion, the primary weapons that we have always used to fight it are being taken away because of ESOH (Environmental Safety and Occupational Health) concerns. Our primary corrosion inhibitors, Cd plate and chromates are now recognized as highly toxic, and the environmental and worker safety controls now being mandated will add enormous costs to sustainment over the entire life cycle.

As a result, the treatments that we have used because they were cheap and effective, are ceasing to be cheap, and in some of our most modern weapons systems they are highly restricted or banned. Finding alternatives is not trivial, especially for aircraft and weapons systems where reliable corrosion resistance is critical. These systems require extensive technical data in order to qualify alternatives. In order to meet the needs of the aerospace and defense industries, alternatives must

1. Show technical capabilities equal to (or exceeding) the original material
2. Have an acceptable up-front (purchase) cost
3. Have a lower life cycle cost
4. Fit with the life cycle requirements of the weapons system, including the ability to be maintained at the operational and depot level.

Absent an absolute ban on materials such as Cd and Cr^{6+} alternatives will in reality only be accepted if they demonstrate significantly improved performance or lower life cycle cost.

The question then becomes

- ☐ How do we find alternatives that offer better corrosion performance with lower life cycle cost?
- ☐ How do we evaluate their true costs and benefits?
- ☐ How do we get them qualified and into production?

2. The effects and costs of regulation

European regulations are primarily aimed at product content and disposal. Cd is banned and Cr^{6+} is highly restricted under the new European regulations for electronics and vehicles:

1. Restriction of Hazardous Substances in Electrical and Electronic Equipment (RoHS)[1]
2. Waste Electrical & Electronic Equipment (WEEE)[2]
3. End-of-life vehicles (ELV)[3]

Although at the present time military systems are exempt, and can still use Cd and Cr^{6+}, we are not exempt from worker safety rules or from the immense costs that stem from them – and it is these, not the disposal costs, that constitute the bulk of their life cycle cost. Furthermore, it is only a matter of time before the rules are extended to all types of products – both civilian and military.

With the exception of Cd, US regulations tend to focus on air emissions during production and sustainment operations. In the US, Cd and Cr^{6+} are also being increasingly regulated, as are VOCs and other HAPs. Worker exposure in manufacturing plants is covered by the Occupational Safety and Health Administration (OSHA) and plant emissions to the environment by the Environmental Protection Agency (EPA). Cr^{6+}, in particular, is coming under strict regulation, with proposed OSHA rules setting a limit of 1μgm Cr^{6+} m^{-3} TWA over an 8-hour day[4]. This regulation must be finalized by October 2005, but if retained at this level it will be more than an order of magnitude stricter than any European regulation. It will affect all of our manufacturing and sustainment operations, including

- any operation that uses Cr^{6+}, including chrome plating, chromate conversion, priming and painting
- any operation that exposes workers to Cr^{6+} in sustainment, including corrosion control and paint touch-up operations such as grinding, sanding and blasting
- any operation that produces Cr^{6+} accidentally, including welding of stainless steel and operations that produce very hot (especially molten) Cr alloys, such as steel production, casting, and perhaps even some hot-work operations.

The result of these rules will be a large decrease in the efficiency of operations that involve chromates, owing to the need for suiting up, showering, etc. and the requirement to keep other workers away from a non-attainment area until it has been cleaned up. While we have not done a solid assessment of these costs we expect that this will roughly double the cost of repainting and paint touch-up for aircraft. This could have the effect of doubling the current $280 mm cost of painting and touch-up for the US Air Force fleet[5].

3. Alternatives for corrosion protection

While corrosion costs are driving a search for better corrosion protection products, environmental and health concerns and their concomitant costs are driving the search for cleaner alternatives. The predominant expectation from most engineers is that, while clean alternatives may be technically viable, they will never be as good as today's corrosion inhibitors, and users will not buy into an inferior product. But today's technologies were mostly developed 50 years ago or more, while materials technology in general, and coatings technology in particular, have made significant progress over the past half century. While it does not necessarily follow for corrosion alternatives, our experience with alternatives to hard chrome has been just the opposite – older processes are frequently less reliable than people tend to believe, and modern alternatives often provide superior performance. Although the up-front cost of these alternatives is frequently higher, their life cycle cost is usually lower, precisely because of their improved performance.

