Title: Hexavalent Chromium Substitution

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Abstract

From razor thin tool blade coatings to shiny custom motorcycle parts, hexavalent chromium (Hex-chrome) has historically been the coating of choice for a vast array of industrial applications. Hex-chrome has many advantages over other coating alternatives including hardness, corrosion resistance, coefficient of friction, process maturity, and economic factors. Existing Hex-chrome process technologies are simple and well understood in the industry.

Recent reports and media coverage have brought Hex-chrome into the spotlight. Increased environmental and regulatory pressure on existing Hex-chrome has created a need for companies to investigate alternative coatings. In 1988 [7] Hexavalent Chromium was declared a carcinogen and since has received additional scrutiny and regulation. Recent advances in coating technologies and process methods look to provide feasible alternatives to existing processes while providing Hex-Chrome free options. However, evaluating these potential alternatives is difficult as information from vendors is not easily obtained the decision process is not well documented.

In this project, the team provides a history of hard chromium coatings. We discuss the issues emanating from hard chromium and traditional application processes. Various alternatives are discussed in detail, many of which are considered “Nano-coatings” due to their tiny architecture and deposition methods.

A criteria analysis / decision matrix is provided which provides:

- Multiple selection criteria / key metric scoring (harness, coefficient of friction, corrosion resistance)
- Consideration of cost of ownership
- Environmental impact factors
- Priority weighting of factors (cost vs. environmental)
- Visual results for ease of analysis, helps technology managers prepare for Hex-chrome alternative evaluation

In researching this topic, the team was unable to find such a decision model. The team adds to the existing body of knowledge by establishing this model and providing guidance regarding the model inputs. Although a fully comprehensive decision matrix could not be developed, due to limitations in available data, the team provides a detailed overview of each replacement technology and guidelines for making decisions in the future when such information is available.

Contents

Introduction

Overview:

From razor thin tool blade coatings to shiny custom motorcycle parts, Hexavalent chromium (also called "Hex-Chrome") has historically been the coating of choice for a vast array of industrial applications. Hex-chrome has many advantages including maturity and cost. In 1988 Hexavalent Chromium was recommended a carcinogen by NIOSH (National Institute for Occupational Safety and Health) [7]. Since this time Hexavalent chromium has received additional scrutiny and regulation. Traditional chrome plating processes and materials are no longer deemed safe and present many hazards to workers and the environment. Government regulations and increasing safety concerns have risen to a point where companies are investigating replacement materials for existing processes which use Hex-Chrome.

Increased environmental and regulatory pressure on existing Hex-chrome has created a need for companies to investigate alternative coatings. Recent advances in coating materials and process methods look to provide feasible alternatives to existing processes. However, evaluating these potential alternatives is difficult as information from alternative vendors is not easily obtained and the decision process is somewhat complicated. Evaluating Hex-chrome alternatives is complex; a need for a decision model exists. In this project, we provide a history of hard chromium coatings and discuss the issues emanating from hard chromium and traditional application processes. Various alternatives are discussed in detail, some of which are considered “Nano-coatings” due to their tiny architecture and deposition methods. A criteria analysis and decision matrix was developed, providing guidance to managers and engineers who need to make chrome replacement decisions. Although a fully comprehensive decision matrix could not be developed, due to limitations in available data, the team provides a detailed overview of each replacement technology and guidelines for making decisions in the future when such information is available.

Summary of Contributions:

In researching this topic, the team was unable to find such a decision model. The team adds to the existing body of knowledge by establishing this model and providing guidance regarding the variables. Although a fully comprehensive decision matrix could not be developed, due to availability of quantifiable data, the team provides a detailed overview of each replacement technology and establishes guidelines for making decisions in the future when such information is available. Example model implementation is shown in following sections for a specific application (piston rod). The team also developed a scenario analysis which looks a hex-chrome material alternatives weighted by environmental and cost driven preferences.

History & Background Information

History of Chromium and Electrolytic Plating

The element chromium (Cr) was discovered in 1797 by Louis Nicolas Vauquelin [1]. A professor of chemistry and pharmacology, Vauquelin detected chromium in the mineral crocoite or red lead ore from Siberia. Chromium by itself is a lustrous, grey metal of high hardness and corrosion resistance, and is the only elemental solid that is antiferromagnetic. It is said to be the 21st most abundant element in the earth's crust and is typically mined from chromite in South Africa, Kazakhstan, India, Russia, and Turkey.

The study of chromium and its properties eventually led to its use as an alloying element in a variety of metals including stainless steel. Approximately 85% of mined chromium is used in metal alloys [2], but its useful qualities also make it an excellent choice for chromate conversion and surface coatings on various substrates. Electroplating, which is the deposition of a thin layer of metal onto a cathode, was invented in 1839 with patents issued in 1840 [3]. Soon after, chrome began to be used as a surface coating, although it was not a widely adopted surface coating for industrial uses until the 1920s.

Due to its versatility as a surface coating and its excellent properties and characteristics, chrome plating has been used extensively throughout the world for a variety of industrial and commercial applications. Chrome plating can be applied at a variety of thicknesses from thin coatings of less than 0.0001" to thick coatings of 0.030" or more. Thick chrome plated coatings are often used to "build-up" worn part surfaces, which allows for rebuilding and resurfacing of parts to bring them back to their original part dimensions. From aircraft components, hydraulic actuators, and other wear components to gun barrels, hand tools and automotive trim, Chrome has been the surface coating of choice for almost a century.

There are several different surface preparations that utilize chromium, but the focus of this paper and analysis will be on those concerning electrolytic deposition on steel. The two main types of electrolytic chromium deposition on steel substrates are referred to as decorative chrome plating and hard chrome plating (also known as functional or industrial chrome plating). The variations in chemicals and processes for these two surface coatings impart unique and specific surface coating characteristics.

Decorative chrome plating typically has a thin layer of bright nickel underneath the chrome layer. This undercoat contributes to the lustrous surface of decorative chrome plating and also improves corrosion and tarnish resistance. As indicated by its name, decorative chrome is typically selected for its aesthetic appeal. It is often used as a coating for automotive bumpers, bicycles, plumbing fixtures, and other consumer products where visual appeal and tarnish resistance are desired.

