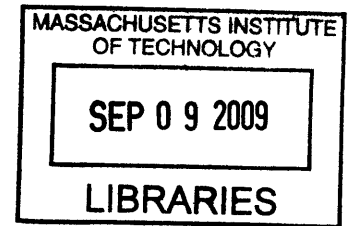# A Technical and Marketing Analysis of Nanocrystalline Ni-W Coating for Oil and Gas Industry Applications

by

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SUBMITTED TO THE DEPARTMENT OF MATERIALS SCIENCE AND ENGINEERING
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A Technical and Marketing Analysis of Nanocrystalline Ni-W Coating for Oil and Gas Industry Applications

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ABSTRACT

Nanocrystalline nickel-tungsten is a new metallic coating technology developed at MIT in the laboratory of Professor Christopher Schuh in 2005. The new coating technology utilizes a special electrodeposition process to achieve precise control of synthesized nanocrystalline coating structure and resulting properties. This method can produce coatings with enhanced properties including excellent corrosion, wear, and heat resistance in addition to being health and environmentally friendly. At a competitive price along with an efficient coating process, it is anticipated that this coating technology will have high impact on the functional coating industry. This will hopefully lead to future development of other nanocrystalline coating systems.

This project focuses on the technology technical and marketing analysis with particular emphasis on the oil and gas industry. The evaluation involves assessing the technology value, highlighting potential applications, comparing with competing technologies and developing commercialization strategies. A comprehensive technical evaluation plan was outlined in order to insure coating suitability for the intended market applications and provide assurance to future clients. This thesis also analyzes several business model strategies to penetrate the oil and gas coating market and proposes what is believed to be the most efficient strategy. Based on the proposed strategy, a detailed cost model is presented to estimate the cost of production and determine pricing options. Finally, several economic outcome scenarios are presented based on the estimated market size and future demands.

Acknowledgment

I would like to express my great appreciation to Professor Christopher Schuh for introducing me to this topic as well as guiding me throughout my study. I am very grateful for his mentorship during my project and his commitment. Working with Prof. Schuh has been a privilege.

To MIT: Thank you for giving me the opportunity to be part of you. It was an honor to join such a wonderful institution.

I would like to thank Saudi Aramco, my sponsor at MIT, for giving me this wonderful opportunity through the company's scholarship program. I look forward to applying the new knowledge and skills acquired during my stay at MIT to the benefit of Saudi Aramco operations and my country.

Last but not least, I would like to thank my wife, Rana, for her patience, care and support. Finally, to my little daughter Sara, thank you for the entertainment, distraction and adding fun to my life.

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Chapter 1: Technical Background

1.1 Nanocrystalline Materials

Extensively over the past two decades, researchers have been studying nanocrystalline materials. The interesting and superior properties of nano materials as compared to coarse-grain materials, which are continuously being discovered, present the main motivation for continuing investigations [1]. Most metals are polycrystalline, meaning that they consist of many grains. Polycrystalline materials are characterized by the presence of grain boundaries that have significant influence on properties [2]. The microstructure, described by the grains' size, shape and orientation, along with many other factors, determines the macro-physical properties of a material. Thorough understanding of a material's microstructure is crucial in determining its structure-property relationship.

A fundamental material strengthening concept is the Hall-Petch principle. It explains the influence of grain size on mechanical properties such as tensile strength and hardness. It has been scientifically proven that, as grains become smaller, materials become stronger and harder. Eventually, as grains approach the nano-scale (<100 nm), materials become even stronger [3]. The empirical Hall-Petch relationship predicts that there is an inverse relationship between the material's strength and the average grain size, as illustrated in Equation 1 [4,5,6].

$$\sigma = \sigma_0 + \frac{k}{\sqrt{d}} \qquad (1)$$

Where σ is the yield stress, k is the strengthening coefficient, σ_0 is the starting stress for the dislocation movement (Materials constant), and d is the grain diameter.

A widely accepted physical explanation for the Hall-Petch principle is related to dislocations and their movement within individual grains and from one grain to another through grain boundaries. Grain boundaries resist dislocation movements from one grain to another, reducing plasticity and increasing yield strength. The larger the grain, the more dislocations can pile up within the grain. Dislocation pile-up reduces the energy barrier required for dislocation movement across grain boundaries, therefore increasing the plasticity of the material. Similarly, the smaller the grain, the fewer dislocation pile-ups within the grain and the less available driving force for deformation. As a result, a higher stress is needed to yield the material [7].

Unfortunately, we cannot make materials that are infinitely strong by reducing their grain size; therefore, as we might expect, there is a limit to this strengthening mechanism. The Hall-Petch relationship breaks down when grains become very small [8]. Extrapolation of equation (1) for grain diameters below 10 nm does not truly increase yield strength. In most cases, the material's strength starts to drop below 10 nm. Figure 1 is a demonstration of this phenomenon for Ni done by Carsley [9]. The breakdown of this relationship has been explained by deactivation of the slipping dislocation and activation of the grain boundary sliding mechanism instead [10,11,12]. It has been experimentally proven that materials have the highest yield strength at a grain size of approximately 10 nm, below which the yield strength starts to drop [13].
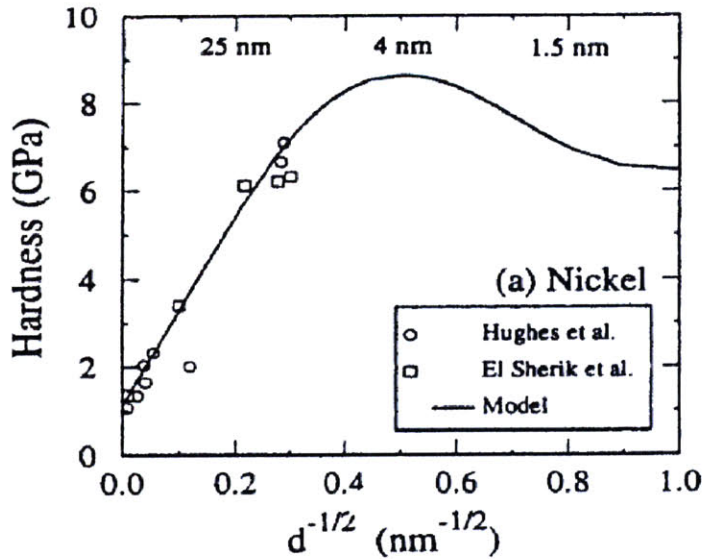
Figure 1: Strengthening of Ni shows the breakdown of Hall-Petch relationship, Carsley [9].

Synthesizing materials with this optimal grain size requires a great degree of control. Furthermore, synthesizing pure materials at the nano scale is still challenging and, even when it is done, the materials are inherently unstable. Figure 2 shows the breakdown of the hall-Petch principle at about 10 nm; yet some people claim that this still debatable due to the scarcity of supporting data at this range, as a result of synthesis difficulties [14, 15].
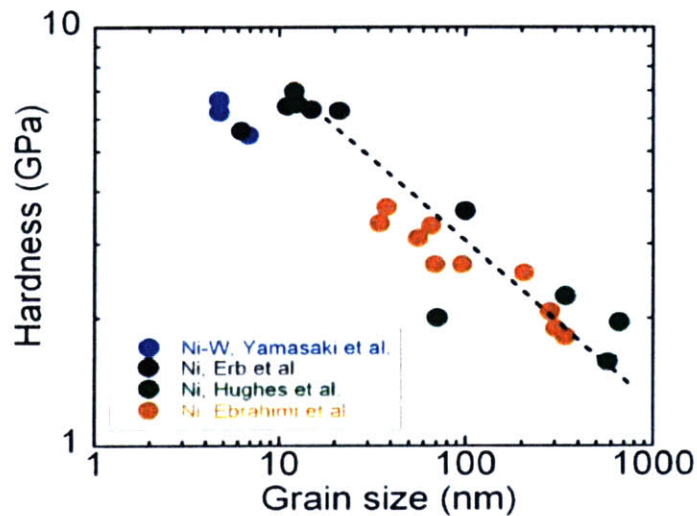
Figure 2: Hardness as a function of grain size of Ni, A breakdown in the classic Hall-Petch principal at about 10 nm [14].

Nanocrystalline materials are inherently unstable because of their high interfacial energy representing a departure from the thermodynamic equilibrium state [16]. A fundamental concept of thermodynamic stability of pure nano materials is derived from the Gibbs free energy relationship, equation (2). Thermodynamic systems always prefer to minimize their energy. One way to do this is to minimize the grain boundary energy. The smaller the grains, the larger the total grain boundary area and the higher the interfacial energy. To reach the minimum desired free energy, the system (grains) will have a strong tendency to grow or coarsen, and thus pure nano materials are unstable [17]:

$$dG = \gamma . dA \qquad (2),$$

where dG is the change in free energy, γ is the grain boundary energy and A is the surface area.

Synthesizing nanocrystalline materials requires energetic processes such as plastic deformation, rapid quenching or electrodeposition, the latter of which is the method used to synthesize nanocrystalline materials in the technology under consideration in this thesis. The other techniques have certain quality and grain size limitations. The electrodeposition method was able to synthesize high quality nano materials and to provide access to a wider range of grain sizes [18].

As indicated, pure nanocrystalline materials, even when successfully made, are thermodynamically unstable. In order to overcome the instability problem, the alloying of two or more elements tends to stabilize the grains against coarsening. In equation (2), grain boundary energy γ is positive; thus the system can reduce its energy by increasing the grain size. The solute species segregates to grain boundaries, creating an opposing force to growth and stabilizing the system. This system becomes stable when the two forces are equal and there is no

net driving force to grain growth [19,20]. The main outcome is that this segregation improves the system's stability and reduces grain boundary energy. Stable nanocrystalline structures are of particular interest to researchers since they allow further investigation and exploration of properties and practical applications.

Furthermore, it has been established in the literature that there is an inverse relationship between the composition (solute content) and grain size. Figure 3 shows this relationship in a Ni-P system [21]. Higher solute content will drive the system to smaller grain sizes in order to create more grain boundaries and space for the segregating species [22]. The underlying principal suggests that we can achieve control over the grain size through the ability to precisely control the solute content.
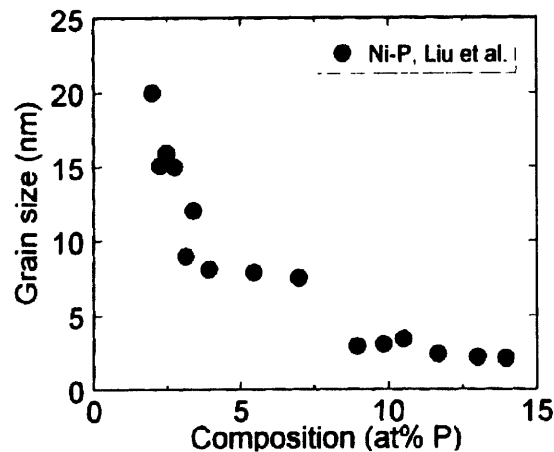
Figure 3: Grain size as a function of P content in Ni-P system [21].

1.2 Electrodeposition Process

Electrodeposition, also known as electroplating, is a vital process in materials science and engineering. It can be used to synthesize a wide range of materials including pure metals, alloys, composites and polymers [23]. The properties of widely available and inexpensive materials can be significantly improved by depositing layer(s) of higher grade materials; thus these materials

13

can extend their application opportunities [24]. A significant cost saving is realized by this method compared to building the entire structure from higher grade materials.

Electroplating is not a simple process, with the quality of the produced coating depending on many parameters. The model in Figure 5, developed by Rudzki, shows the complexity of the electroplating process and involved parameters [25]. Four important zones must be considered when choosing to protect a surface by electroplating. Those zones are: 1) the substrate, 2) the substrate interface, 3) the coating and 4) the coating-environment interface. Several parameters pertaining to each zone must be carefully controlled in the electroplating process as shown in Figure 4 [26].