A number of Cd alternatives are coming into use in the aerospace and DoD communities[6,7]:

- IVD Al (Ivadizing) – Ion Vapor Deposited Al, developed by McDonnel Douglas, was one of the earliest Cd alternatives. Most DoD depots now use IVD Al for at least some of their work load, despite the fact that it is a relatively complex vacuum process.
- Electroplated Al (AlumiPlate in the US, Aluminal in Europe) – this process has been available for some time, and has recently qualified for use on a number of aerospace components, including new fighters.
- Electroplated Zn-Ni (the original acid process developed by Boeing and the alkaline process are both in production).
- Various other alloy electroplates are used or are being developed. These include SnZn alloys, ZnFeCo alloys, and AlMn alloys.
- Zn- and Al-filled polymers have been used on fasteners in place of Cd plate by the automotive industry for a number of years.
- The ultimate alternative is, of course, to avoid the use of a steel that has to be corrosion protected in the first place. Most aircraft actuator outer cylinders are now made of 15-5 PH stainless steel, modern turbine engines use stainless steel (CRES) fasteners, titanium alloys are used to reduce both weight and corrosion, and a new high strength stainless steel (S-53 from QuesTek Innovations), developed by the use of modern computational metallurgy, is currently being tested by the US Air Force as a replacement for Cd-plated 300M high strength steel for aircraft landing gear[8].

Note, however, that all of the coatings listed above presently require chromate conversion for use in aircraft. However, several chromate alternatives are also coming onto the market, although many are still in the development and testing stage:

- Trivalent chrome pretreatment alternatives are now available commercially for use on Al, Zn coatings.
- Pretreatments for Al are being developed or are available that are based on molybdates, rare earths, permanganates, zirconates and silanes.
- Primers are coming onto the market that are based on rare earths and proprietary inhibitors.

Although engineering hard chrome (EHC) plating is primarily used for wear resistance and for rebuilding worn components, it does supply some corrosion protection. Because it uses a Cr^{6+} bath several alternatives have been developed:

- A successful alternative does not have to be the same type of process. The primary EHC alternative, which has been validated for aerospace use by the DoD-funded Hard Chrome Alternatives Team (HCAT), is High Velocity Oxy-Fuel thermal spray (HVOF) WC-Co and WC-CoCr[9]. Figure 1 shows the application of this type of coating. These HVOF coating materials are far more wear resistant than EHC. Although their performance in the standard ASTM B117 salt fog test is inferior to EHC, their actual corrosion performance in service is significantly better than EHC.
- HVOF is not a good solution for complex shapes and internals, however. For these applications it is possible to use plasma spray coatings for diameters above about 4cm. Various types of Ni plating are often used for IDs, including electroplated and electroless Ni and Ni composites.

- ☐ Since Ni is also an ESOH concern, Integran Technologies of Toronto, Canada, has developed a hard nanophase Co-P electroplate as an alternative for EHC in internal diameters, which is currently being validated in DoD testing[10].
- ☐ There are a number of developments under way attempting to deposit EHC from a trivalent bath, including products from Faraday Technology, a brush plate from LDC, and a trivalent solution being developed by the international EcoChrom team[11].