Functional chrome coating often has a dull, gray appearance and imparts many desirable physical properties. These include high hardness, abrasion and wear resistance, corrosion and chemical resistance, as well as high adhesion strength. These attributes make hard chrome a suitable surface coating for engine components, hydraulic cylinders, cutting tools, and a multitude of other items. As mentioned previously, hard chrome plating is also used extensively to repair worn parts and tools. This is very common for expensive components used in heavy equipment and ships. A large consumer of this service is the U.S. Department of Defense.
Chrome electroplating is well understood since it has been around for nearly a century. The process is relatively simple and inexpensive. However, it is not without issue. Chrome electroplating is normally considered a line-of-sight plating process. This means that there must be a clear and direct path between the cathode (part to be plated) and the anode for movement of electrical current. This makes fixturing and positioning of small parts difficult, and plating of holes is very challenging. The distribution of chromium on part surfaces can be inconsistent when compared to other surface coating technologies, and the electrical efficiency of this process is very low.

Health, Safety, and Environmental Issues

Although chrome plating is very versatile and indispensible as an industrial surface coating, it does have major drawbacks of which health, safety, and environmental concerns top the list. Most hard chrome plating processes use plating solutions that contain hexavalent chromium which is a known carcinogen and mutagen [4]. Contact with chromic acid can cause dermatitis, and in severe cases, ulcers or burns on the skin. Prolonged inhalation of fumes or mist can result in ulcers and perforation in the nasal septum and esophagus. Hexavalent chromium is also extremely toxic if taken orally. Once reaching the bloodstream, hexavalent chromium causes damage to the kidneys, liver, and blood cells [4].

During the electroplating process, large amounts of hydrogen gas are produced at the anode/solution and cathode/solution interfaces. The evolution of hydrogen gas results in the formation of tiny hydrogen gas bubbles. As these bubbles reach the surface of the plating solution and burst, they create a fine mist of plating chemistry. Once airborne, the risk of these chemicals coming in contact with workers and being released into the atmosphere is high. Precautions must be taken to mitigate worker and environmental risks involving airborne hexavalent chromium. This commonly involves the enclosure of open plating tanks and the addition of air handling equipment to draw mist and vapors from the surface of the plating solution where it is pulled into a scrubber system which removes all chemicals and gases before releasing the air in to the atmosphere.

In addition to equipment needed to reduce airborne chemicals, people working near plating chemicals must also wear extensive PPE (personal protective equipment) to reduce or eliminate direct contact with plating chemicals. Plating chemicals have a very low pH (near 0) and, as stated above, can cause burns along with other long-term reactions. Common PPE includes safety goggles or face shields, water-proof and chemical resistant gloves, aprons, sleeves, and leg spats with shoe covers. To prevent workers from carrying contaminated clothing home with them, it is often recommended that all clothing and PPE worn while working around plating chemicals is left at the job site.

Chrome plating also creates a lot of toxic waste as everything that comes in contact with the plating solution must be decontaminated and disposed of as toxic waste. All fluids involved in the plating process must be treated before disposal. This includes water used to rinse plating solution from parts. This fluid is typically sent to an in-house water treatment facility where a filter press removes all solids, and then the remaining fluid is analyzed and treated to neutralize its pH before sending to the sewer system or to a waste disposal site.

Safety and Environmental Regulation

1970 was a pivotal year for worker and environmental protection. It was in this year that President Richard M. Nixon signed executive orders to create Occupational Health and Safety Administration (OSHA) and Environmental Protection Agency (EPA) [5,6]. In 1975, National Institute of Occupational Safety and Health (NIOSH) documented the carcinogenic effects of water-insoluble Cr(VI) compounds, and in 1988 they recommended that all Cr(VI) compounds be considered occupational carcinogens [7]. In 1998, EPA's Integrated Risk Information System (IRIS) classified hexavalent chromium as a known human carcinogen via inhalation [8].
Formerly known as the Federal Water Pollution Control Act, the Clean Water Act was reorganized and expanded in 1972 with additional amendments and renaming in 1977 [9]. During this same timeframe the Clean Air Act of 1970 and its amendment in 1990 were enacted. These acts gave the EPA the authority to limit emissions of pollutants affecting air and water quality [10]. Since the formation of these entities, scientists have studied the toxicity of hexavalent chromium. Armed with this information, OSHA and EPA have continued to set and update regulations to safeguard the environment and people.

As previously mentioned, regulations mandated by OSHA and EPA create the need for extensive equipment and processes meant to protect workers, the community, and the environment. Industry has come up with some ingenious methods to reduce the risk of working with hexavalent chromium plating solutions, but these are only successful when used properly. To ensure conformance to regulation requires constant monitoring of systems, processes, and working environments. All these precautions add cost to chrome plating operations. This additional cost has put many smaller plating facilities out of business, but hasn't been great enough to deter larger facilities from using chromium-based plating chemicals up to this point.
Regulation of hexavalent chromium and electrolytic chromium plating has raised public awareness of its harmful qualities. This has resulted in many stories, investigative news reports, and law suits regarding standards violations and contaminated lands and water near industrial sites. Public consciousness and recent interest in care for the environment, sustainable energy and products, and other "green" technologies may end up being the tipping point for a major reduction in hexavalent chromium plating. Regardless of what "tips" the use of hexavalent chrome, it is clear that it will not always be a viable surface coating technology.

Economic Issues & Trends

Initially, the team expected to see downward trends related to hex-chrome manufacturing and production due to regulatory trends. However, through literature review and research the team discovered that upward trends in manufacturing are continuing. The data suggests that Companies are simply pushing more of their manufacturing and production to developing countries.

Since the turn of the century, costs of high grade chromium have been increasing. Figure 1 shows an increase from roughly 6,000$/ton in 2000 to almost 10,000$/ton in 2010 [20]. Production capacity, shown in Figure 2, in developed countries has been flat to down, while developing countries have seen increased production [24,25,26,27].

