AN ECONOMIC AND ENGINEERING ASSESSMENT OF PLASMA-SPRAYED CERAMIC COATINGS

by

OLIVIER DE BOTTON

Ingenieur de l'Ecole Nationale Superieure d'Electricite et de Mecanique
Nancy, France (1987)

Submitted to the Department of
Mechanical Engineering
in Partial Fulfillment of the
Requirements of the
Degree of

MASTER OF SCIENCE IN TECHNOLOGY AND POLICY

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

January, 1988

Signature of Author _ Signature redacted
Department of Mechanical Engineering
January, 1988

Certified by Signature redacted
Professor Joel P. Clark
Thesis Supervisor

Accepted by Signature redacted
Professor Richard de Neufville
Chairman, Technology and Policy Program

Accepted by Signature redacted
Professor Ain A. Sonin
Chairman, Graduate Committee

AN ECONOMIC AND ENGINEERING ASSESSMENT OF PLASMA-SPRAYED CERAMIC COATINGS

by

OLIVIER DE BOTTON

January 1988

AN ECONOMIC AND ENGINEERING ASSESSMENT OF PLASMA-SPRAYED CERAMIC COATINGS

by

OLIVIER DE BOTTON

Submitted to the Department of Mechanical Engineering
on January 15, 1988 in partial fulfillment of the
requirements for the Degree of Master of Science in
Technology and Policy

ABSTRACT

This thesis provides an overview of the major coating technologies and their applications. Deposition processes are described and compared, with emphasis on the plasma-spray technique.

An engineering cost model has been developed to assess the economics of the plasma-spray process for almost any kind of coating applications. The coating operation as well as optional steps, such as grinding and substrate preparation, are reviewed. The analysis points out the need for improvements in process automation and control. Relationships between plasma-spray factors and coating characteristics must be established thoroughly if the technique is to emerge from art to science.

The model has been applied to evaluate the potential for Thermal Barrier Coatings. Under the optimistic assumption that Partially Stabilized Zirconia may achieve technical feasibility as a coating, the processing was analyzed from a purely economic standpoint. Even though smaller amount of raw materials are used in plasma-sprayed coatings than in any structural ceramic fabrication process, the powder remains a critical cost factor for this specific application. In fact, Thermal Barrier Coatings produce high material cost inputs because they are thick, use expensive ceramic materials produced in small quantities, and yield a low deposition efficiency. Although the analysis suggests that Thermal Barrier Coatings are presently an expensive option, they offer benefits which may outweigh their cost in future applications.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

ACKNOWLEDGEMENTS

I would like to thank all the members of the Materials Systems Laboratory for their support. I am especially grateful to Professor Joel Clark for giving me the opportunity to join the group and helping me in the progress of my work.

Along with the members of the Materials Systems Laboratory, with whom I enjoyed working so much, I would like to extend my gratitude to professors and students of the Technology and Policy Program who opened my mind to different views.

I would also like to thank the Ecole Nationale Superieure d'Electricite et de Mecanique for allowing me to come at M.I.T., and giving me the engineering background I needed.

I would like to express appreciation for the assistance of Darcy Phillips who carefully edited drafts of the manuscript.

Finally, many thanks to the 1% of the universe that is not plasma. I also acknowledge the other 99%.

This thesis is dedicated to " mon Papa et ma Maman ".

1. INTRODUCTION

A ceramic coating is generally defined as an inorganic, non-metallic compound which modifies the surface of a substrate material to enhance its engineering properties. An overview of the different deposition technologies used for coatings and commercial applications related to these technologies will be given to show their diversity.

Among coating technologies, plasma-spraying is one of the most reliable and promising. A computerized model was created on Lotus 123 to analyze the economics of the process. The cost of a ceramic coating is regarded as value-added to the primary cost of the component, and the model can help manufacturers assess whether to include a plasma-spray workshop in their facility.

In view of a 25% annual growth forecast for ceramic coatings in engines, a case study of Thermal Barrier Coatings will also be provided. Thermal Barrier Coatings users include different and important industries such as aircraft, automobile and power generation. The case study shows by economic analysis that if automobile-makers in particular support the development of ceramic coating technologies, they may become an excellent alternative to structural ceramics in engine applications.

The problem

The current trend in the coating industry is increasingly for equipment suppliers to integrate. The analysis will show that potential or existing ceramic coating users should also get involved in the fabrication process. Some of the major incentives for industry to participate in the development of ceramic coatings technology development are:

- the significant market for ceramic coatings that already exists.

- that coatings will find earlier commercial applications in engines than structural ceramics.