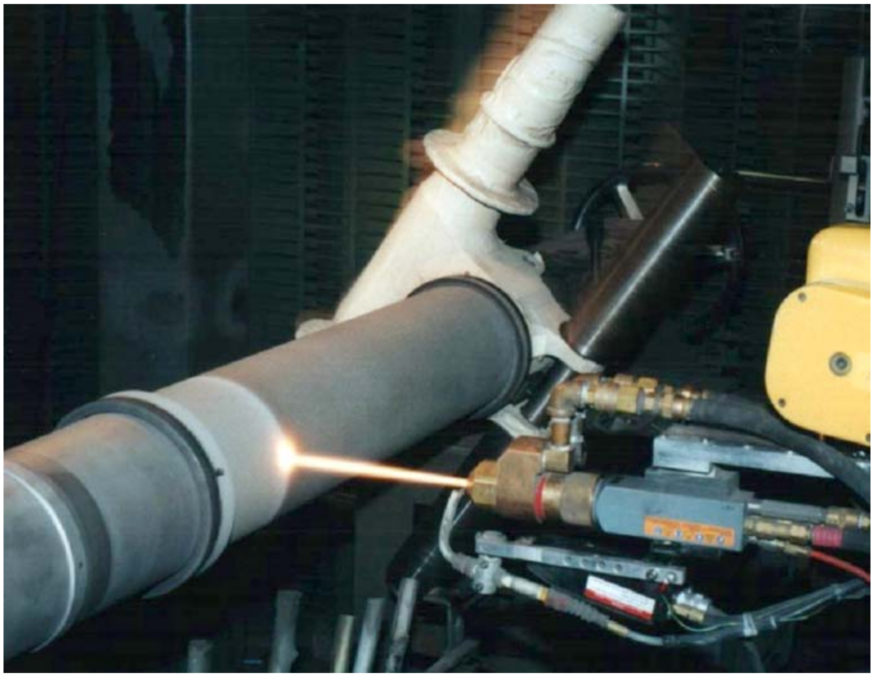

Figure 1 HVOF spraying of aircraft landing gear inner cylinder (NADEP Jacksonville).

4. Analytical tools

Our original two corrosion control materials, Cd and Cr^{6+} have become fragmented into a host of choices. In attempting to adopt technologies that are both clean and provide better corrosion protection, we are thus faced with a huge matrix of possible combinations of substrate, coating, and treatment. The best choice depends on the materials, the operating environment and the sustainment system. In order to make the best choices we need to know:

1. What are the options
2. What are the costs and benefits
3. How we can best go about adopting an improved technology.

To answer these questions we have, over the years, developed a suite of tools that we provide to our team members over the web.

4.1. Web-based Team workspaces

We work on several distributed teams whose members are spread throughout the country and the world. We have found that it is essential to have a passworded central website available to all the team members, which can be used both as an information repository and a location for team members to easily upload and download documents, data, specifications, and drafts of work in progress.

Using commercially available software on our own server we initially set up a collaborative web site for the members of the HCAT chrome replacement team at www.materialoptions.com. This has proved so useful that we have subsequently set up separately passworded workgroups for each of the other collaborative teams with which we work. Although this is not itself an analytical tool it is a location from which our analytical tools can be downloaded and it is an essential tool for keeping critical information readily available to all the team members. Each workgroup is password-protected separately, but a number of team members, who work on different but related projects, are able to interact closely and keep up with progress in diverse areas.

4.2. Technology analysis

There is no simple analytical tool for determining the best alternative, although there are tools that will help. Capabilities must be matched with the full range of requirements by someone with sufficient technical knowledge and an understanding of the systems in which the alternative will be used. Technology Analysis is usually used to overview a whole set of possible solutions to find the best fit as a general replacement or a replacement for a specific application.

Proponents of alternatives frequently fail to recognize that is not enough for a chrome plating alternative to be hard, or for a Cd or chromate alternative to resist corrosion. To be of use a technology must be sufficiently developed to become qualified in a reasonable time, and it must work in a way that provides performance analogous to that of today's products. For example, we cannot replace Cd (which provides galvanic protection) or chromates (which make scratches self-healing) with a simple barrier layer. Nor can we replace EHC (which is primarily used in MRO to rebuild worn components) with a thin PVD coating, no matter how wear resistant. The technology must also fit into the production and sustainment environment so that it can realistically be used when and where it is needed.