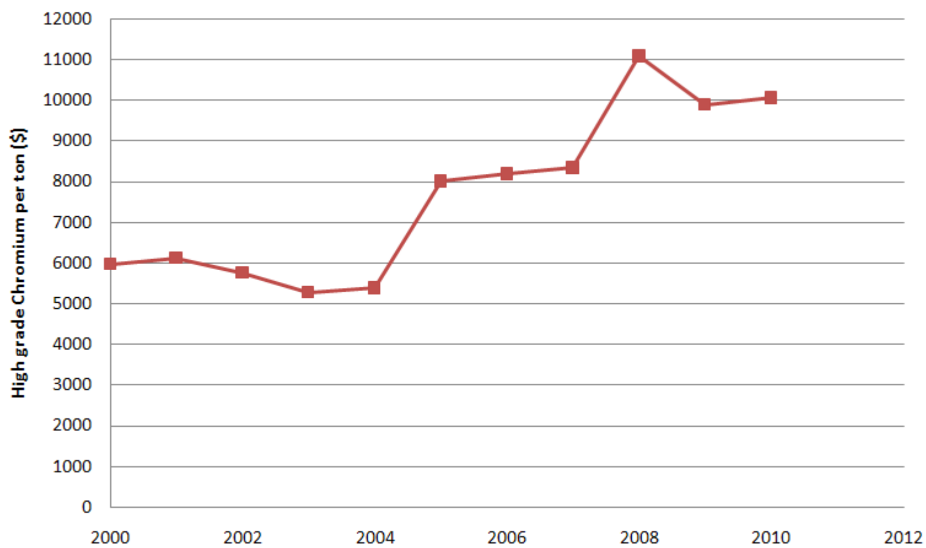

Fig 1: Historical cost of Chromium per ton in USD

There are multiple reasons for this switch of roles, both economic as well as environmental. Environmentally, the maximum respiratory limit in China for Chromium exposure is 0.05 mg/3. This is 2.5 times the same limit in the US. (0.02 mg/m3) and 3 times the EU limit (0.015 mg/m3) [21]. This means that workers can be exposed to higher levels of Chromium in a plant atmosphere in China than in the US or EU. Combining this with significantly lower costs of labor and transportation have led to multiple new manufacturing facilities in China. For example, there are slightly more than 1000 manufacturing facilities in the entire US, while there are more than 800 facilities in the Pearl River Delta area of China alone [28,29].

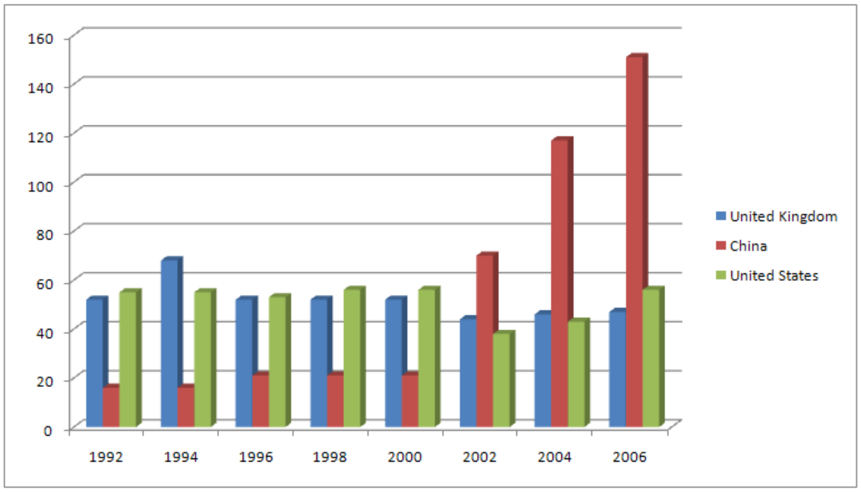

Fig 2: Historical production capacity for China, United Kingdom and United States 1992 to 2006

This leads to the disposal factor of Chromium waste. China has more than 6 million tons of Chromium waste awaiting disposal [22], which is roughly twice the worldwide production of Chromium per year. By comparison, the total Chromium waste within the US in 2009 was only 7500 tons [23]. The point can be made that the environmental waste impact of Hexavalent Chromium in developing countries does not carry as much concern as in developed countries and companies are finding ways to get around these restrictions by moving their manufacturing to countries with lower environmental regulations. However, environmental regulations covering the usage of Hexavalent Chromium in developed countries are becoming more restrictive. There are regulatory movements underway to restrict imports of products manufactured with Hex chromium and even exemptions for areas like defense are being denied [30,31].

There are many available alternate materials to replace Hexavalent Chromium for multiple uses; however these are typically highly proprietary, as they're basically variations in the chemical and elemental properties of Chromium. Because of this proprietary nature, there is not a lot of data available in the public domain regarding the usage and industrial experience of these materials. Which, has essentially led to a "Catch-22" situation where the lack of workplace data has slowed down the adoption of these new materials which, in turn has restricted the creation of an industrial need for widespread usage of the technology.

Patent & Article Data

The following figure illustrates the data that was collected using the Patent Search method as illustrated in Appendix B. When the data is plotted in cumulative fashion, as shown in Figure 3, the information exhibits a linear upward trend-line. This trend would infer that the developments with respect to standard Hexavalent Chromium have continued without interruption from outside forces.