Coating-Environment Interface	• Corrosion • Wear
Coating	• Stress • Structure • Properties • Additives • Porosity
Substrate Interface	• Diffusion • Adhesion
Substrate	• Hydrogen embrittlement
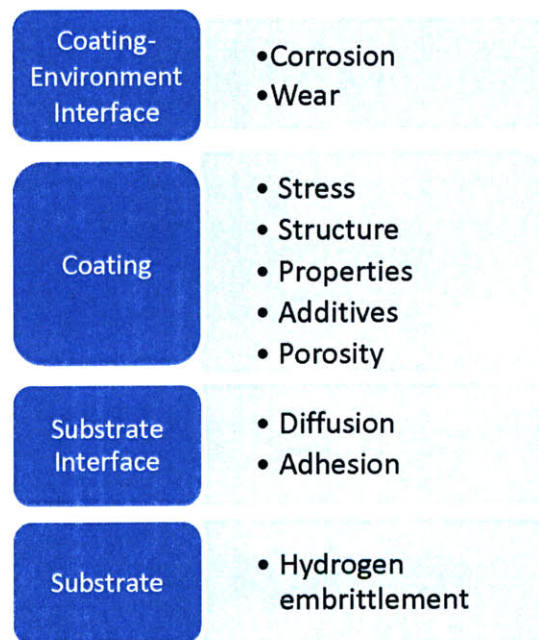
Figure 4: Factors affecting coating by electroplating; reproduced from Dini, J. [26].
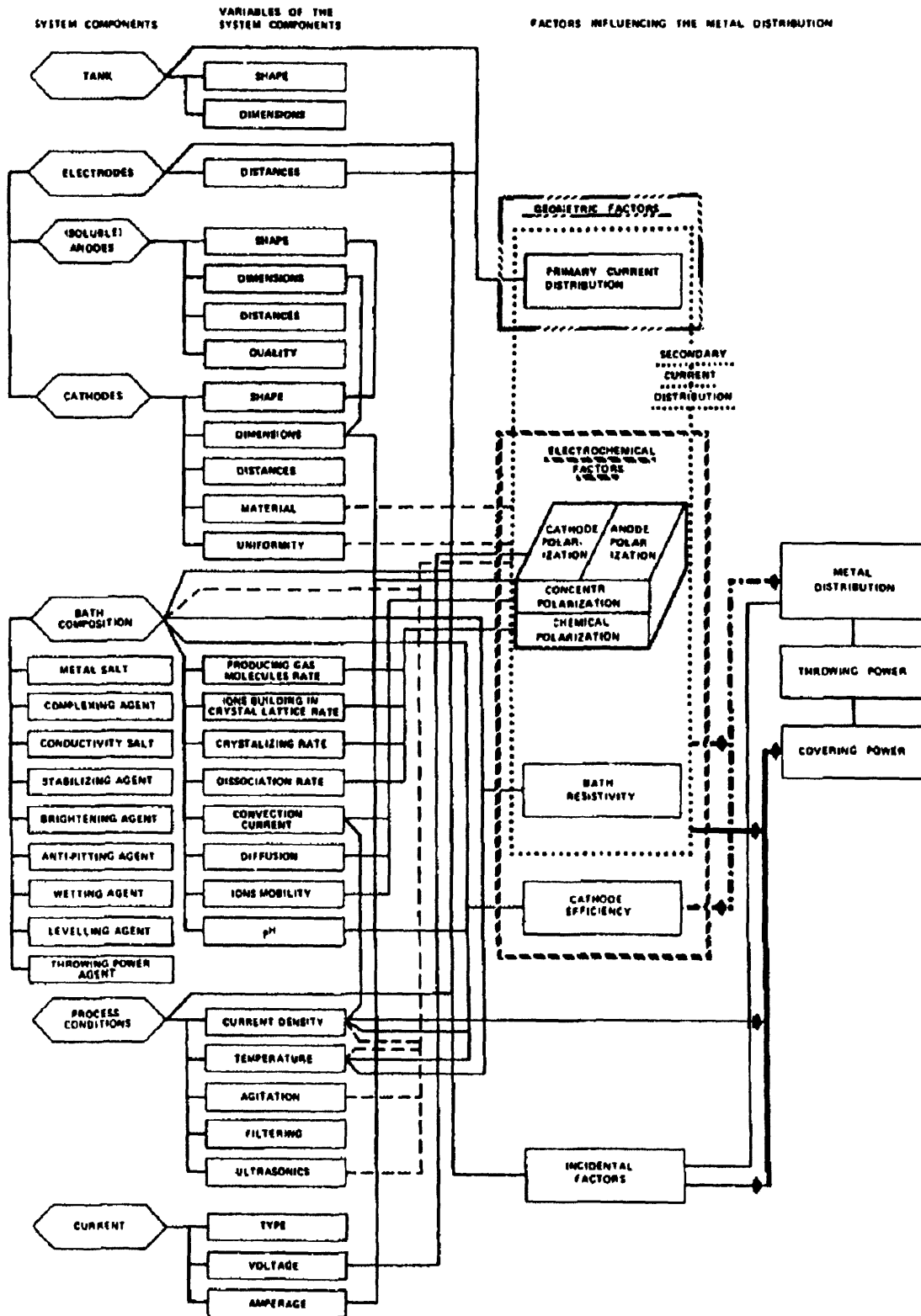
Figure 5: The Electroplating process model by Rudzki illustrates the complexity of electroplating process parameters [25].

Chapter 2: The Technology

The research leading to the present technology was conducted by Andrew Detor, a 2007 MIT PhD graduate, and supervised by Professor Christopher Schuh. In light of the above scientific challenges, the motivation for the research was to:

- Establish a reliable method that offers precise control over nanocrystalline grain sizes of a Ni-W alloy. It can possibly be applied to other alloy systems.

- Explore new and interesting properties of nanocrystalline systems that are superior to traditional coarse-grained materials.

- Gain a better understanding of already established grain size - composition relationships.

- Produce new materials with better properties for current and new applications.

Detor explicitly states that the main objective of his research was:

"To exploit the thermodynamic effects of alloying to tailor microstructures over a wide range of the finest nanocrystalline grain sizes with focus on Ni-W as a model alloy system" [27].

2.1 Summary of Research Outcome

The Ni-W alloy system was extensively investigated to further explore structure-property relationships, leading to discoveries that include establishing a new and robust synthesis technique able to precisely tailor properties by controlling solute content. Ni-W form a unique combination when deposited by a special electrodeposition process, described in the next section, and produce alloys with interesting mechanical and corrosion properties. Tungsten cannot be electrodeposited by itself from its own soluble compounds; however it can be, for example, codeposited with Ni when it is put in a bath with nickel sulfate [28].

Grain size has a crucial effect on material properties. The average grain size is controlled by the alloy composition; the W content controls the grain size over a wide range, from 2–140 nm. This degree of control and ability to access such a wide range of grain sizes was not achievable using conventional electrodeposition processes. Experimental observations also showed that W has a weak tendency to segregate to grain boundaries; therefore, W-Ni was predicted to have special characteristics [29].

During the electrodeposition process, crystal size and structure can be controlled to suit the targeted application and achieve the required properties [30]. By varying the electrodeposition parameters, namely reverse current density and duration, many coating layers can be created in a single coating step, each with a different composition and grain size. As a result, we can create a soft initial coating layer, with excellent adhesion strength, to the bulk material and hard final surface with excellent erosion and wear resistance. Conventionally, this has been done using a multistep process with different bath solutions and/or temperatures in order to achieve such a coating profile. In a single coating step, the present coating process can achieve the same set of desirable properties including strength, toughness, wear and erosion-corrosion resistance [31].

The time and energy savings from using a single coating step result in significant cost savings, especially in large scale production. In addition to the significant cost savings, this technology is environmentally friendly, without the health and safety risks associated with many other metal coatings [32].

2.2 Reverse Pulse (RP) Electrodeposition Process

A new synthesis technique, namely "reverse pulse" electroplating, was developed to allow precise composition control during the electrodeposition of Ni–W alloys. Electrodeposition process is a widely used technique in the coating industry. However, it is used here with a slight modification that had a significant impact on the synthesis of nanocrystalline materials. A typical electrodeposition system set-up is shown in Figure 6 [33]. The system consists of a cathode (substrate), anode, electrolyte bath, heating system, stirrer, and power supply. Clearly, there are many process parameters that can be varied during an electrodeposition process. However, in this study, all parameters were kept constant except the bath temperature and current. These two parameters were varied independently and their effects on composition, quality and structure of created samples were investigated. Details of the experiment are explained in Detor's thesis document.
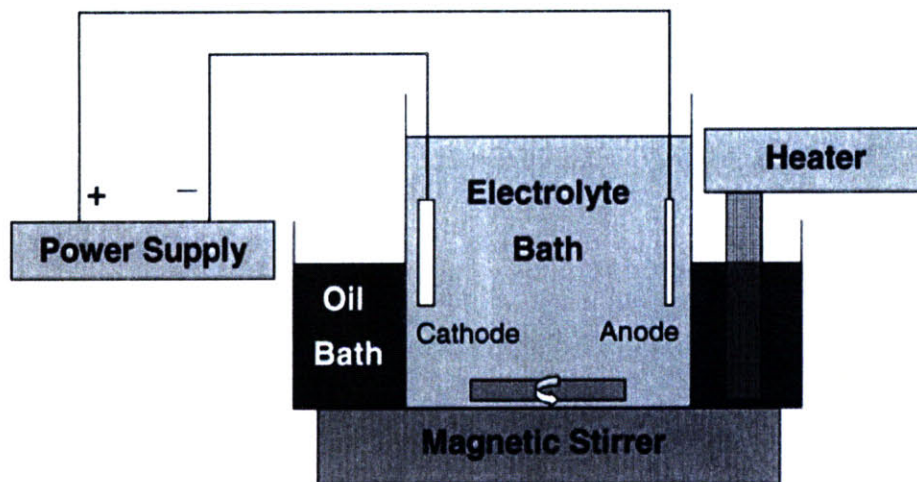
Figure 6: Schematic of electrodeposition system [33].

The electrolyte bath temperature was found to have a significant impact on the electrodeposited Ni-W structure, as shown in Figure 7 [34]. There is almost a linear relationship

between the bath temperature and the W content. This relationship suggested a possible ability to control W composition and the resulting grain size by just controlling the bath temperature. However, it was found that samples produced using this control method have poor quality. Therefore, this method was ruled out and considered to be unreliable for any further structure-property relationship investigations.
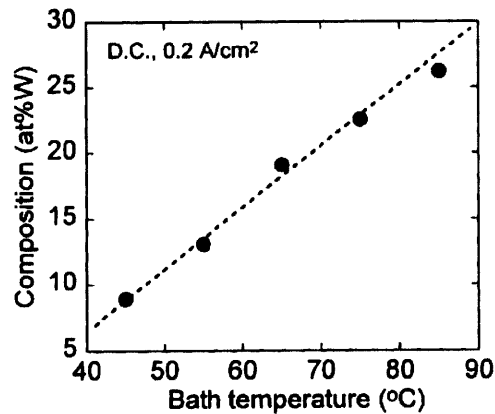
Figure 7: The effect of electrolyte bath temperature on composition [34].

Reverse pulse waveform

The second parameter investigated was the effect of changing the current amplitude, direction, and duration. Figure 8 shows the shape of the reverse pulse waveform [35]. Effects of the reverse pulse amplitude and time on the W content are plotted in Figure 9 [36]. We can see a strong correlation between the reverse current amplitude and time, and composition of the deposited structure.
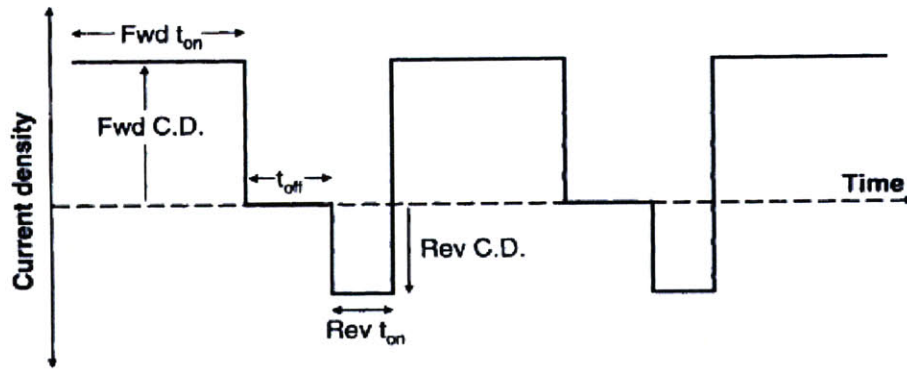
Figure 8: A waveform showing the reversed pulse signal [35].
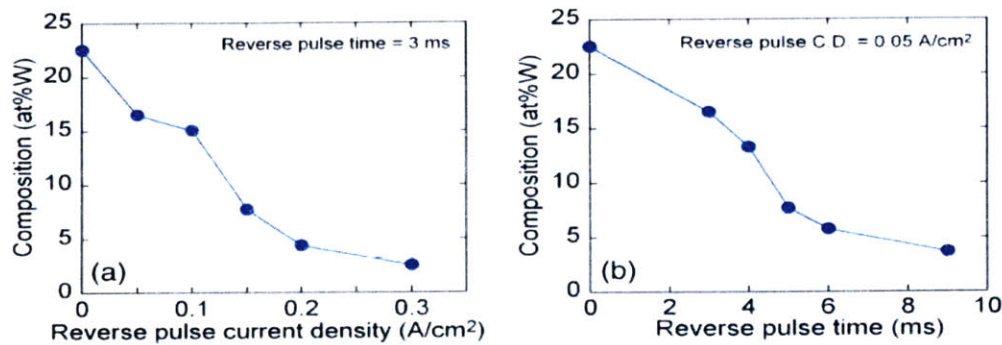
Figure 9: Effects of RP current amplitude and time on W composition [36].

Establishing a reliable method that can precisely control the amount of solute in an alloy system is challenging. Once this goal is achieved, a great control over the system's average grain size is possible. In the present system, the average grain size and W content relationship was established. Figure 10 shows the relationship between the W content and grain size over a wide range of W content (2-23%) [37]. The conventional electrodeposition technique offered similar results yet a much narrower range of grain sizes, 2-40 nm, compared to 2-140 nm using RP technique [38]. The RP technique also offered high-quality homogeneous deposits.
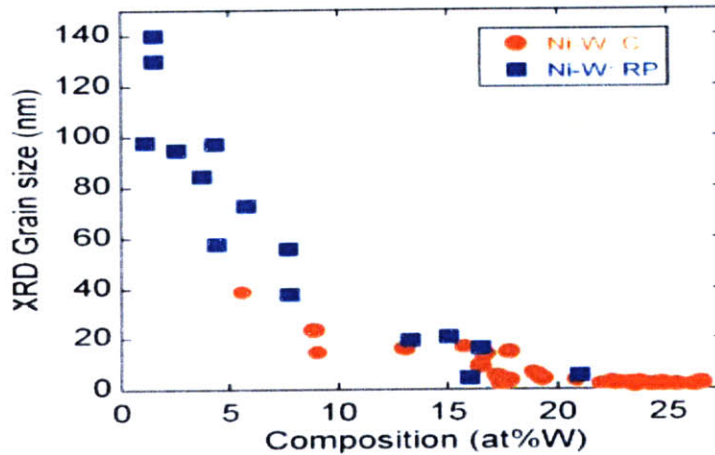
Figure 10: Composition-grain size relationship using RP vs. conventional electrodeposition technique [37].

2.3 Practical Advantages

The new nanocrystalline Ni-W synthesis technique has many practical advantages that can lead to many potential applications, especially in the metal coating field. Several of these advantages are described below.