We have made a number of technology analyses of Cr and Cd alternatives that have been cleared for unlimited distribution and are available on the material options web site. These analyses always contain an summary of the requirements and specifications that the alternative must meet, including the technical performance, capabilities, advantages and limitations, the fit with manufacturing and sustainment, and the developments needed.

An important tool that we use to determine the degree of readiness of a technology is the Technology Readiness Matrix (TRM). It is common to quote the Technology Readiness Level (TRL) for an entire technology. The TRM is used to assess the TRL, not just of the technology as a whole, but also of each part of the process that is essential to running it in production. This matrix considers the entire production process, from starting materials to finished product, and assesses the degree of readiness of materials, property and performance data, production methods, production equipment, and quality assurance and control.

The graphical output of the matrix (Figure 2) shows the general status of the technology and immediately highlights gaps. This figure, for ID plasma spray, shows that the technology is not yet ready for use as a general ID chrome plating replacement. While the equipment and spray powders are fully developed, along with finishing and testing methods, the coating properties and performance are not yet well-defined, and there is a lack of development in the details of processing (primarily removal of heat and excess undeposited spray powder). These gaps have been bridged for several specific applications, so that, for example the technology is now qualified for coating H-53 helicopter blade dampers.

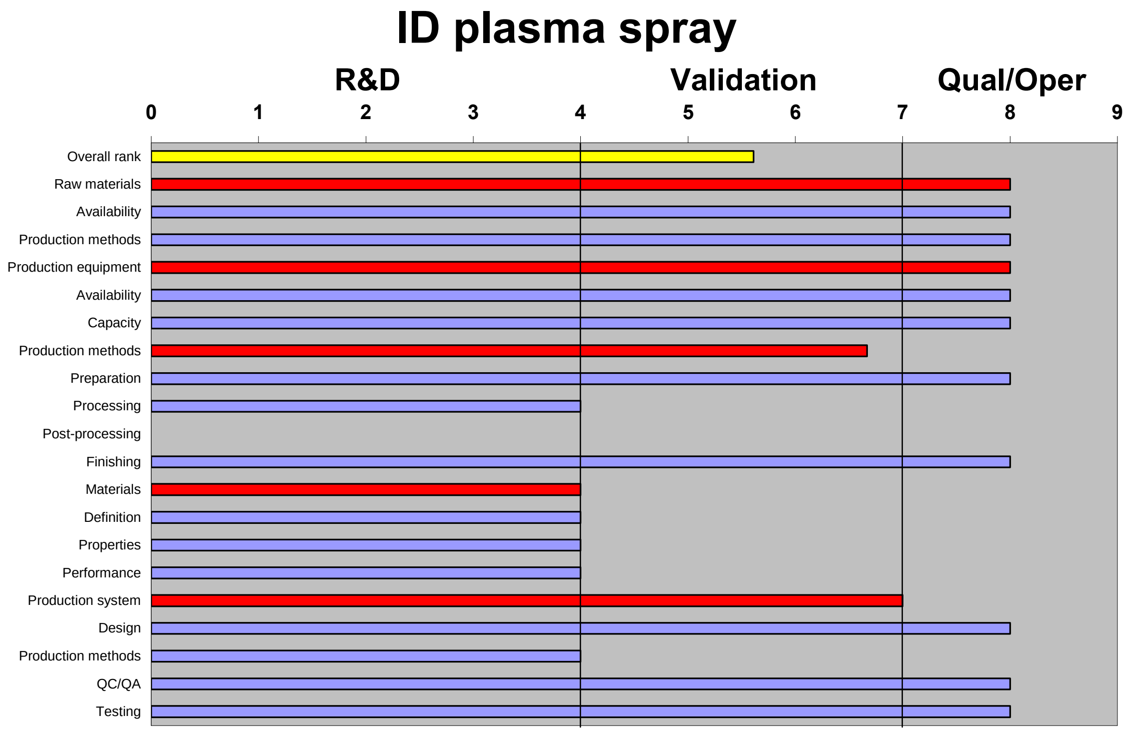

Figure 2. Technology Readiness Matrix for ID plasma spray.