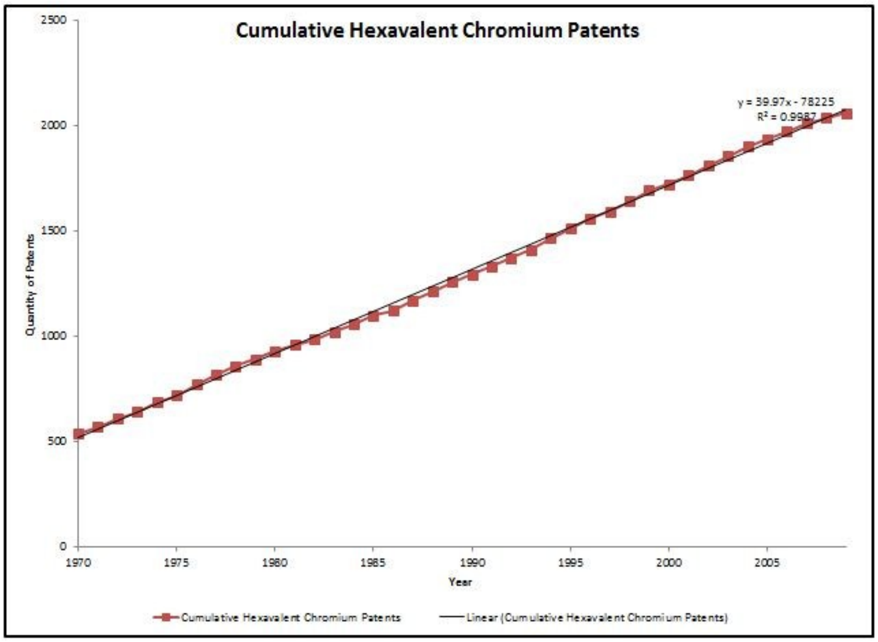

Fig 3: Patent data trend

The following figure 4 illustrates the data that was collected using the article search method as defined in Appendix A.

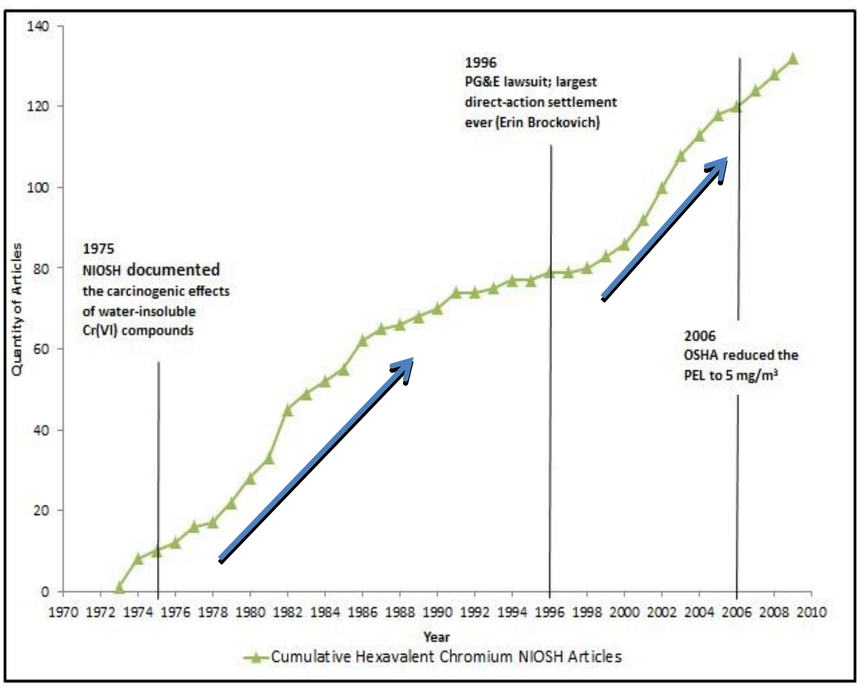

Fig 4: Article trend showing periods of increasing articles (blue arrow) after major regulatory events

As indicated by the above data, the first NIOSH article occurred in 1974; this article documented the carcinogenic effects of water soluble hexavalent chromium compounds. The research in the field has continued since the publishing of the initial article, although the data does exhibit distinct S curve trends. The first S curve appears to originate from the publishing of the initial article. Then as indicated by the plot, the interest plateaus. Then in 1996, the articles published continue to rise after settlement of the PG&E lawsuit. Therefore, the data suggests that as more research and exposure is completed, the regulatory environment with respect to Hex-Chrome is likely to increase as well.

Summary

A Force Field analysis was used to visually study the forces *for* change and the forces *against* change. Figure 5 shows the results of this analysis. We see that most of the forces for changing to alternate materials are environmental regulation based. The only economic based force for change is the cost of chromium waste disposal. Of the forces against change, they're primarily economically driven.

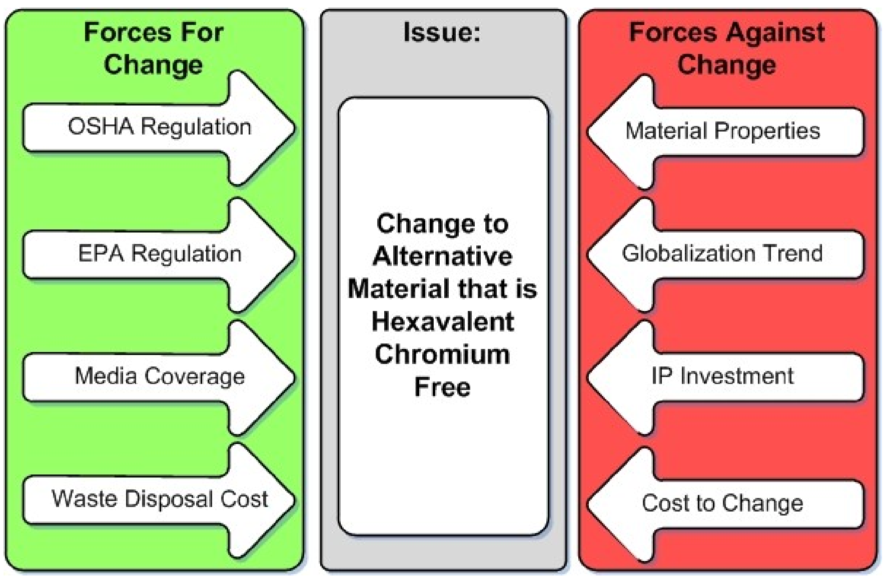

Fig 5: Force Field Analysis

Eventually, a tipping point will be reached where the environmental impact outweighs the economic advantages. At the current time it is easier to invest in equipment to meet safety and environmental regulations, or to move production to developing countries. Environmental regulations covering the usage of Hexavalent Chromium in developed countries are becoming restrictive. If past events are a predictor for future events we expect chromium will eventually be regulated to the point where it is not feasible in most applications. In the past other hazardous materials (e.g. lead, mercury, and halogens) followed a similar regulatory and environmental trajectory.