Deposits with tailored properties

A main advantage of the current work is that it enables the production of Ni-W nanocrystalline deposits with a wide range of grain sizes. This capability has been achieved by adjusting only current density and duration. Precise control over the solute (W) composition directly correlates with the average grain size of the deposit. The properties of the deposit, whether mechanical or electrochemical, depend on the grain size of the structure. Therefore, accessing a wide range of grain sizes and associated properties enhanced our capabilities in designing nanocrystalline materials and coatings for various applications. Figure 11 shows the relationship between grain size and hardness of the present system compared to others from the literature. The RP technique is able to synthesize specimens over a wider range of grain sizes

from 2 to 140 nm with corresponding hardness that can be as high as 8 GPa. The hardness can be further enhanced with post heat treatment. More importantly, the specimens are thermodynamically stable over the entire range of grain sizes [39].
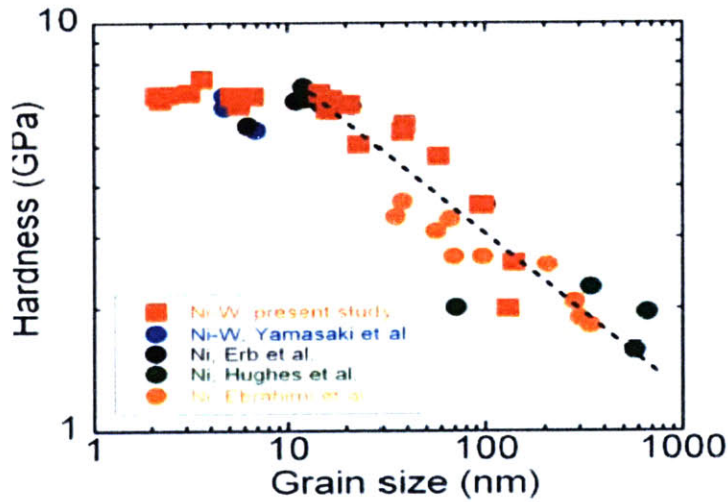
Figure 11: Hardness data plotted as a function of grain size of the current work and from literature [40].

The concept is simply illustrated in the following diagram:
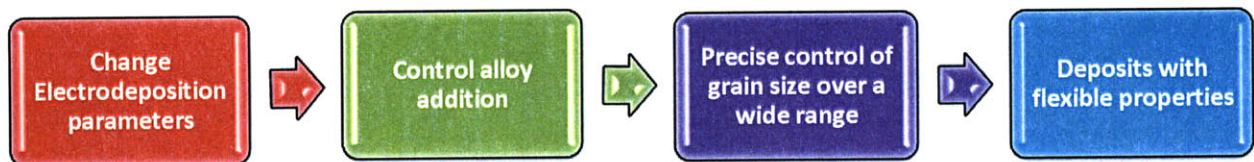
Figure 12: Process concept.

High quality deposits

The RP electrodeposition synthesis technique can produce high quality deposits. Unlike many other synthesis techniques or using the bath temperature to control alloy composition in the electrodeposition process, the deposited samples are homogenous and free of cracks and defects,

as shown in Figure 13. The quality of the as deposited structure remains unaffected up to a temperature of approximately 450 $^{\circ}$C [41].
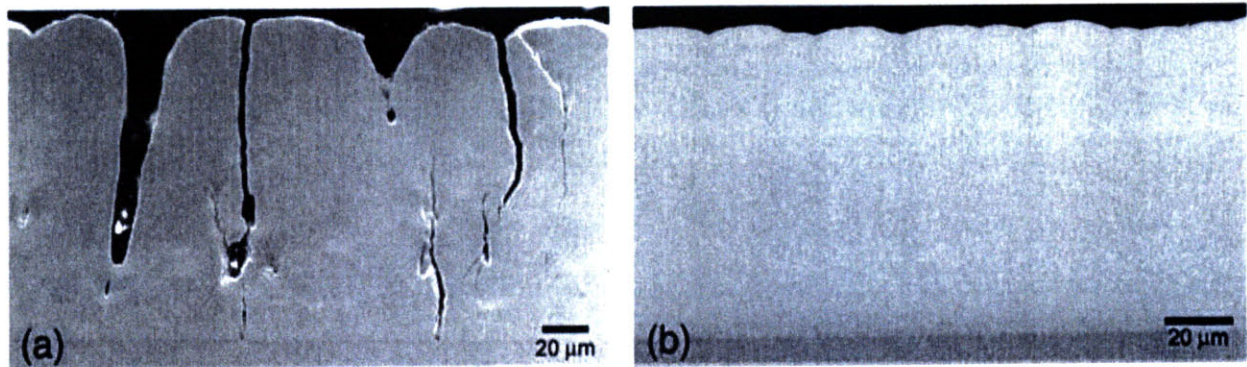
Figure 13: SEM micrographs of nanocrystalline Ni-W specimens prepared by (a) bath temperature and (b) reverse pulsing control [38].

Patterned Nanostructured Coating

With this degree of grain size control, the current technology is capable of building multilayer nanocrystalline Ni-W coating in a single step. Since the only control parameter in the electrodeposition process is the current density and time, a particular waveform can create a single layer with desired grain size and properties. Having consecutive different waveforms programmed into the pulse rectifier, a multilayer coating with changing properties of each layer can be easily created. This offers a great deal in designing an optimum coating for a particular application. It allows compromises of desired properties such as wear and corrosion resistance in each layer. The coating can also be deigned to have smooth transition from the bulk material by tailoring the properties of the adjacent coating layer to the substrate [42]. Traditionally, this has been done using a multi-step process that involves changes in many parameters including bath chemistry, temperature, and others. Examples of graded and an alternating coating structures along with the properties of each layer, are shown in Figure 14.
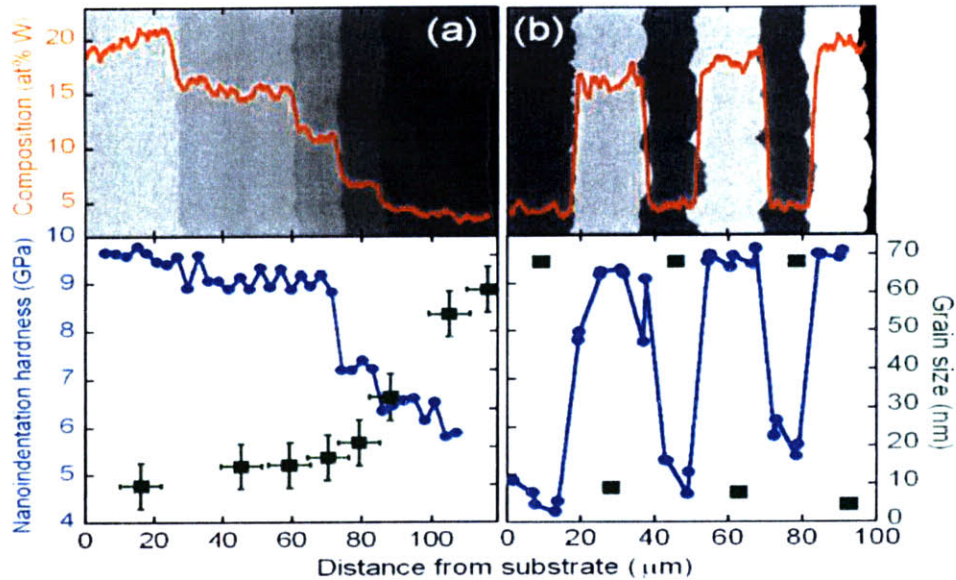
Figure 14: SEM images of a) graded structure with decreasing W content, B) alternating structure. The corresponding grain size and hardness of each layer is shown in the bottom graphs [42].

In summary, the current coating technology is capable of designing Ni-W nanocrystalline coating with tailored and enhanced properties. This tremendous enhancement in nanocrystalline metallic coatings has many potential market applications. The ability of this coating to deliver enhanced corrosion, wear and heat resistance in addition to being health and environmentally friendly, will enable it to penetrate and compete with current coating technologies in most industries. Market analysis for the oil and gas industry and its potential applications will be discussed in this paper.

2.4 Current Applications

The technology has been exclusively licensed to Xtalic Corporation, Marlborough MA. Xtalic Corporation was founded in 2005 by Professor Schuh and his partners to commercialize this technology and bring it to the marketplace. So far, the technology has been limitedly

implemented in decorative applications such as vehicle exteriors and sporting equipment, and in other electronics applications.

Xtalic has used the nanocrystalline Ni-W synthesis technique developed at MIT and converted it into an industrial process that can be widely used to create nanocrystalline metal coatings. Xtalic has been focusing on the development of key coating properties such as corrosion resistance, wear resistance, and appearance in the commercialization process [43].

Chapter 3: Oil and Gas Market Analysis and Competing Technologies

3.1 Overview

Many coatings are designed to serve a specific environment by first indentifying its key properties. For example, thermal resistance, magnetic properties and electrical conductivity are crucial when designing coatings for electronics applications. Similarly, other properties become crucial when designing coatings for oil and gas applications. Oil and gas operations involve more complex environments that require coatings with superior properties. Severe corrosion and wear environments, along with other mechanical and thermal loadings, can be present in such operations; i.e. high temperature, high pressure, corrosive chemicals, and high velocity particles may be present. These environments range from mild to severe with very harsh conditions. Most existing coatings have serious limitations and are not suitable for most oil and gas applications. Others are good for mild to moderate environments but are not suitable for more severe ones. For example, chrome plating serves well in an erosive and high-wear environment while it shows poor performance in a corrosive environment. Nickel plating, on the other hand, serves well in corrosive environments while it shows relatively poor performance in high wear systems. Coating systems that can simultaneously protect against both corrosion and wear rarely exist [44].

Coatings can be used to improve a component's mechanical properties such as hardness, strength, and toughness. Similarly, resistance to environmental conditions such as high temperature oxidation, aqueous corrosion, and solidification can be enhanced by selecting a proper coating. Four of the most significant problems that need to be addressed in oil and gas applications are: corrosion, erosion-corrosion, fatigue and wear [45].

Wear due to high velocity particles as well as corrosion failures in aggressive environments, such as sour service and chloride rich solutions, have been a major concern in the oil and gas industry [46]. Significant research and development efforts have been devoted to solving these problems, but there remains a need for improved coating technologies.

3.2 Technology-Market Relationship

Many applications in the oil and gas industry, ranging from drilling and producing wells to the farthest downstream refineries and gas plants, are potentially viable for the present technology. The ability of this technology to produce high quality metal coatings with improved corrosion, wear and abrasion resistances at a competitive cost will enable it to penetrate this industry where such coating characteristics are in high demand.

For many reasons, the present coating technology was predicted to have high-potential applications in the oil and gas industry. In addition to the enhanced coating properties and ease of application, oil and gas is a huge global market in which industry size plays a major role in profitability; economic benefits can be realized even at a low market share. Also, this industry is still in need of improved coating technologies as the current technologies are not able to solve many problems. It is believed that the present coating technology can offer solutions to many of the corrosion, wear and other failure mechanism problems. In addition, downtime periods in an oil and gas facility are very costly due to loss of production. Durability, performance and reliability, rather than cost, are the key factors when evaluating new products. Competition is usually driven by performance rather than price, so a high potential profit margin can be expected. A common expression used is "buy better product even if more expensive." Better

performance can increase service life and reliability of critical equipment and components which eventually compensate for the additional initial cost.

Nonetheless, an extremely expensive technology is unlikely to find its way to any industry. The additional cost for high quality products described above should be within acceptable limits, because it will be always considered but not necessarily the primary factor. For example, another solution to most problems is building the entire structure/equipment part from a higher grade material. This strategy is not viable due to the extremely high cost and availability issues of such materials. As one might anticipate, building a whole refinery or gas plant from titanium or a similar metal is not feasible. Similarly, an extremely expensive technology will fall in the same category.

3.3 Oil and Gas Applications

As part of the information gathering process, a visit to a major oil and gas company was conducted. During the visit, the author personally met with several personnel from technical and management staff. Useful information about the currently used coating techniques and their applications and limitations was documented. More importantly, needs were identified that highlighted applications and environments currently coating technologies cannot satisfy. It is reasonable to assume that the operations of most oil and gas companies are similar. Therefore, the information gathered from one company can provide a good idea about the industry.

Many metallic coating processes including thermal spray and plating are being used in the oil and gas industry. Among these widely used processes are High Velocity Oxygen Fuel (HVOF), Nickel plating and Chrome plating. The aggressive operating environment narrowed the number of the used coating processes and only a few techniques proved to be reliable for

certain applications. Coatings can be applied to new parts or used as a repair method for surface damage. Figure 15 shows examples of damaged equipment parts. There are many applications that require reliable metallic coatings to protect against corrosion and wear, and the most common are:

- Rotating equipment shafts;

- Motors and compressors rotors;

- Valve bodies and components;

- Pump and compressor casings;

- Turbine blades;

- Sealing joints and joint surfaces;

- Drilling equipment.

Restoration of Worn Machine Parts

Daily, machine shops in major oil and gas corporations are busy repairing damaged equipment parts. Some parts however are beyond repair. Most of the repairable ones exhibit surface damage. Very often, these parts need to be returned to service as soon as possible; therefore, the most efficient repair processes must be used. Usually the cost of the repair is negligible compared to the incurred cost from equipment idle time and the consequent loss of production. When a damaged part is received, several repair parameters are considered by the machine shop technical staff, and a repair method is carefully chosen [47]. The following parameters help to select the appropriate coating process.