4.3. Cost-benefit analysis

The simplest type of cost-benefit analysis compares the cost of using the original material with the cost of using the alternative. However, a primary reason that alternatives are not adopted is the cost of generating the engineering data to qualify them, since this frequently involves very expensive rig testing and years of in-service evaluation. Our cost-benefit decision tool (C-MAT, Calculation of Material Alternative Technologies) was designed under DoD funding specifically for replacing materials and coatings. It compares the cost of continuing to use the current technology with the total cost of implementing an alternative and using it in production. To do this it includes:

- Materials cost
- Production cost (direct and indirect) – including inventory cost

- Capital and depreciation cost
- Environmental cost – emission control and waste handling, including the potential cost of new regulations
- Changes in the overhaul cycle for periodic depot maintenance
- Adoption cost – the cost of developing data, changing drawings and contracts, specification development, qualification, configuration control, training, decommissioning of old equipment, and the host of other costs encountered in changing technologies.
- Service failure cost – New technologies often have different failure modes, and can make a large difference in the number of service failures. Service failure costs include failed part replacement, but their primary cost is the collateral damage to the system as a whole, which can include anything from damage to surrounding equipment to loss of an entire aircraft.
- We are currently adding logistics and demil and disposal costs.

While some of these costs can be obtained quite accurately, many of the biggest items are poorly known at best, or, in the case of service failures, are few in number and vary statistically in cost from year to year. To accommodate this we include an estimate of the overall reliability of the result based on the accuracy with which the input data are known. (For service failures the tool permits input of the actual historical failure statistics.)

In addition, it would be unusual for an organization to adopt an alternative across the board on all its products simultaneously. Materials and coating modifications tend to be applied to one system first and then migrated to others as experience is built up. This is especially true for complex military systems, where an alternative technology is usually tested first in non-critical areas, expanded into critical areas and ultimately qualified broadly by similarity as it is adopted across the weapons system.

Some of these factors are illustrated Figure 3, which shows how the net present value (NPV) varies with the time over which it is measured. (We use this type of graph rather than a single NPV number since, as can clearly be seen, the NPV of any project is a strong function of how many years are included in it.) This evaluation was carried out as an initial estimate of the costs and benefits of changing a landing gear component from Cd plated 300M to the newly-designed S-53 high strength stainless steel. At first glance, replacing a component made with \$6/kg steel with one made with \$30/kg steel would seem to be a poor idea. And indeed, an initial simple comparison of the costs and benefits, even assuming that the stainless gear would never need depot maintenance, showed a payback period of about 30 years (well to the right of the top graph). However, when we take into account the service failures that happen with landing gear due to corrosion and stress corrosion cracking (using rough estimates of annual failure costs and the probability of failure for the stainless gear), the picture changes dramatically to a large payback, even when we include the typical \$1-2 million cost of a landing gear qualification test. The reason for this is that when a landing gear component fails the cost in collateral damage can be very high, and this risk remains all the while the assets are fielded. As they are replaced the risk (and failure cost) drops until all the old components are removed from the inventory, at which point corrosion-related failures are minimized.

This calculation is currently being refined and we are now carrying out a detailed evaluation to determine the cost-benefit of replacing other landing gear and their components with S-53 alternatives.

Note how in Figure 3 the expected NPV and payback period depend on the accuracy with which costs can be predicted. Although estimates of costs and benefits are essential in materials decisions, their inherent inaccuracy should always be recognized and taken into account.