In summary, companies are currently finding ways around regulation but regulatory trends indicate that eventually alternatives must be considered. As with other materials, hex-chrome will be very difficult for companies to use.

Decision Model

Overview

Prior to implementation in software, the team developed a mathematical model. An overall score is established for each alternate material type as well as the process of record (standard hex-chrome). The overall score, called the "selection material rating score" is a function of the priority given to the category (i.e. hardness, corrosion resistance, friction coefficient, environmental cost, economic cost). The model provides an overall score for each material type as well as visual charts (bar charts) for easy material comparisons.

Functional Description

The evaluation process takes several steps. First, the user determines the application as the criteria weighting is highly dependent on the specific application. Next, a benchmark (control) must be selected; in our case we chose the existing hex-chrome process. The evaluation model compares alternate materials to the benchmark. Identifying performance criteria is the next step; our team chose hardness, corrosion resistance, friction coefficient, environmental cost, and economic cost. Selecting the materials to evaluate is the next step.

Our team chose various alternatives as described in future sections. Next, a priority must be assigned to each of the performance criteria for the given application. For example, if hardness is the most important factor for a given application, then hardness would be given a higher score (weight) than the other performance criterion. After assigning proper weighting, scoring guidelines must be established. Depending on what information is available, different scoring approaches may be selected. Future sections of this paper discuss the scoring guidelines out team used in detail. An evaluation scenario must be selected next in order to properly evaluate alternatives. In some applications cost might be the primary driver. In this case, a "cost driven" scenario would be selected. The final step in the process is the ranking materials step using the evaluation model. Once ranked, the user would move to a feasibility stage with the selected material(s). Since the material would still need to be proven in a real-world application, this step is beyond the scope of this project. The process as stated is flowcharted in figure 6.

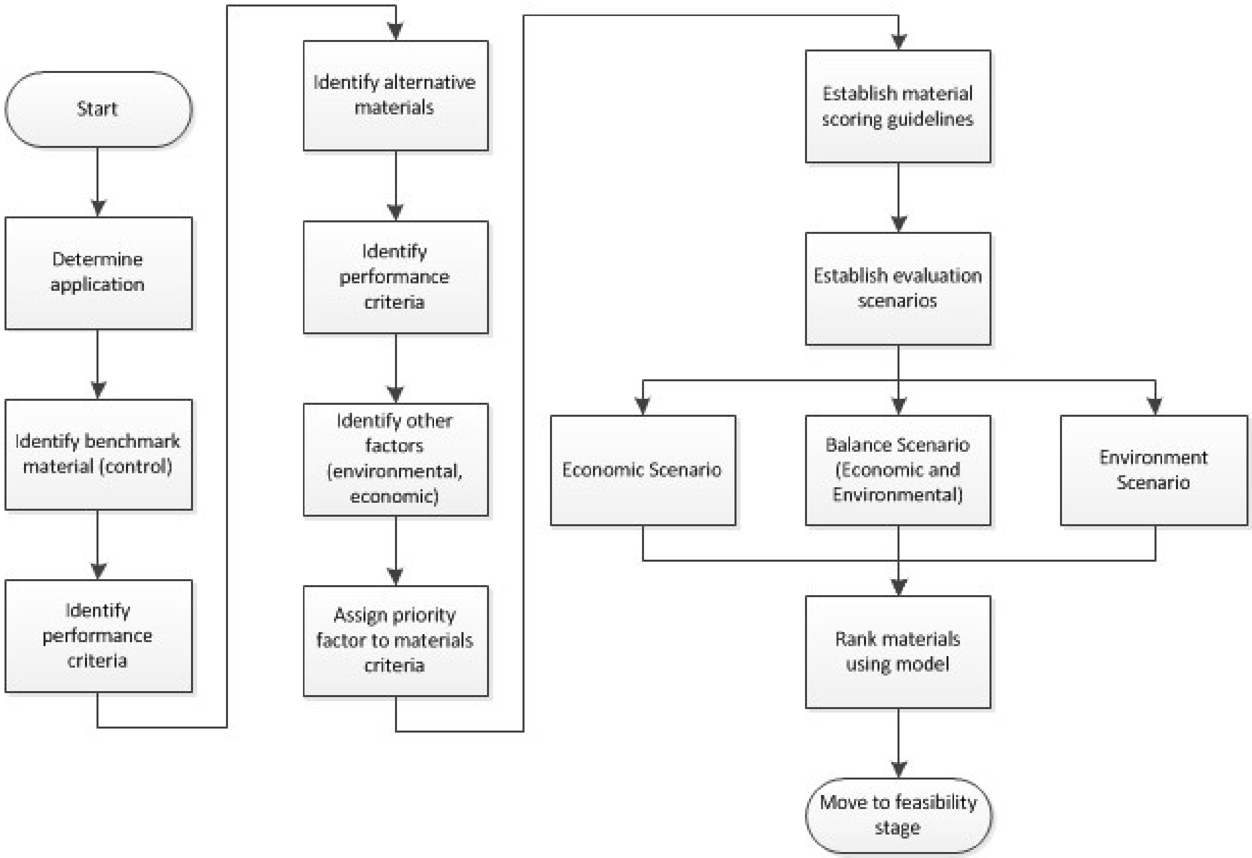

Fig. 6: Evaluation Process Flowchart

Detailed Description

The mathematical model is shown below. A selection total ranking is calculated for each material (S_i) which is the summation of the weighted performance criteria $P_j C_{i,j}$ for all the criteria scores.

$$S_i = \sum_{j=1}^{n} P_j C_{i,j} \quad \forall i,j$$

Where:

$S_i = Selection\ Material\ Rating\ Score\ for\ material\ i$

$P_j = Priority\ for\ Criteria\ j$

$C_{i,j} = Criteria\ Score\ j\ for\ Material\ i$

$n = Number\ of\ Selection\ Criteria$

Data Gathering & Model Implementation

Material Selection Criteria

The component that was chosen for the material selection analysis was a hydraulic piston rod. Hydraulic pistons are used in several applications such as vibration dampening in automobiles, mechanical movement of objects such as lift stations, and compression applications such as waste collection [19].