- Depth of damage
- RPM for rotating parts
- Weight
- Size
- Type of fit
- Corrosion severity
- Temperature
- Material type
- Abrasion severity
- Pressure

15 A- Ball valve	15 B- Joint face
15 C- Broken pump shaft	15 D- Compressor rotor
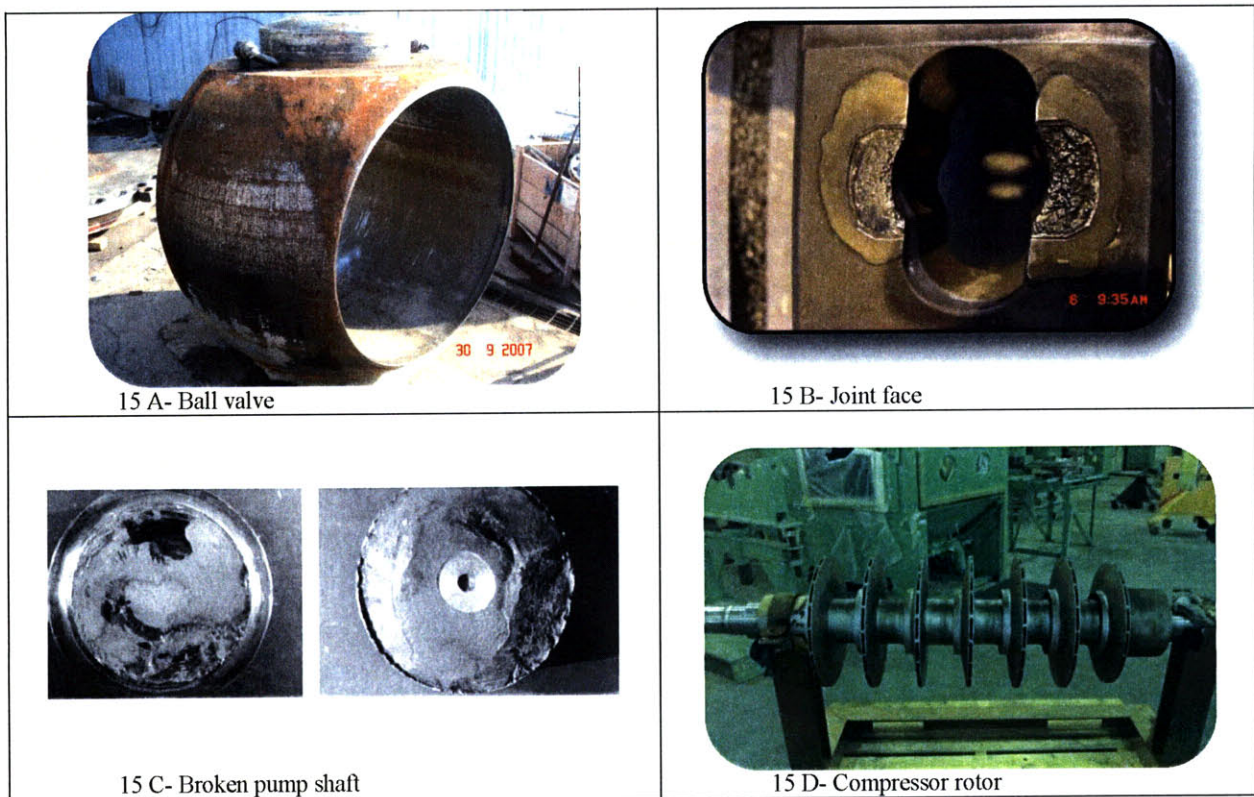
Figure 15: Examples of damaged equipment parts.

Application to New Parts

New parts, spare or installed in equipment, are already coated when purchased from their original equipment manufacturers (OEMs), with specifications of these parts usually determined by the end user. Successful implementation of the present coating technology to repair applications will helpfully lead to its incorporation as part of new equipment specifications. Details of this strategy will be discussed in Chapter 6.

Intended Environments

The present coating technology is intended to be used in the above applications for equipment operating in seawater and sweet hydrocarbon services, oil and gas that contains CO_2. For the time being, this coating is not intended for sour hydrocarbon services, i.e., oil and gas

that contains H_2S, because there is a growing concern among oil and gas companies that all electroplating processes charge substrates with atomic hydrogen. Materials that contain atomic hydrogen can develop hydrogen-related damage when installed in a sour service environment. For this reason, some companies have banned the use of electroplated materials in sour hydrocarbon services. There are several prevention methods that can be used to minimize hydrogen embrittlement, one example of which is post processing heat treatment (baking) to diffuse the atomic hydrogen out of the material [48, 49]. Qualification tests such as ASTM F 519 must be conducted to ensure the suitability of those materials for sour hydrocarbon services.

3.4 Competition

Many coating processes are being used in the oil and gas industry. The most common ones are briefly described below.

High Velocity Oxygen Fuel (HVOF)

HVOF, a commonly used thermal spray coating process in the oil and gas industry, is a multi-step process that involves mechanical preparation and finishing. It starts with pre-machining samples, then grit blasting, applying the coating and finally grinding to the desired thickness. Many powder materials can be used with the HVOF process to deliver the desired coating properties for different applications. For example, nickel based alloys such as Inconel-625 is used for corrosion protection, and tungsten carbide powder is used for wear resistant applications [50,51]. The two powder materials manufactured by METCO, NY will be used for the purpose of comparison with other coating technologies. The composition of Inconel-625 is shown in Table 1.

Table 1: Chemical Composition of Inconel-625 Powder [52].

Powder material	Ni	Cr	Mo	Co	Fe
Inconel-625	58 min.	20-23	8-10	1 max.	5 max.

Unlike electroplating techniques, coatings produced by HVOF do not have a low thickness limitation. Deposit thicknesses above 0.01-inch can be easily achieved. The final coating properties highly depend on the type of powder material, size of sprayed particles, feed rate, spraying distance, and on many other complicated process parameters [53]. For example, a study by Ghabchi showed that wear rate of tungsten carbide HVOF coating can be reduced by 50% by tailoring the carbide particle size [54].

A high degree of automation and robotic technologies are usually needed to achieve proper control of the HVOF coating process. Also, it is a line-of-sight process, i.e. only surfaces that are seen by the coating gun can be coated. In addition, the process is highly dependent on the spraying angle; thus, it is difficult to coat internal surfaces and small diameter parts. Also, the high heat input involved during the coating process can potentially cause distortion to the substrate. With Inconel-625, a hardness of 30-34 Rc (Rockwell C) can be obtained while, with tungsten carbide, a hardness of 55-60 can be obtained [55]. With different powder materials, HVOF can be used to enhance surface properties against corrosion and wear.

HVOF is a relatively unclean process that generates a lot of waste that must be handled during an application. Usually, HVOF shops have a water bath that washes process material waste and collects the great amount of dust generated.

Nickel Plating (Electroless Nickel Plating)

Electroless nickel generates deposits with good corrosion resistance. Unlike conventional electroplating, the process does not require a supply of electrical current; therefore, there is no need for a power supply. Instead, the reducing agents react with the metal ions to produce the deposits. Usually Ni is codeposited with phosphorus, and the amount of the latter determines the final set of coating properties [56]. The hardness of the as-deposited coating can reach 50 Rc,

which gives it a decent resistance to wear but lower than that achieved by chrome plating. Similar to most plating techniques, the maximum thickness that can be deposited is around 0.02in (500 μm) [57].

Chrome Plating (CP)

The chrome plating process referred to here is hard chrome plating or functional chrome plating. The main advantage of chrome electroplated coating is its excellent wear resistance. Hardness between 66-70 Rc can be easily achieved as deposited. CP is not a very efficient process because of its low plating efficiency (15-20 %) and its low rate of metal deposit, 15 μm/hr. In addition, CP offers poor corrosion protection for substrates, and as in other electroplating techniques, the maximum thickness that can be deposited is around 0.02 in (500 μm) [58]. More importantly, the CP process has been banned in several industries due to the environmental and health hazards that the process imposes on workers. As a result, the hard chrome industry is facing strict environmental regulations by many government agencies such as EPA and OSHA. Chrome plating baths use hexavalent chrome, which is very toxic and dangerous to human health [59].

3.5 Comparison Matrix

The following table is a comparison matrix of our coating technology compared to its main competitors in the oil and gas industry.

Table 2: Performance Matrix.

coating / Property	Chrome Plating	Electroless Nickel	HVOF (inc. 625) [60]	HVOF (WC)	Ni-W Nano coating
Wear protection	Excellent	Moderate	Moderate	Excellent	Excellent
Corrosion protection	Poor	Excellent	Excellent	Moderate	Excellent
Hardness (Rc)	66-70	50	30-34	55-60	60-64
Hydrogen embrittlement risk	Yes	Yes	No	No	Yes
Process time	Slow	Moderate	Slow/multi-steps	Slow/multi-steps	Fast/single step
Deposit rate (μm/hr) [1]	≈ 15	15-20 [2]	Varies	varies	≈ 35
Deposit Efficiency %	20-30	≈ 90	≈ 70	≈ 70	≈ 95
Thickness (μm)	< 500	< 500	< 2500	< 1250	< 250
Uniform coverage	Poor	Good	Good	Excellent	Good
Flexibility	Limited	Limited	Broad	Broad	Broad
On-Site Capability	Yes	Yes	Yes	Yes	No
Internal surfaces	Yes*	Yes	No	No	Yes
Heat Input	Low	Low	High	High	Low
Health and Env. Hazards	High	Low	Moderate	Moderate	Low
Cost ($/mil/sq.ft)	1-2	2-3	Varies	Varies	4-5

*Only with the presence of an internal anode

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[1] Theoretical deposit rate calculations are shown in Appendix B. The calculated values are slightly different from experimental values.

[2] SurTec; Electroless Nickel Data sheet: mail@SurTec.com

Chapter 4: Technical Evaluation and Testing

4.1 Overview

Commercialization is a crucial stage for any new technology or product. Some technologies are at the beginning stage of entering the market and others are looking to expand into new areas and target new potential customers. In both cases, industrial technologies and products for critical applications are adequately tested before being used or widely commercialized. Similarly, in the oil and gas industry, new technologies, before being implemented, are commonly subjected to field trials or tests that can closely simulate actual field conditions. In addition, most new technologies and products are expected to meet minimum international qualification and technical standards. Examples of international standards for materials related products and technologies are ASTM [3] and NACE [4]. In addition to complying with those standards, major oil companies have developed their in-house standards which suppliers are required to follow.

4.2 Methodology

In order to confirm the present coating technology's suitability for the intended oil and gas applications and provide assurances to future clients, a comprehensive technical evaluation plan was developed. This starts with identifying the key coating properties essential for oil and gas applications, as highlighted in section 4.3. The technical evaluation process consists of two parts. First, the key properties are to be evaluated through tests conducted by the technology owner. At this point, several of these tests were already conducted and the rest are recommended to be done at the earliest opportunity. Second, a partnership with an end user is recommended to

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[3] American Society for Testing and Materials
[4] The National Association of Corrosion Engineers

jointly test the coating performance. One way to do this is by obtaining samples from an oil and gas operator and coating them according to the customer requirements. The coated samples are sent back to the customer for testing and evaluation. The goal of the second part of the evaluation is twofold: first, obtaining samples from a customer gives a better understanding of the actual substrate materials that will be used with our coating. Second, the opportunity to have the coating tested at a customer's facility, with specialized tests that can better simulate actual operating conditions, validates in-house tests and increases customer confidence in the product. Finally, results from both evaluation parts should be combined and analyzed to provide a final assessment.

4.3 Tests and Results

Performance tests are usually conducted according to international testing standards such as ASTM, NACE and others. Most of these standards provide detailed testing procedure and acceptance criteria that users strictly follow. On the other hand, other specialized tests provide only general guidelines; therefore users can tailor them to simulate an expected service environment. For example, ASTM G73 (Standard Practice for Liquid Impingement Erosion Testing) can be specialized with various test media such as seawater, sweet and sour hydrocarbons. For the oil and gas industry, key coating performance properties and their international testing standards are highlighted below.

- Bending (ASTM D790)

- Fatigue (ASTM E739)

- Tensile (ASTM E8)

- Residual stress (ASTM B849/B850)

- Hydrogen Embrittlement (ASTM F519)

- Hardness (ASTM B578)

- Adhesion (ASTM B571)

- Porosity (ASTM B765)

- Corrosion (ASTM B117)

- Erosion (ASTM G73)

- Wear (ASTM G99)

- Thickness (ASTM B689)

Several of the above tests were conducted by Xtalic Corporation covering the following properties: corrosion resistance, wear resistance, and coating thickness and distribution. The rest are recommended to be done at the earliest opportunity.

Corrosion Resistance

The corrosion resistance testing was conducted according to ASTM B117 [5]. Nanocrystalline Ni-W coating showed superior resistance to corrosion exceeding that of hard chrome and electroless nickel. The coating exhibited no red spots (start of corrosion) after 1000 hours of exposure. On the other hand, hard chrome exhibited red spots after 2 hours of exposure. Also, the intensity of corrosion on the Ni-W samples was significantly less than hard chrome samples [61].

Wear Resistance

Standard pin-on-disk (POD) test, according to ASTM G99-05 [6], was used to test for wear resistance. Ni-W coating showed wear resistance significantly superior to hard chrome and

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[5] Standard Practice for Operating Salt Spray (Fog) Apparatus
[6] Standard Test Method for Wear Testing with a Pin-on-Disk Apparatus

electroless nickel coatings, as illustrated in Figure 16. There is significant difference in wear resistance between Ni-W coating and electroless nickel [62].
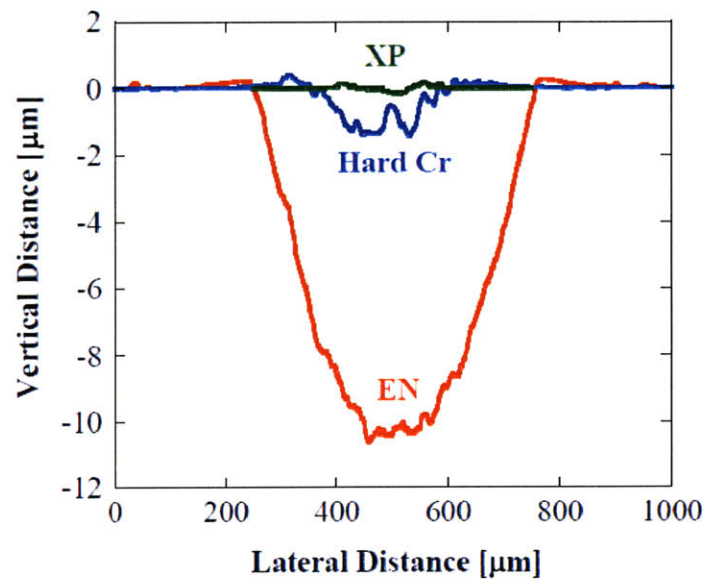
Figure 16: POD test result for XP(Ni-W), hard chrome (HD) and Electroless Nickel (EN), [62].