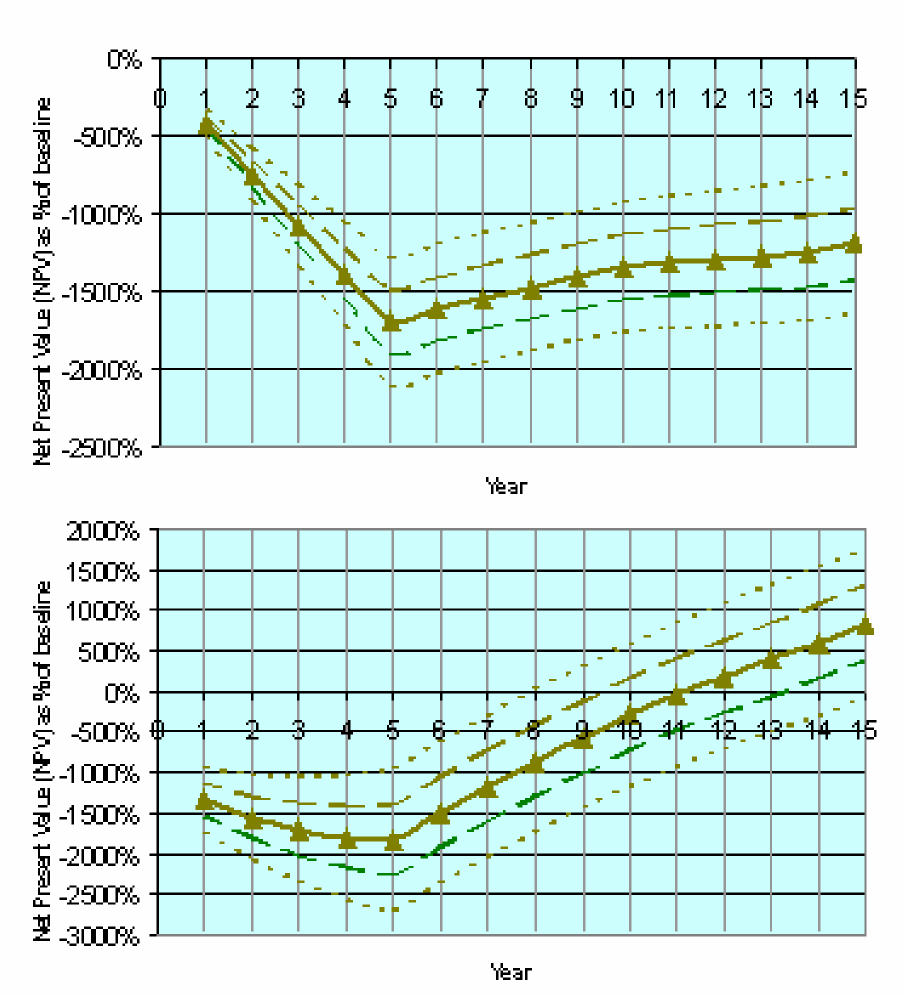

Figure 3. Comparison of cost analyses for stainless steel landing gear replacement as a % of current overhaul cost. Top, purchase and processing cost only; bottom, including cost of qualification testing service failures. (Dotted lines are ±1σ and ±2σ.)

There are situations, however, where cost-benefit analysis alone does not provide an adequate answer. Figure 4 shows the result of an analysis carried out to determine whether one of our depots should replace ID hard chrome with plasma spray coating. The result is that, even assuming the new OSHA PEL is enacted and raises the cost of chrome plating twofold (as we estimate that it might, based on Navy data), the replacement is barely worthwhile, given the accuracy of the estimates. However, the depot still considers the alternative process a good option because it will contribute to faster turnaround time in the depot cycle, returning aircraft to the troops more rapidly and raising the total number of fielded assets. This type of benefit is not easily incorporated into a cost benefit analysis.