In order to analyze hydraulic piston rods effectively, the several criteria were selected that were necessary for performance and functionality of the component. The following table identifies the selection criteria with respect to product performance.

Table #1 - Selection Criteria

Material Property	Description
Surface Roughness	Material having the capability of a smooth surface.
Surface Hardness	Adequate hardness to prevent wear from the friction and contact with mating components during operation.
Corrosion Resistance	Ability of the coating to resist corrosion.

In addition to the above required criteria, additional criteria that were nonphysical or mechanical properties were analyzed. These properties are of importance, since the evaluator since it is the responsibility of the evaluator and management to predict and anticipate internal and external market forces when making decisions. The following table identifies the additional selection items that were weighted in the decision analysis.

Table #2 - Additional Selection Criteria

Material Property	Description
Material Cost	The cost of ownership should be similar to the current material and process
Environmental Cost	The cost incurred by the environment for the use and disposal of products and by-products should be lower than the current material

In order to analyze the non-Hexavalent Chromium materials several assumptions needed to be made with respect to the selection criteria as listed above. Assumptions are needed because of data availability and the qualitative nature of the available data. In the situation were raw data is available, the raw data will supersede the assumptions, and be used in the selection methodology. However, when unavailable the assumptions will lead the selection.

Criteria & Priority Scoring

We used a priority scale of 1 (not important), 2 (somewhat important), and 3 (very important). For the rating scale, we used a similar scoring method: 0.5 (property not listed in datasheet), 1 (bad), and 3 (good).

Criteria and Material Analysis Assumptions

In order to test the functionality of our decision model, some assumptions were established. If material data was not available from the manufacturer for the alternate material, the assumption was the given property was less than that of hex-chrome. The environmental cost and impact of the alternative material was considered to be less than that of hex-chrome. The material cost for the alternative material was considered greater than the cost of hex-chrome.

Alternate Materials Evaluated

The alternative materials were chosen based on the explicit identification that the materials were hexavalent chromium free in the marketing brochures, and material specifications sheets. The material information was searched and compiled utilizing information that was publicly available on the internet. The following table identifies the alternate materials that we evaluated in the analysis, specifically, the manufacturer, product name, and web address.

Table #3 - Potential Materials

Manufacturer	Product Name	Web Address
A Brite	Enviro-Alloy	http://www.abrite.com/acs.htm
Shining Surface Systems	Mettex 6	http://www.surface-systems.com/
U.S. Chrome	Hard TriCom	http://www.uschrome.com
Integran	Nanovate CR	http://www.integran.com
Sub-one	Inner-Armor	http://www.sub-one.com

Strengths and Weakness

In order to analyze the materials, the strengths and weaknesses were recording from all the material data sheets identified for analysis. Appendix C lists all the strength and weakness tables collected for the materials analyzed. The following table summarizes the strengths and weaknesses of the subject materials, as they relate to the criteria identified for the hydraulic cylinder.

Table #4 Material Summary

Material Property	Material Type				
	Enviro-Alloy	**Mettex 6**	**Hard TriCom**	**Nanovate CR**	**InnerArmor**
Corrosion Resistance	Good	NA	Good	Good	Good
Hardness	NA	Good	Good	NA	Good
Coefficient of Friction	NA	Good	NA	Good	Good
Environmental Cost	Good	Good	Good	Good	Good

Table Key
NA = Material Property Data Not Available
Good = Material Property Equal to or Greater than Chrome
Bad = Material Property Less than Chrome

Additional Assumptions:

1) If listed as strength the performance is equal to or better than the traditional Hexavalent Chromium product.
2) If a physical performance characteristic is not listed, then the physical property is less than traditional Hexavalent Chromium.

Model Implementation & Results

Five alternative materials were compared to the standard existing Hexavalent chromium process. These five materials were evaluated using the mathematical model outlined above. The initial evaluation consisted of five primary factors as described above: surface roughness, surface hardness, corrosion resistance, cost, and environmental impact. An overall score was calculated for each potential replacement which is the summation of each of the weighted (priority) criteria scores. These scores were then compared to each other for a cursory decision. As previously discussed, the goal of this project was to build a decision process, rather than a conclusive decision analysis, due to limitation of alternative coating data.

The decision model was implemented using MS-Excel version 2007. Input cells were created which allow engineers and managers to enter data for each vendor and view the results visually in easy to read charts.

Data was used for each alternative based on information obtained from the manufacturer's data-sheets or input was empirically decided based from research. The following example illustrates a typical output results, for Enviro-Alloy.

		Enviro-Alloy		
Chemical Property	Priority	Value	Rating	Score
Corrosion Resistance	3	Good	3	9
Physical Property	Priority	Value	Rating	Score
Hardness	3	Not Listed	0.5	1.5
Mechanical Property	Priority	Value	Rating	Score
Coefficient of Friction	3	Not Listed	0.5	1.5
Economic	Priority	Value	Rating	Score
Economic Cost	1	Bad	1	1
Environmental	Priority	Value	Rating	Score
Environmental Cost	3	Good	3	9
		Total Score		22

Fig 7: Enviro-Alloy model results

Scenario Analysis

In order to analyze the implication of economic and environmental criteria on material selection, the methodology of scenario analysis was utilized. For the material selection process, three separate scenarios of the model stated above were conducted and compared.

For the analysis, the priority levels of the Environmental and Economic factors were altered from a high (value of 3) to low (value of 1) level, and the resulting preferred material was determined mathematically. The following figure titled Scenario Analysis Summary identifies the three different scenarios that were utilized for the decision model and corresponding priority levels. Note: all other material criteria were held constant for the evaluation.