Coating Distribution

Coating distribution is an important property that affects coatings' quality and their applicability. If the coating is not uniformly distributed, thicker coating must be applied on low current density sections to meet the specified minimum thickness requirement. Post machining/grinding of thicker sections will be required after coating. Post-machining is not always possible, especially with complex geometry parts such as gears. Thickness measurements of coated samples showed that the Ni-W coating has more than two times better distribution than a chrome coating. For example on a coated gear, Ni-W showed a 4:1 peak to valley thickness ratio compared to 10:1 for hard chrome [63].

Chapter 5: Intellectual Property Review [7]

The purpose of presenting the following patent review is to demonstrate that none of the existing patents interfere with the present technology; therefore, there is no obligation to previous inventors for any royalty. Furthermore, MIT and Xtalic co-own an exclusive right to the special electrodeposition process and bath chemistry used to produce nanocrystalline Ni-W coatings.

5.1 Existing Patents

- **US Patent 5389226**

The "Electrodeposition of nickel-tungsten amorphous and microcrystalline coatings" patent was issued in 1995 to Scruggs, et. al. The coating process, covered in this patent, utilizes specific bath chemistry and applies a direct current to produce the coating. The deposits consist of Ni, W and B. The bath chemistry, coating composition, and other process parameters are different from the present technology.

- **US Patent 5433797**

The "Nanocrystalline metals" patent was issued in 1995 to Erb, et al. The patent covers a special process for producing nanocrystalline materials using a specific pulsed direct current technique. This process can be used to produce hard coatings and it covers a wide variety of metallic materials including Ni-W. The bath chemistry and the process are significantly different from the present technology.

- **US Patent 6080504**

The "Electrodeposition of catalytic metals using pulsed electric fields" patent was issued in 2000 to Taylor, et al. It is a special electrodeposition process to produce catalytic metals for fuel cell electrodes using both pulsed and reversed pulse current.

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[7] All information in this chapter was obtained from "The United States Patent and Trademark Office" website at http://www.uspto.gov.

- **US Patent 6773817**

The "Antiabrasion coating" patent was issued in 2004 to Sagel, et al. It protects against using wear-resistant layers applied for surface protection using various coating processes. The layer can be made from a Ni-W based alloy or many other alloy systems.

The above patents were evaluated before filing patents for the current technology. They also helped in defining the scope of the current patents. There are many other patents that exist in this field. However, those were the most relevant to the present technology.

5.2 Present Technology Patents

- **US Patent 7425255**

The "Method for producing alloy deposits and controlling the nanostructure thereof using negative current pulsing electro-deposition" patent was issued in 2008 to Detor, et al. It protects against the use of a special electrodeposition process, namely, revere pulse electrodeposition to produce nanocrystalline coatings. The patented process precisely controls the amount of alloy addition to many nanocrystalline alloy systems, thus controlling structure grain size and resulting properties. Details of this technology were mentioned in chapter 2.

- **US Patent 7521128**

The "Methods for the implementation of nanocrystalline and amorphous metals and alloys as coatings" patent was issued in 2009 to Schuh, et. al. This patent is mainly based on the previous patent. In addition, it scales up the process to be widely used as an industrial coating process for large production volume. It also uses the same process to produce composite coating structures that have different grain size, composition and properties of each layer.

The above two patents were granted for the current technology. This confirms that the present technology is novel with respect to prior existing patents. There is no obvious concern of infringement during commercialization of this technology. Furthermore, these two patents protect against unauthorized use of anything defined in their claims. They also play a major role in the commercialization process and in designing the business model for the current technology, as described in the next chapter.

Chapter 6: Business Model

6.1 Overview

Several business model options have been evaluated. In all of them, there are two main business channels, both delivering the product to the end user. One channel covers the repair and general maintenance requirement works, and the other supplies coating to original equipment manufacturers (OEMs). Before discussing these business model options, the value-chain members of the supply chain are highlighted, as in Figure 17.

Figure 17: Value-chain members.

The Ni-W coating process can be implemented in any typical industrial electroplating facility with slight modifications to the production hardware. The main difference is the type of power supply. The process requires a periodic pulse reverse (PPR) rectifier rather than a direct current (DC) rectifier used in a typical electroplating process. Integrating this process into an existing electroplating facility should not be of major concern because the majority of the modification cost is only due the new pulse rectifier.

6.2 Business Model Options

Option 1

Major oil and gas operators have in-house coating shops where they perform most of the repair activities in-house. Depending on the size of the corporation, these shops range from basic to very sophisticated ones capable of applying advanced coating processes. This model considers introducing the present technology directly to the end users by supplying them with chemicals and process, as illustrated in Figure 18. The second business channel, which is through OEMs, is the same in all business model options. Some OEMs have in-house coating shops and others have long-term contracts with coating service providers (CSPs). In both cases, the model considers supply of chemicals and process directly to OEMs. This model has some advantages: it shortens the supply chain, therefore maximizing the profit margin extracted by each value-chain member; it provides more information about client needs and direct feedback about the product.

During recent years, many oil and gas operators have adopted outsourcing strategies, where they keep the core business and outsource other business units, especially service support units. Therefore, with this new trend, it is difficult to convince end users to add a new product to their support service line. Because of this, this business model option was ruled out.

Option 2

Another business model option that was considered is to build a full-scale electroplating facility capable of providing coating service to end users, as illustrated in Figure 19. In addition to the advantages highlighted in Option 1, this model ensures the quality of service and product. However, for many reasons, this business model is not a viable option. Oil and gas producers are scattered all over the world. Providing the service efficiently requires being within proximity to

end users. Time of the service and transportation cost of coated parts are the main obstacles to providing the service from a central location. On the other hand, huge capital cost and high risk are associated with building many facilities in different countries to be within proximity to end users.
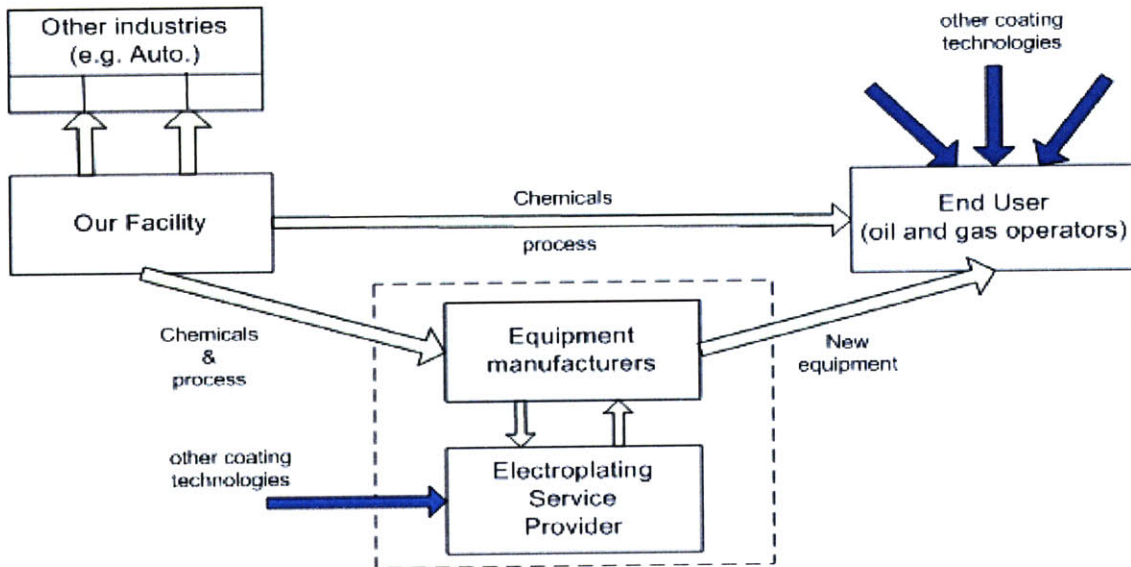

Figure 18: Business model-option 1.
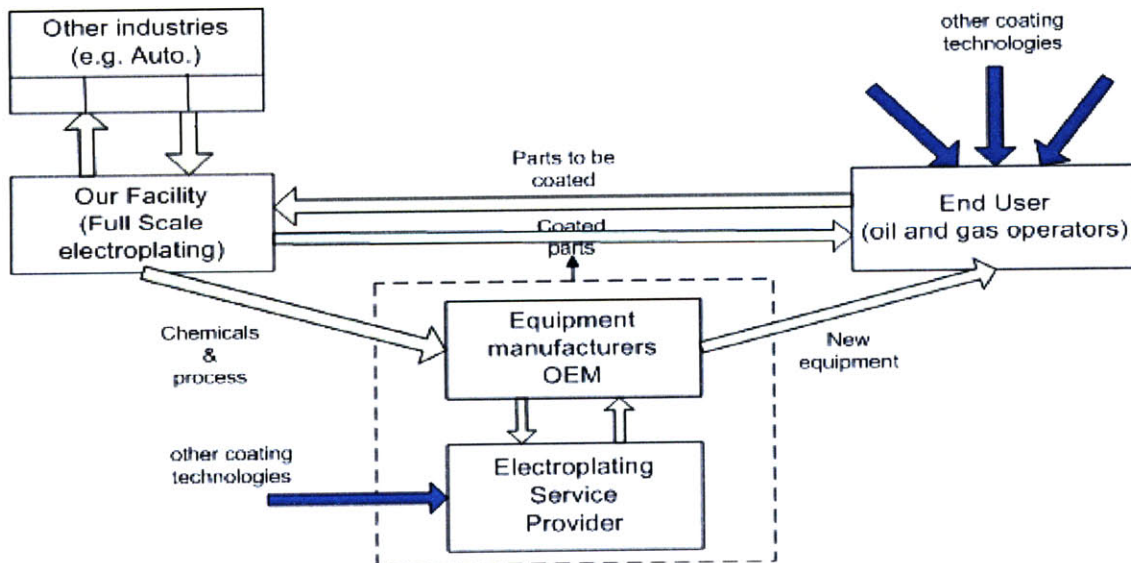
Figure 19: Business model-option 2.

6.3 Proposed Business Model

The proposed business model, highlighted in Figure 20, delivers the technology to intended end users through two channels as well. First, the coating technology will be provided through CSPs within proximity to end users. The chemicals and the coating process will be supplied to CSPs around the world through partnership agreements. CSPs will provide coating services for damaged and defective parts. The second channel is through OEMs supplying equipment such as pumps, motors, compressors and valves to end users. This strategy requires building and operating a small electroplating and testing facility. The purpose of this facility is to:

1. Produce chemical solutions specifically designed for our electroplating technology. The bath solutions are the main commercial products.

2. Coat samples, per client request, for trial purposes. The samples will be subject to size limitations.

3. Use the facility for continuous product and process development.

4. Provide technical support to clients.

Advantages of Proposed Business Model

- Small to medium capital cost required. Therefore, project financing should not be of major concern, especially under bad macroeconomic conditions.

- Most clients are overseas and scattered around the world. This model is able to serve many customers from one location.

- Ability to focus on research and enhancement of current technology will extend product life. Also, it will help to develop new products for future applications.

- Lower risk and easier exit option.

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- Minimize complications from dealing with many customers for every single job. Instead, the company deals with CSPs and OEMs on major technical support issues which minimizes time and cost of support.
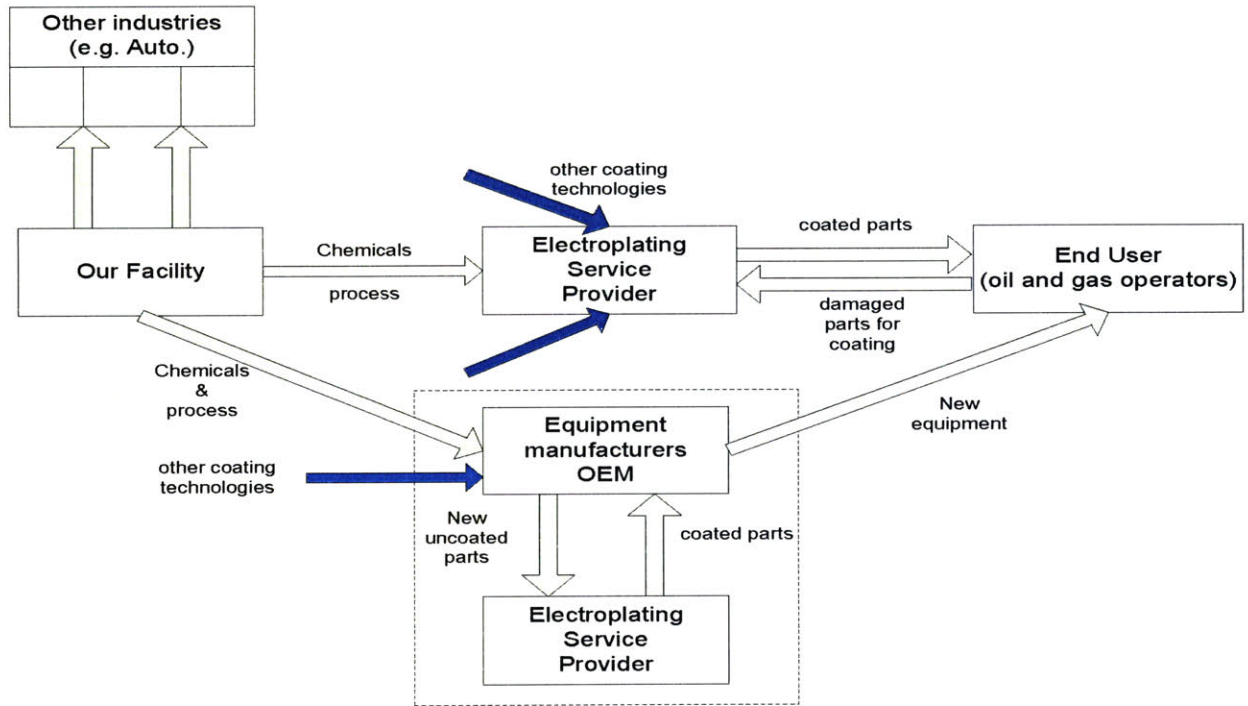
Figure 20: Proposed Business Model.