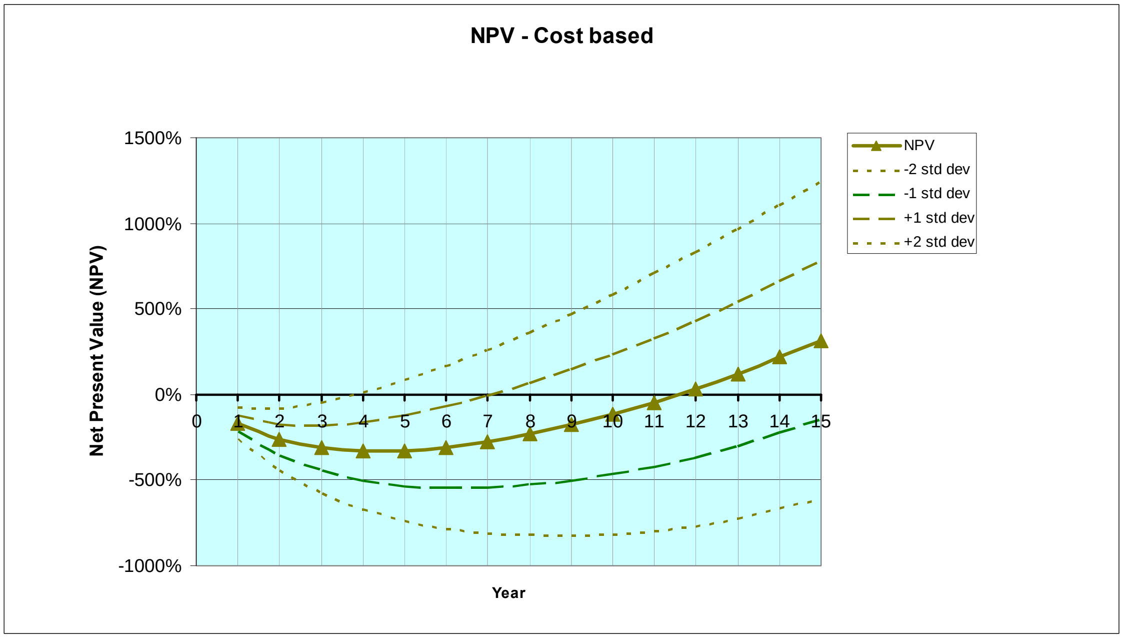

Figure 4. NPV as a % of overhaul cost as a function of years over which it is taken, for ID chrome replacement using plasma spray, assuming OSHA PEL of 1μgm^{-3} and improved wear performance. Assumes 10 year changeover.

A major disadvantage of cost benefit analysis is that it is time consuming and expensive since all the costs must be estimated anew for each situation. In addition there are many costs that cannot be gathered into most CBAs. A strategic decision-making tool is needed that engineers can use to decide which problems provide the biggest return on investment of engineering time and money, and to communicate that information up the management chain. We are therefore developing a Simplified Cost Model that will incorporate default values for many of the costs of using standard and alternative processes, including the environmental costs. To do this we are attempting to capture all of the major costs that are not usually incorporated, including the periodic capital costs of replacing major plating lines, air handling, and water treatment plants. This model will be available for use by DoD engineers to help in assessing the value of different materials and process replacement technologies.

4.4. Implementation Assessment

An Implementation Assessment is a structured reporting tool that provides an assessment of what it will take in time, effort and money to implement a specific new technology for a particular site or application. It combines

- ☐ Technology Description – both the existing technology and the technology chosen to replace it, including specifications. This also includes what modifications to plant or process will be required to accommodate the new technology.
- ☐ Cost-Benefit Analysis – using the C-MAT tool described above.
- ☐ Gap Analysis – This is an analysis of any technological and financial gaps that

must be filled before the technology can be brought to production.

- Risk Analysis – This assesses the degree of technical and financial risk in using the technology, including performance and regulatory risks.
- Environmental Assessment – This assessment summarizes changes in hazardous wastes and worker safety and health.
- Readiness Impact – It is especially critical for military systems to evaluate the impact that a new technology is likely to have on military readiness, i.e. on up-time in service and on turnaround time in overhaul.
- Production Implementation – This summarizes how the technology can best be put into production, including filling the gaps identified the Gap Analysis, minimizing the risks identified in the Risk Analysis, and options such as vendor processing and initial demonstration systems, where appropriate.