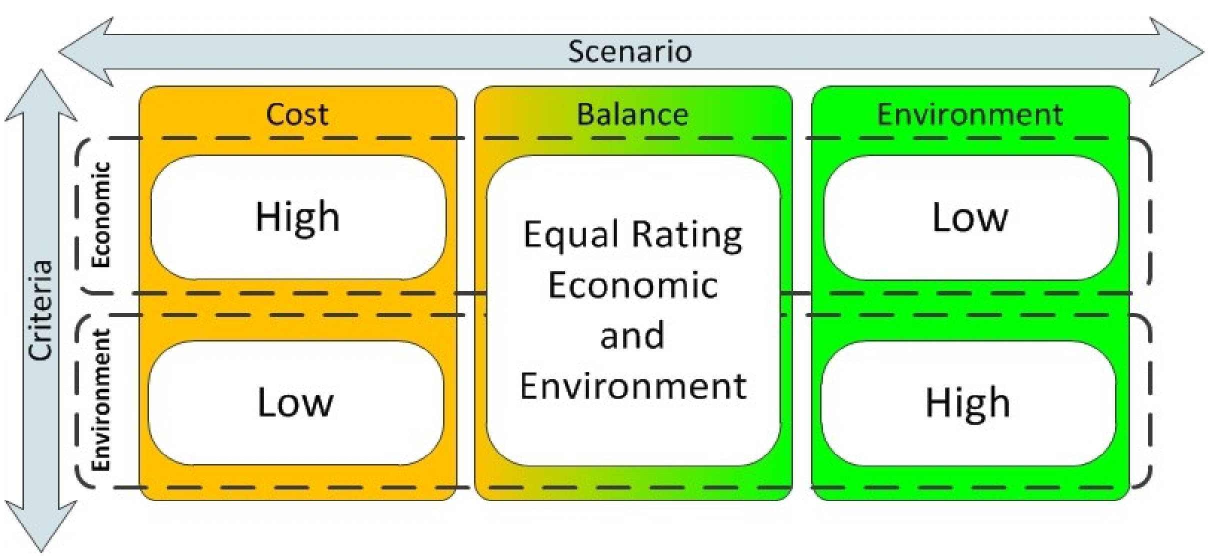

Fig 8: Scenario Analysis summary

Cost Scenario

A cost driven scenario is defined as a high priority value on economic costs, and low priority value on environmental costs. Under this scenario the preferred material of choice is standard Hexavalent Chrome. The following figure titled Cost Driven Scenario Model Output, illustrates the results of the model under a cost driven scenario.

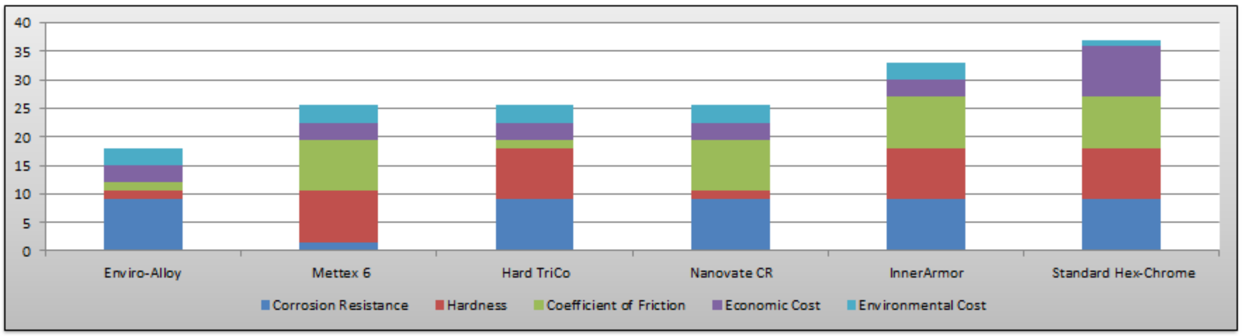

Fig 9: Cost driven scenario model output

Balanced Scenario

A Balanced scenario is defined as setting the economic costs are equal to the environmental costs. Under this scenario the preferred material of choice is either standard Hexavalent Chrome or the InnerArmor material. The following figure titled balanced scenario model output, illustrates the results of the model under a balanced scenario.

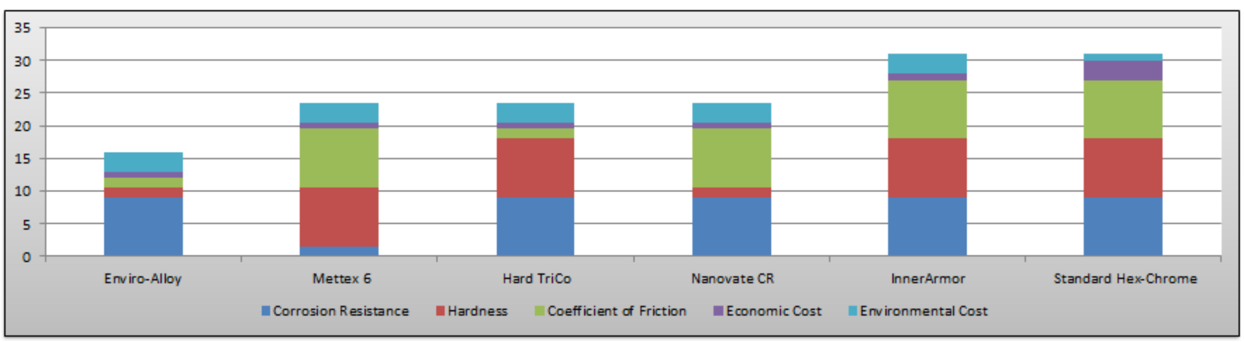

Fig10: Balanced (environment = cost)

Environmental Scenario

An environmental driven scenario is defined as a high priority value on environmental costs, and low priority value on economic costs. Under this scenario the preferred material of choice is

InnerArmor. The following figure titled Environmental Scenario Model Output, illustrates the results of the model under an environmental driven scenario.