In the first stage of introducing this coating technology, it is recommended that advertisement and commercialization efforts focus on penetrating the industry as a repair method for surface damaged or defective parts through CSPs business channels. In the second stage, this coating can be used in newly purchased parts, which are usually coated by their manufacturers. If oil and gas operators approve the coating, they will likely influence equipment manufacturers. Very often, the company's own standards are submitted with a purchase request for which

manufacturers need to comply. The ultimate goal is to have the coating technique incorporated into those standards, and therefore, applied to new parts. Of course, modification of standards requires more comprehensive testing and actual field trials; hence, a comprehensive testing plan is recommended as highlighted earlier. It is expected that one business channel (CSPs) can facilitate and eventually help the other business channel (OEMs).

Risks of Proposed Model

Though the technology requires use of special chemicals and the know-how to produce those chemicals is proprietary, there is a potential risk for customers to replicate the chemicals. The proposed business model adopts dual strategies with OEMs and CSPs, which are explained in the next section. The price of chemicals sold to OEMs will be lower than that for CSPs. There is a risk of OEMs reselling chemicals to coating service providers and taking advantage of the price difference.

Secondly, fluctuation in the price of raw materials and energy propose great risk to any business model. For example, the price of nickel has fluctuated between $9/kg to $50/kg in the past three years [64]. It is often difficult to pass on such fluctuation to customers. On the consumer side, oil and natural gas prices face even more drastic price fluctuations. In 2008, there was an unprecedented peak in the price of oil when it reached close to $150/barrel compared to the current price of about $60/barrel. In contrast, in the 1990's, there were years when oil prices sunk to $10/barrel. During such years, the profit margins of oil and gas operators were greatly reduced, and most of them struggled to survive and had to implement extreme cost minimization strategies.

6.4 Implementation Plan

The common practice among coating companies is to supply the coatings, as a complete technology, to service providers or end users who have the capability of applying them. This package includes chemicals, software, training and technical support.

Commercialization of the current technology started in 2005 in a few areas such as decorative coatings, functional coatings and electronics applications. Applying this technology to oil and gas industry applications is a major expansion of the functional coatings area. A recommended target is for 30-50 % of total sales to be generated from the new business line and the rest to be generated cumulatively from other industries. More on the quantitative analysis will be explained in chapter 7. Included in the implementation plan are two mechanisms for penetrating the market, which are explained in the next section.

IP Model with OEMs

It is proposed that an IP model may be applied with OEMs. Most OEMs operate in developed countries where IP laws are enforced and OEMs are well informed about intellectual property laws and regulations. Therefore, it is effective to apply an IP model as a mechanism for revenue generation. Though the chemicals are still centrally manufactured, the price at which they are sold to OEMs is slightly marked up to cover only production variable costs. In addition, OEMs are charged an annual license fee.

Chemicals Supply Model with CSPs

Coating service providers are scattered around the world, ranging from small to large companies. Some are well informed about IP regulations and others are not, and even those who are informed often operate in countries where IP laws are not enforced. Also, applying the IP model to CSPs might discourage small and medium-size companies from using the technology.

Therefore, it is not effective to apply a similar mechanism, as with OEMs. In this case, revenue will be based solely on the amount of chemicals sold, with the amount of chemicals purchased representing the coating activity volume. The cost of chemicals, technology, technical support and other operating costs are built into the price of the chemicals.

With both implementation plans, software that controls the coating process will be supplied to clients. In addition to containing process information, the software records the amount of chemicals consumed. Clients are required to submit this report annually. The amount of chemicals consumed should be similar to the amount of chemicals purchased; otherwise, the client has violated the contract agreement. For example, if the amount of chemicals consumed is more than those purchased, the client has used other chemicals with the licensed process. In the opposite case, if the amount of chemicals consumed plus inventory is less than purchased, it is the case that the client is reselling the chemicals. Both cases are considered violations of the contract agreement and disqualify the client from using the technology.

Chapter 7: Cost Model and Economic Analysis

Based on the proposed business model, a detailed cost model was designed to estimate the cost of production and forecast future possible revenues. The model estimates the cost of building and operating a small facility that performs the previously described functions. The main components of the facility are: a chemical production section, a small electroplating shop, a laboratory and offices.

7.1 Cost structure

- Electroplating equipment

  The major equipment necessary to run an electroplating operation is listed in Appendix A. Depending on the size of operations, many tanks for pretreatment, cleaning, plating and final rinsing are needed. Also, a periodic pulse reverse (PPR) rectifier specific for this operation is necessary. The cost of PPR is about five times the cost of a traditional DC power supply [65].

- Laboratory equipment

  It is important to equip the facility with advanced laboratory testing equipment and instruments. Analyzing and testing coated samples are important for quality assurance and control.

- Design and installation cost

  Building a full scale electroplating facility requires a detailed engineering design of equipment, operation and floor plan. For example, each tank in the system and its auxiliary components need to be designed according to the chemical process governing its operation.

- Plating solutions production

  The main commercial product of the facility is not application of coatings but selling plating solutions necessary for the process. The main cost elements include raw materials to synthesis plating solutions, mixing process, packing and transportation.

- Labor cost

  Continuous research and development to enhance the process and possibly expand to other alloy systems and processes is essential to insure sustainability in a strongly competitive environment. This requires recruiting researchers and scientists, along with facility operators. Labor cost is a substantial part of the operating cost.

- Operator training

  Training operators to become familiar with the present specific electroplating process requires time and money. Also training them to use various testing equipment is needed.

- Building and office supplies

  The cost model calculations were based on leasing an industrial building, which should consist of a shop and office spaces. A long term lease, five years or more, is recommended since moving the facility to another location is costly.

- Overhead cost

  Overhead expenses include advertising, insurance, legal fees, maintenance, taxes, telephone bills, travel and other similar indirect costs.

- Environmental regulations compliance cost

  Before starting an electroplating operation, acquiring necessary licenses and permits from the EPA and other government agencies is mandatory. Electroplating facilities

are required to install sufficient treatment systems for discharge water, air and other disposable materials in order to ensure compliance with environmental regulations. The present electroplating process is fairly clean, not involving toxic disposal materials that require intensive treatment. Therefore, unlike the required treatment systems in a chrome plating operation, the cost of installing a treatment system is not significant.

7.2 Cost Analysis

Details of the cost model are included in Appendix A. Table 3 shows a summary of the production variable cost in $/L, $/\mu m/m^2$ and $/mil/ft^2$. [8] The variable cost per unit is constant and independent of production volume. Figure 21 shows the variable cost, fixed cost and total cost per liter at various production volume levels.

Table 3: Product variable cost.

Variable Cost ($)	Per L	per μm/m2	per mil/ft2
Materials cost	1.02	0.269	0.634
Processing cost	0.20	0.054	0.127
Packing and labeling	0.20	0.053	0.125
Total Variable Cost ($)	1.42	0.38	0.89

It is not easy to visualize coating production volume in units of volume (liter). Therefore production volume was converted into more familiar coating units, μm-m^2 and mil-ft^2. The production volume was represented in units of coating area (m^2 and ft^2) and its cost is shown at various thicknesses. Figures 22 and 23 show the cost per μm-m^2 and mil-ft^2 respectively for various production volume levels and average coating thicknesses.

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[8] Coating mixing specifications were obtained from Xtalic Corporation and were used to estimate the chemicals production cost.
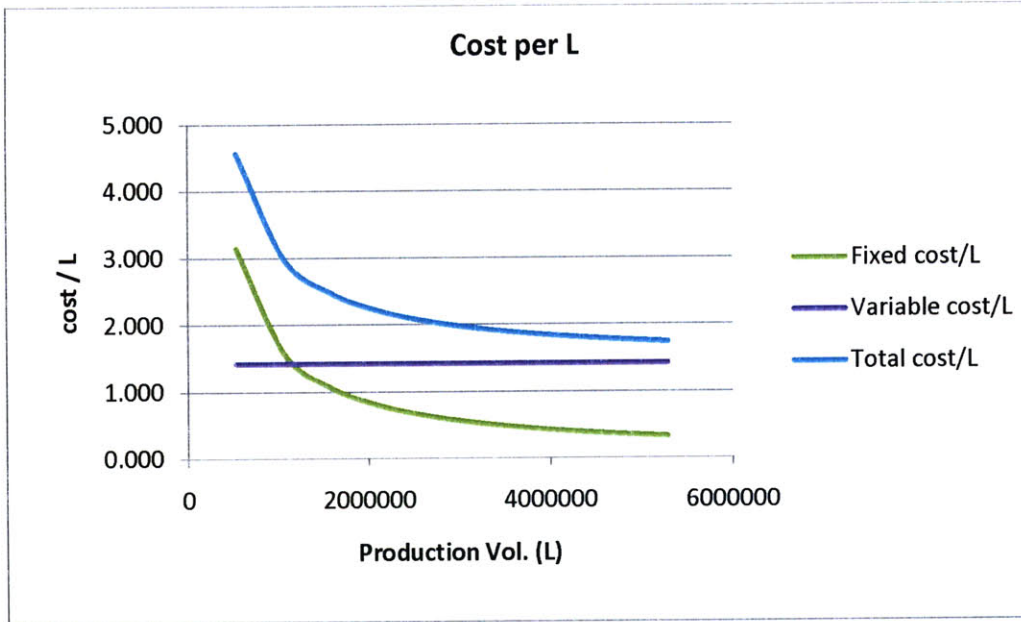
Figure 21: Cost per liter of production at various production volume levels.

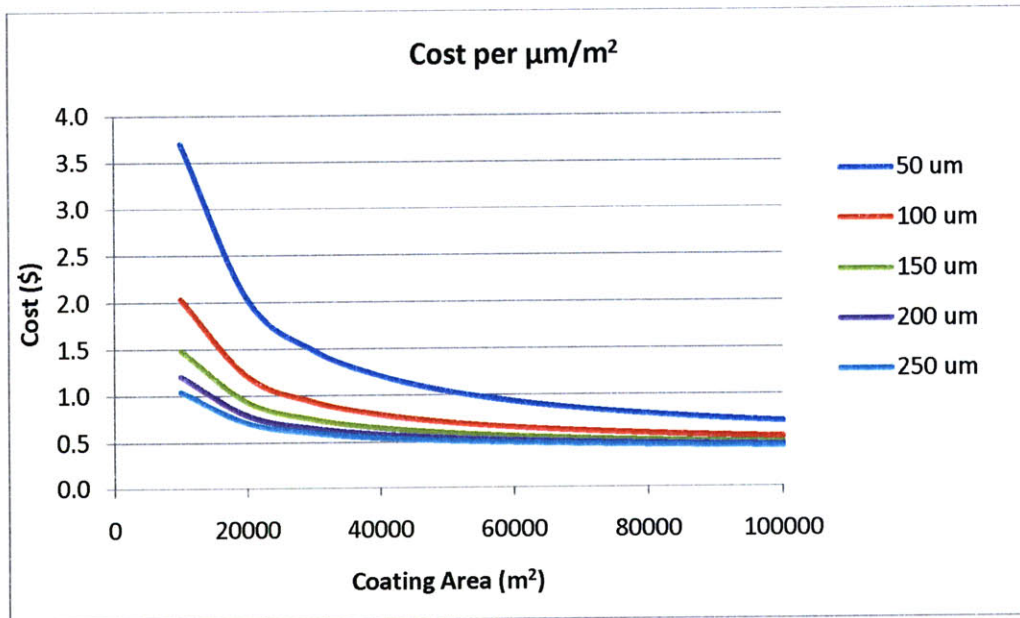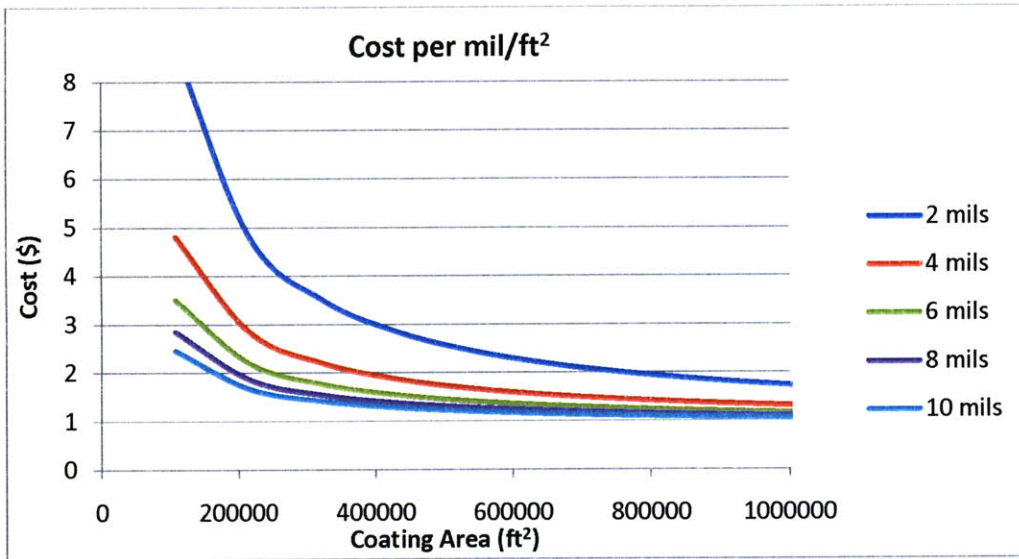**Figure 22: Cost of production per μm/m² at various production volume levels.**

Figure 23: Cost of production per mil/ft² at various production volume levels.