4.5. Roadmapping

In designing or modifying complex systems it can be a daunting task to decide how best to budget limited resources to ensure that all the gaps are filled to bring the correct technologies into place at the appropriate time. We have developed a structured Powerpoint-based Roadmapping tool, interactively linked with a detailed spreadsheet, that is designed for managing overall technology development and briefing engineers and project managers.

The Roadmap, whose structure is illustrated in Figure 5, lays out the basic timeline for fielding the overall system, together with the gaps to be filled and the projects in which technologies are being developed to fill them. Clicking on any project brings up a Project Summary that contains overheads summarizing the technical and financial aspects of the project. For engineers and technical managers, the Project Summaries provide technical summaries with links to detailed technical reports and data. For weapons system Program Office managers the technical details are hidden and a linked spreadsheet is provided to rank project proposals and show the distribution of funds.

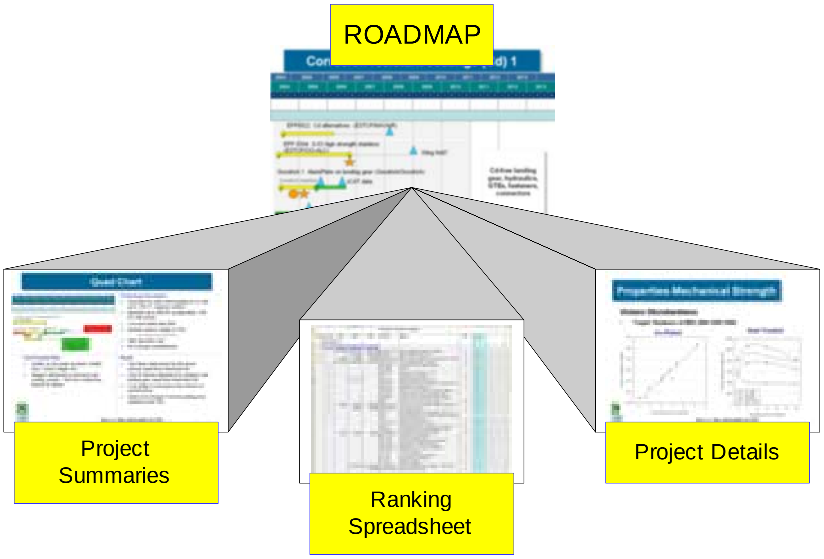

Figure 5. Roadmap structure.

The Roadmap provides the following information:

- A graphical timeline, with decision points and the technology insertion point.
- A fund-track matrix showing which projects are to be funded and what additional

technologies or other projects are to be tracked for future use.

- A list of projects with links to their Gantt charts, Project Summaries and Project Technical details.
- A summary of gaps for which there are not yet any potential solutions.
- A Capability Matrix linked from the spreadsheet showing the primary requirements to be met and the capabilities of the technologies to meet those requirements.
- An interactive Project Ranking matrix that allows the Program Office to rank proposed projects and assign funding levels.

Each project is captured in a Project Summary that contains the following information:

- A Quad Chart and Project Gantt Chart.
- Budgetary information.
- Program and Technical Status Summaries.
- Summary Technical Data with links to detailed reports and specifications.
- Summaries of applications, value of the technology to the weapons system, risks and gaps.
- Decision points and milestones.
- The business case for the technology, with links to details as appropriate.

5. Conclusion

Bringing new corrosion preventive technologies into production on military systems is a complex task, since it involves choosing the most useful technologies, developing them as necessary, carrying out extensive testing, qualifying them on the weapons system, and implementing them at military depots and at vendors. While there is no substitute for solid data and sound engineering judgment, various tools can be of value in choosing the best and most cost-effective approach and bringing it to production. Over the course of a number of years we have developed a suite of tools that we have found to be valuable in helping to make the best decisions and to manage the process of bringing clean technology alternatives to production.

ACKNOWLEDGEMENTS

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