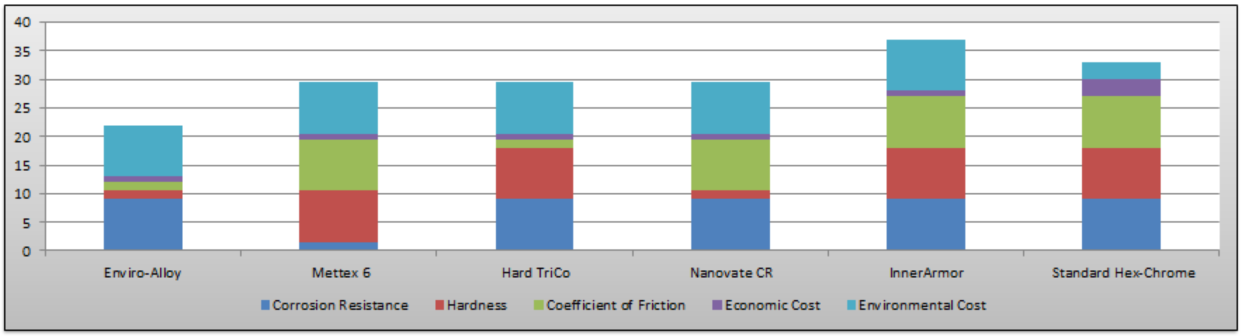

Fig 11: Environmental driven scenario output

Conclusion

From a pure cost standpoint, existing Hex-chrome is the most cost effective followed by Inner-Armor. Currently Hex-chrome is not the best choice when environmental criteria are considered. Inner-Armor looks to be the best choice in this category followed by three other alternate vendors. When a balanced scenario is analyzed, where cost and environmental impact are both considered, Inner-Armor and the existing Hex-chrome appear to be the best choices.

Conclusion and Recommendations

Project Summary

In this project, the team provided a history of hard chromium coatings. We discussed the regulatory, environmental, and economic issues emanating from hard chromium. Various alternatives are discussed in detail, many of which are considered “Nano-coatings” due to their tiny architecture and deposition methods. An evaluation model / decision matrix was developed. This model evaluates various alternatives using a multiple selection criteria along with weighted scoring and scenario analysis. The team added to the existing body of knowledge by establishing this model and providing guidance regarding the model inputs.

Future Direction

As data becomes available, scoring factors should be a gradient of the actual values. For example, the model could support actual hardness data for each material normalized to the baseline (hex-chrome). Weighting factors could also be added to the model to comprehend additional factors such as professional, organizational, and other factors. This expanded model is shown below:

$$S_i = \sum_{j=1}^{n} k_j P_j C_{i,j} \qquad \forall i, j$$

Concluding Remarks

In this project, the team provides a history of hard chromium coatings. We discussed the issues surrounding hard chromium and traditional application processes. Various alternatives were discussed in detail, and a decision matrix / evaluation model was developed.

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Appendix A: Article Search Methodology

In order to understand the future of hexavalent chromium, a article search was conducted using data that is available on the National Institute for Safety and Health (NIOSH) website. The NIOSH site provided an internal search engine that was used to data mine the information on the site. The following table identifies the search criteria that was utilized to search the website.

Table #10 Article Search Criteria

Find Results: with **all** the words	Issue Date: Start	Issue Date: End
Chromium, Hexavalent	January	December

For each of the above searches the years that were analyzed were from year 1970 to year 2009 (inclusive). For each of the samples the issue date was changed for both the Start and End values to represent the year of interest.

For Example:
Entry 1) January 1980 and December 1980
Entry 2) January 1981 and December 1981

For each of the samples, the number of articles published was recorded in the responding data set.

Appendix B: Patent Search Methodology

In order to understand the future of hexavalent chromium, a patent search was conducted using data that is available on the United States Patent and Trademark (USPTO) website. The search engine that was used to data mine the information on the USPTO site was Google patents[11]. Through Google patents, data was collected using the following search criteria:

Table #9 - Patent Search Criteria

Find Results: with **all** the words	Find Results: **without** the words	Document Status:	Issue Date: Start	Issue Date: End
Hexavalent Chromium	Trivalent	Issued	January	December

For each of the above searches the years that were analyzed were from year 1970 to year 2009 (inclusive). For each of the samples the issue date was changed for both the Start and End values to represent the year of interest.

For Example:
Entry 1) January 1980 and December 1980
Entry 2) January 1981 and December 1981

For each of the samples, the number of patents issued was recorded in the responding data set. In order to obtain the y-intercept for the number of patents issued before 1980, data set was searched without an opening Issue date, and with the closing date of December 1979.

Appendix C: Alternate Materials Strengths & Weaknesses

Table #4 - Material: Enviroalloy Strengths and Weaknesses [14]

Strengths	Weaknesses
Corrosion Resistance Electrical Throw Coverage	No Data Listed

Table #5 - Material: Mettex 6 Strengths and Weaknesses [15]

Strengths	Weaknesses
Hardness Heat Treat Hardness Friction Coefficient Surface Roughness Throwing Power Covering Power Current Efficiency Deposition Rate	Wear Rate

Table #6 - Material: Hard TriCom Strengths and Weaknesses [16]

Strengths	Weaknesses
Hardness Wear Resistance Fatigue Debit Thermal Stability Corrosion Resistance Coverage	No Data Listed

Appendix C (Continued)

Table #7 - Material: Nanovate CR Strengths and Weaknesses [17]

Strengths	Weaknesses
Friction Coefficient Sliding Wear Corrosion Protection Fatigue Debit High Temp Durability Deposition Frequency Throughput Energy Consumption Bath Stability	No Data Listed

Table #8 - Material: Inner-Armor Strengths and Weaknesses [18]

Strengths	Weaknesses
Hardness Corrosion Resistance Coefficient of Friction Coverage/Uniformity Thinner Application Environmental	No Data Listed