At medium to large production volume levels, the cost can be as low as $ 1 per mil/ft² or $0.5 per μm/m². To illustrate the calculation of unit cost, the following example for a simple part is presented.
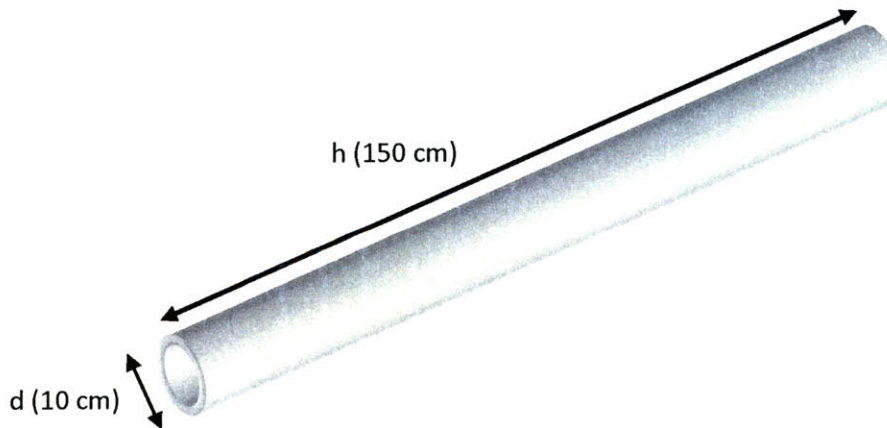
Figure 24: Pump shaft drawing.

Example:

A stainless steel pump shaft, shown in Figure 24, is required to be electroplated to a thickness of 200 μm.

To calculate the price of coating this pump shaft, the following values are required:

Surface area: $A = 2 \times \pi \times r \times h + 2 \times \pi \times r^2 = 4867$ cm^2

Coating volume = surface area X coating thickness = 97.34 cm^3

Coating cost (price) = $/μm/sq meter X surface area X coating thickness

At a production volume of 40,000 m^2 the rate is $ 0.5/μm/m^2, the cost is $ 48 [9]. This figure covers the cost of materials and technology; it is not the cost of the final coated part. The deposition rate is approximately 35 μm/hour; therefore, the time required to plate the above sample, after cleaning and pretreatment, is about six hours. Table 4 summarizes the results of the above example.

Table 4: cost calculation summary for the pump shaft example.

Pump Shaft (L:150 cm, d:10 cm)	
coating area (cm^2)	4867
coating thickness (um)	200
coating Volume (cm^3)	97.34
coating area (m^2) → production vol.	40000
Cost per um/m^2 at production vol.	0.5
# of parts per year	51366
Cost /part ($)	48

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[9] The Conversion factor from ($/mil/ft^2) to ($/μm/m^2) is to multiply by 0.424.

7.3 Economic Analysis

The final price per unit is determined by the cost per unit calculated from the cost model. Hence, the price is similarly dependent on the production volume level. To illustrate various revenue scenarios, a plot of total revenue along with production total cost, for prices of $1.5, 2, 2.5 and 3 per mil/ft^2, at different production volume levels, is shown in Figure 25.
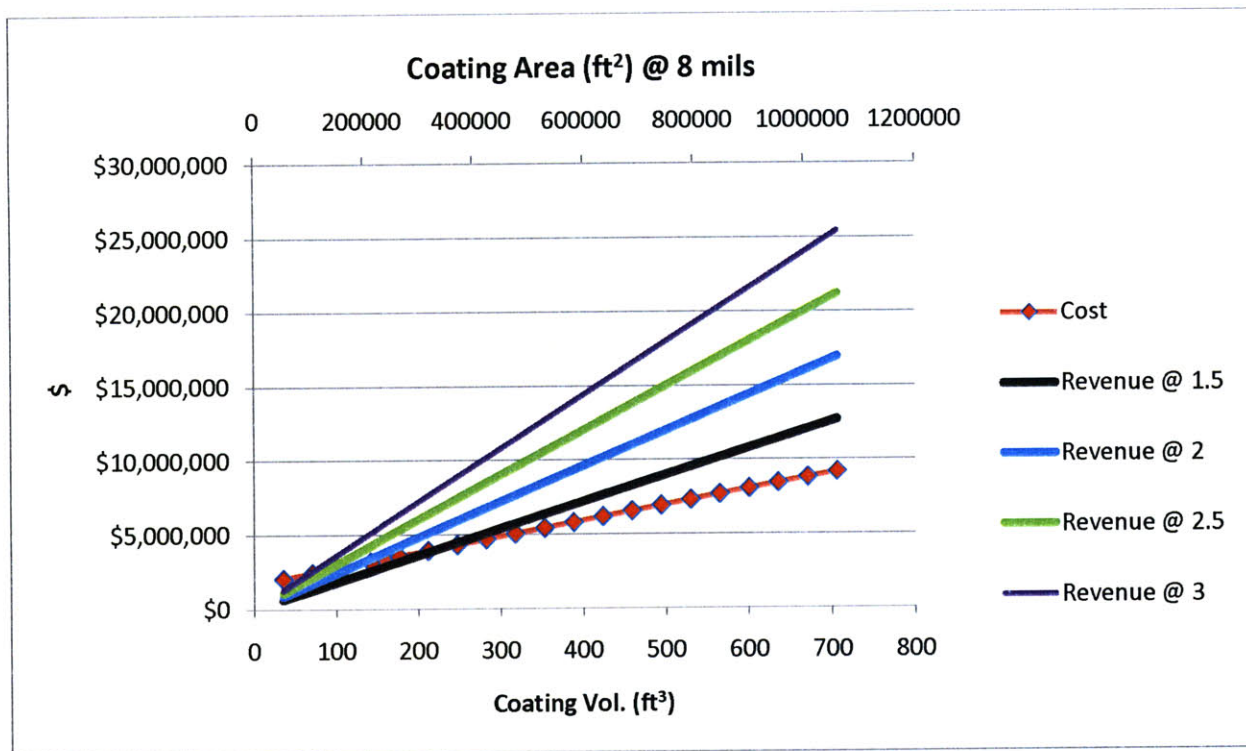
Figure 25: Cost- Revenue analysis

The above graph shows the break-even point at the intersection between the cost line and revenue lines. The associated profits (cost – revenue) of Figure 25 are plotted in Figure 26. Figure 26 shows that it is possible to make a profit even at low production volume levels, where the profit graphs intersect with the zero-horizontal line.
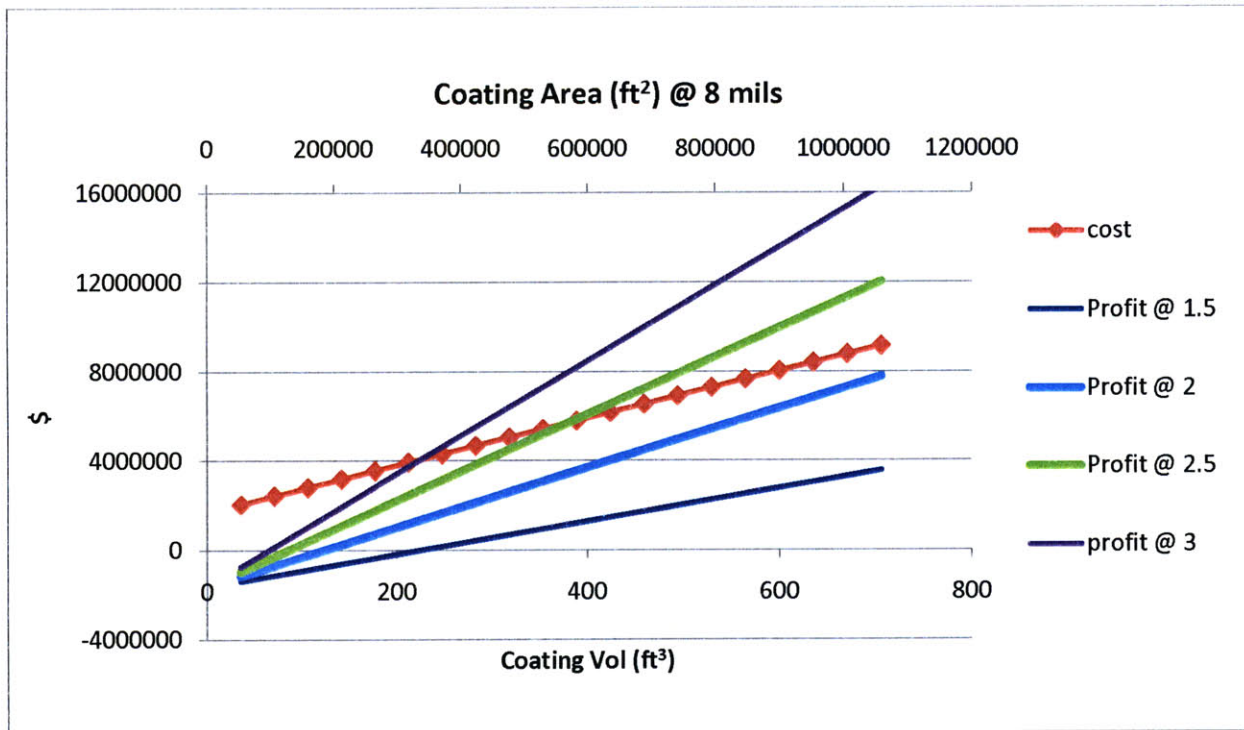
Figure 26: Profit Analysis.

In setting the price of the product, the cost of production as well as the price of competing technologies were considered. As highlighted in chapter 6, two implementation plans are recommended. The above calculations cover the cost-revenue analysis for the chemical supply model for CSPs. In this model, chemicals were priced such that - $1.5, 2, 2.5 and 3 per mil/ft^2, as illustrated in the previous calculations - covers the cost of materials, technology and other associated operating costs. On the other hand, for the IP model, it is recommended to charge a lower price in addition to an annual license fee. Based on similar coating technologies, an annual license fee is estimated at $50,000. The unit price in this case is $1 per mil/ft^2, which covers only the variable production cost.

Figure 27 shows the profit analysis for a different number of licenses at various production volume levels. It shows that profit can be made with 20 licenses at high production volume and with 30 licenses at low-medium production volume.
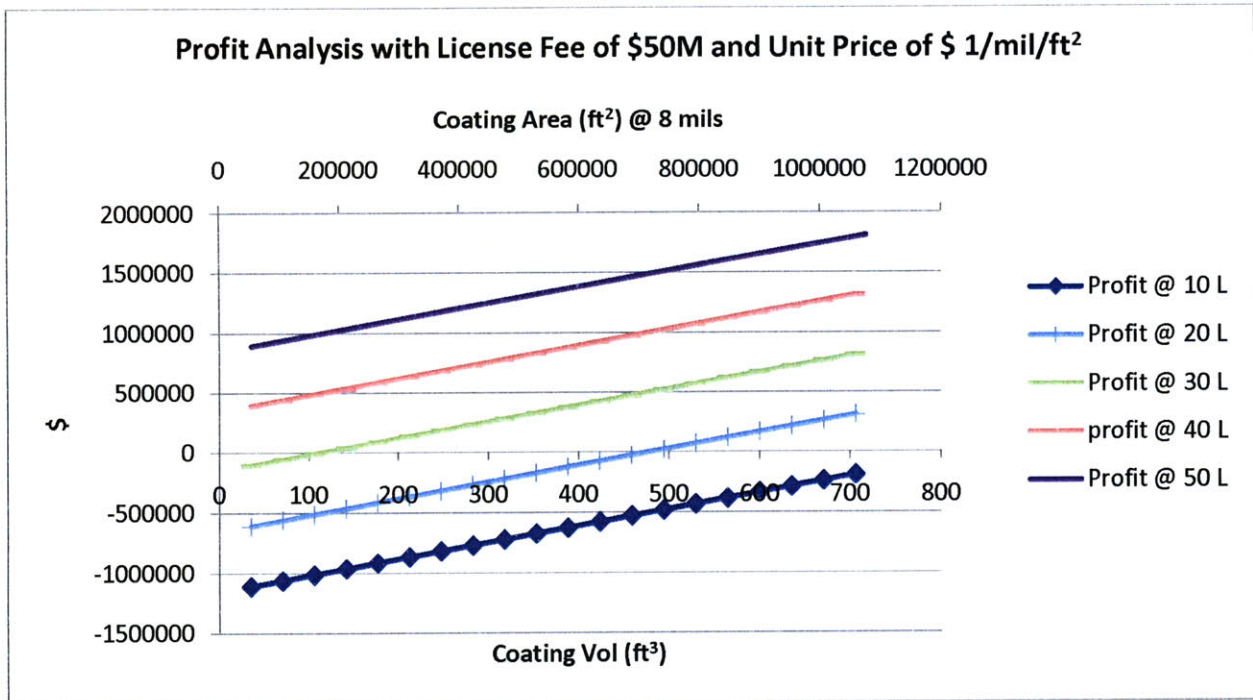
Figure 27: Profit Analysis with License fee of $50M and unit price of $1/mil/ft².

7.4 Market Size and Demand Estimation

Demand for protective coatings and market size vary in different countries. Coatings for the oil and gas industry are classified either as protective coatings or industrial coatings. Demand data were gathered for different countries to estimate the total market size for coatings in the oil and gas industry worldwide. Unfortunately, data for European countries and some other countries that have significant oil and gas operations were not available. Also, the current estimation does not include the OEM market. Figure 28 shows the data collected from different sources. Total market size is estimated to be around $ 1 billion.
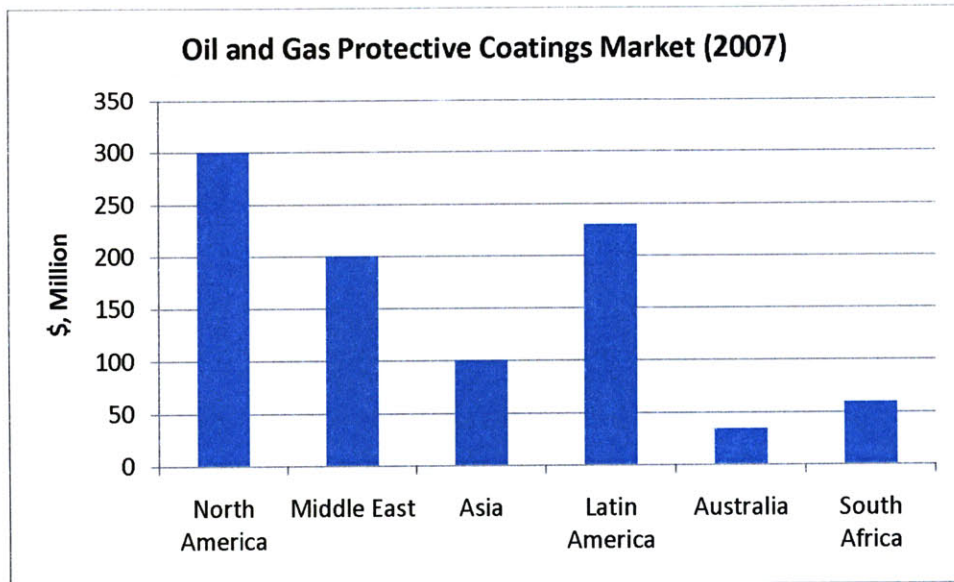
Figure 28: Oil and gas protective coatings market (2007) [10].

Based on a $1 billion market size value, demand for the current product was estimated at various market share possibilities. The total market size was also doubled to roughly account for the OEM market. The calculations are based on a unit price of $2/mil/ft^2.
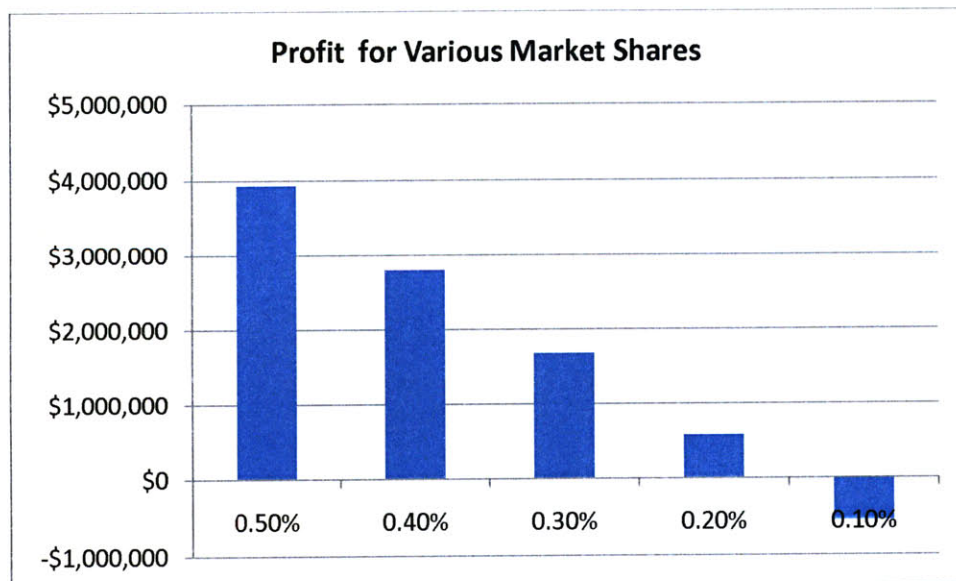
Figure 29: Profit for various market shares.

[10] Frost & Sullivan, 2007

Table 5 shows the calculation summary for 0.5 % market share[11].

Table 5: Profit summary for 0.5 % market share.

Market Size	$2,000,000,000
Market share	0.50%
Sales	$10,000,000
price/mil/ft2	2
Production volume (mil.ft^2)	5000000
Production volume (ft^3)	416.7
cost ($)	6071698
Profit ($)	$3,928,302

Figure 29 shows that a profit can be made even at as low as 0.2% market share. In the above calculations, it was assumed that all sales are generated from the oil and gas industry. However, the actual target is to generate 30-50 % of sales volume from coating sales to the oil and gas industry. That said, an even lower market share or smaller market size, than shown above, is plausible for the operation to still make a profit.

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[11] Profit Analysis for various market shares at a unit price of 2/mil/ft2 is included in Appendix A

Chapter 8: Conclusion and Recommendations

It is anticipated that the present Ni-W coating technology will have significant impact on the oil and gas coating industry. The coating produced using the present materials and process is superior in quality and properties to most metal coatings. The coatings are highly resistant to corrosion, wear and high temperature, and are delivered through an efficient coating process to satisfy customer needs. In addition, it is possible to supply the coating at a competitive price. Many applications, such as rotating equipment parts and drilling equipment, were identified to have high potential for future use of the coating. In addition, we highlighted a comprehensive technical evaluation plan to insure the coating suitability for the intended market applications and provide assurance to clients.

Also, a thorough analysis of cost and market aspects was presented, a comprehensive financial analysis was carried out, and various economic outcome scenarios were presented. This analysis predicted that introducing this coating technology to the oil and gas markets significantly increases sales and eventually leads to profit. The analysis also showed that cost minimization can be realized through high production volume, i.e. economy of scale. The price of materials and technology can be between $1.5 and $3 per mil/sq ft depending on the final cost of production and the price of current competing technologies. The market value for the final product was estimated to lie between $4 and $5 per mil/sq ft.

It is recommended to apply the proposed business model in the first iteration, e.g. first year of operations. It is possible to converge to a traditional IP model later if sales volume falls significantly below expectations. With this IP model, the technology is licensed to customers for an annual fee or a percentage of sales. Also, under the IP model, chemical production is licensed to chemical companies to supply CSPs and OEMs.

There are always areas of improvement to consider in the future. The coating industry is very mature and competitive; therefore, in order to insure product sustainability in such a highly competitive environment, several recommendations are highlighted. First, it is strongly recommended to further develop this coating technology by including the brush plating technique in conjunction with tank plating. With the current process, coating larger parts or coating in the field is difficult. In the oil and gas industry, most equipment parts are large and others cannot be dismantled and transferred to a coating shop. Brush plating is a portable process and is not limited by the size of the coated part. As a result, machine downtime and consequent loss of production can be significantly minimized. Brush plating has also an advantage in coating a section of a part without a need for a large amount of masking. It also minimizes the risk of hydrogen embrittlement [66]. However in most cases, brush plating cannot replace conventional tank plating but rather complements it in certain applications.

The oil and gas industry is characterized by a variety of operating environments with different degrees of severity. There might be cases where Ni-W alloys are not suitable for some environments. Therefore, it is recommended to expand this coating technology to other alloy systems in order to be able to serve a wider area of applications.

Electroplating and its risk of causing hydrogen embrittlement in sour service environments is a major concern in the oil and gas industry. For example, Saudi Aramco has banned the use of electroplated materials in sour applications. In most cases, post treatment is required to diffuse the atomic hydrogen from the material and decrease its susceptibility to hydrogen damage. ASTM F 519 is used as a qualification test for new plating processes against hydrogen embrittlement. The result of this test or similar is recommended to be supplied to end users.

Appendix A: Cost Model

The cost model consists of fixed and variable costs.

A. Fixed costs

1. Initial capital cost

Electroplating Equipment	Q	$ cost	Total cost
Tanks (including plating tanks)	10	1000	10000
Anodes	10	100	1000
Rectifier (PPR)	2	30000	60000
Heating/cooling elements	4	1000	4000
Temp. indicator/controller	8	100	800
Filters	10	50	500
Pumps	4	500	2000
Design and installation	1	20000	20000
Total cost ($)			**98,300**

Laboratory Equipment	total
SEM with EDS	100000
Hardness tester	4000
Microhardness tester	6000
Polishing machine	20000
Optical Microscope	5000
cutting machine	4000
Other lab tools	20000
Total cost ($)	**159,000**

Chemicals Production equipment	Q	cost	total
Mixing tanks	10	500	5000
Facility construction cost	1	50000	50000
Analyzing equipment	-	10000	10000
Other production tools	-	20000	20000
Total cost ($)			**85000**

Waste treatment system	30000

Building cost (others)	total
Furniture	30000
Office supplies	20000
Total cost	50000

2. Annual fixed costs

Labor cost	No.	Avg. Annual salary	total
Management and marketing team	5	80000	400000
Technical staff	8	80000	640000
Operators	8	50000	400000
Training and turnover costs	1	10000	10000
Annual labor cost			1450000

Fixed Overhead Cost	79026

Fixed overhead cost = 5% x (Amortized Capital Cost ($/year) + Annual fixed cost)

Building cost	per year
Building (annual rent)	60000
Energy Cost	15000
Total Annual cost	75000

Fixed cost summary table

Capital cost ($)	422300
Amortized Capital Cost ($/year)	55521.38
Annual fixed cost ($)	1604026
Total annual fixed cost ($/yr)	1659547
Estimated life time (Amortization period in years)	15
Annual Interest Rate (Discount Rate) or opportunity cost of capital	10%

B. Variable costs

Variable Cost ($)	Per L	per um/m2	per mil/ft2
Materials Cost	1.02	0.269	0.634
Processing cost	0.20	0.054	0.127
Packing and labeling	0.20	0.053	0.125
Total Variable Cost ($)	1.42	0.38	0.89

The calculations of the variable costs were based on the following:

1. Materials Cost

Materials Cost	$/kg	Mat. cost/L	processing cost /L	total cost/L
Nickel	11	0.36	0.07	0.43
Tungsten	35	7.79	1.56	9.35
processing & other materials (%)	20%	-	-	-

100 L plating solution	Vol (L)	mass (kg)/100 L	Kg/L conct.
Distilled water	58.61	-	-
Nickel conct.	20	0.65	0.0325
Tung. Conct.	14.6	3.25	0.2226
Ammonium Hydroxide 28-30 %	6.5		
Wetter	0.25		
Brightener	0.04		
Total	100		

1. Processing cost

Processing cost = 20 % X materials cost

2. Packing and labeling

Packing and labeling cost = $4/20 L * production volume (L)

*20 L per container

One liter of production volume has the following coating characteristics

Production Volume (L)	1.00
Ni Concentrate (L)	0.91
W Concentrate (L)	0.09
Coating Produced	
coating area (cm2)	380.00
coating thickness (um)	100.00
coating volume (cm3)	3.80
coating area (ft2)	0.41
coating thickness (mil)	3.94
coating mass(kg)	0.05
Ni consumed (kg)	0.03
W consumed (kg)	0.02

The following table present profit analysis for various market shares at a unit price of 2/mil/ft2

Market Size	$2,000,000,000	$2,000,000,000	$2,000,000,000	$2,000,000,000	$2,000,000,000
Market share	0.50%	0.40%	0.30%	0.20%	0.10%
Target % of Sales	30%	30%	30%	30%	30%
Sales	$10,000,000	$8,000,000	$6,000,000	$4,000,000	$2,000,000
price/mil/ft2	2	2	2	2	2
Production volume (mil.ft2)	5000000	4000000	3000000	2000000	1000000
Production volume (ft3)	416.7	333.3	250.0	166.7	83.3
cost ($)	6071698	5205026	4323346	3422907	2541227
Profit ($)	3,928,302	2,794,974	1,676,654	577,093	-541,227

Appendix B: Deposit rate calculation

A Theoretical method that uses Faraday's law to calculate metal deposition rate is outlined below [67]. The deposition parameters are

	Ni-W	Nickel Plating	Chrome Plating
Current density (A/ cm$^{2)}$	0.1	0.02-0.1 **	0.06
Current efficiency (%)	95	95	20
Density * (g/ cm^3)	13.04	8.9	7.19
Valence electrons, z	8	3	6
faraday's constant, F (A s/mol)	96485	96485	96485
Molecular weight, M (g/mol)	109	58.7	52
Deposition rate (um/hr)	37	15-77 **	5.4

*(Ni-W) with 60 % Ni and 40 % W
** Depends on the type of electroplating solution

The following example illustrates the calculation for Ni-W coating process.

Deposited number of moles per surface and time:

$$\frac{dn}{Adt} = \frac{\gamma}{zF} \times \frac{dQ}{Adt} = \frac{\gamma}{zF} \times j = \frac{0.95 \times 0.1\,A}{8 \times 96485\,A \cdot s/mol} = 1.23 \times 10^{-7}\,\frac{mol}{cm^2\,s}$$

Deposited mass per surface and time:

$$\frac{dm}{Adt} = M \times \frac{dn}{Adt} = \frac{109\,g \times 1.23 \times 10^{-7}\,mol}{mol \quad cm^2\,s} = 1.34 \times 10^{-5}\,\frac{g}{cm^2\,s}$$

Deposited layer thickness per time:

$$\frac{dx}{dt} = r = \frac{\frac{dm}{Adt}}{\rho} = \frac{1.34 \times 10^{-5}\,\frac{g}{cm^2\,s}}{13.04\,\frac{g}{cm^3}} = 1.02 \times 10^{-6}\,cm/_s = 37\,um/_{hr}$$

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