- that ceramic powder prices tend to fall.

- that manufacturers such as in the automobile industry may implement robotized plasma-spraying processes to lower the cost of the labor intensive process.

- that ceramic coatings research may be a step to learn about the properties of ceramic materials.

All the above statements demonstrate clearly the benefits of the implementation of plasma-sprayed ceramic coatings.

The hypothesis

* Technical performance vs. fabrication feasibility.

Ceramic coatings have a long history. Technical performance has been demonstrated through their commercialized applications.

However, experience with coatings has been gained empirically, and fabrication techniques will improve with modern technical features such as automation, expert systems, and improved quality control. The cost model is useful only if fabrication problems are solved, and the required level of coating quality is attained.

* Cost vs. Utility

Ceramic coatings must be cost-competitive with a more resistant bulk material, system redesign or more frequent component replacement.

* Application of the technique to Thermal Barrier Coatings

Thermal Barrier Coatings show three benefits:

1. Protection against hot corrosion;
2. Improvement of power by increasing the temperature of operation;
3. Reduction of fuel consumption.

Thermal Barrier coatings have been used for years on gas turbine engine combustion chambers. They are also candidates for use in exhaust systems, turbochargers, valves and piston heads. However, the technical reliability of Thermal Barrier Coatings will preclude a different engineering approach; Thermal Barrier coatings should be considered as the integration of a two-part system (substrate + coating). Consequently, parts must be designed in view of the application of a ceramic coating.

Data collection

Information was collected through personal contacts with industrial researchers in the coating business. Several visits paid to plasma-spraying equipment manufacturers and workshops also permitted a better understanding of the process. Finally, literature was a major input in the research process.

2. OVERVIEW OF COATING TECHNOLOGIES

2.1 Coating processes

This chapter will give the reader a general understanding of several coating technologies. Each way of applying a coating which introduces a new technical feature may be patented as a coating process. Consequently, although a large number of coating processes can be listed, some of them are not fundamentally distinguishable. This analysis emphasizes deposition technologies which have been commercially developed, or which show potential for high technology applications.

There are many different ways to classify these coating processes. In general, deposition technologies are distinguished by the nature of the reaction which occurs during the process, e.g., Chemical Vapor Deposition (CVD) fits into the category of chemical processes. However, classifications can easily become confused when two or more reactions take place during the process. Chemical and physical methods may overlap, especially when it comes to sputtering and plasma reactions. The classification used here offers five categories: conduction, evaporation, chemical, physical, and thermal spraying processes (See Table I). It is not intended to classify the processes legitimately but to avoid confusion.

2.1.1 Conduction processes

Conduction processes can be mainly divided in two categories: electrostatic deposition and electrolytic deposition. The first technique uses an electrostatic field to direct the material in a liquid form onto the substrate. The solvent is then evaporated to form a coating. Electrolytic deposition is primarily concerned with the deposition of ions. The technique is elementary: two electrodes immersed in an electrolyte of an ionic salt solution make positive ions to deposit onto the cathode.

TABLE 1. CERAMIC COATING PROCESSES

Process	Rate of Deposition	Characteristics	Materials	Applications
Conduction Processes	Low to high	Limited to metallic materials	Cu, Au...	Decoration
Evaporation processes including air-spraying	High	Poor line-of-sight coverage on complexly shaped objects	Silica-Alumina Zirconia	Furnaces
Chemical processes including Chemical Vapor Deposition	Moderate	Good for complexly shaped objects	SiC, TiC, Si_3N_4, Al_2O_3	Cutting Tools
Physical Vapor Deposition including sputtering	Low	Growth interface perturbation	TiB, TiN...	Metal Matrix Composite fibers
Thermal processes including plasma-spray	High	Good adhesion to substrate	WC, CrC, Partially Stabilized Zirconia	Thermal Barrier Coatings

These techniques depend upon a coating material that can be ionized or charged. The basic materials used in this process are metals, not ceramics. For this reason, applications of electrodeposition technologies will be assessed in this paragraph rather than in chapter 2.2 which will report ceramic coatings applications. Copper is used to coat wires and to provide thermally conductive coatings on cooking utensils at low cost. On the other hand, gold and palladium are expensive materials which can be used not only for decorative applications, but for various electronic parts, electrical contacts, and laboratory apparatuses.

2.1.2 Evaporation processes

In these processes, materials are applied in liquid form and then become solid by solvent evaporation. The category would include air spraying which uses a high pressure air source to break up the liquid into small droplets. The atomized droplets can then be sprayed on the substrate. The coatings are usually applied at room temperature and air dry in less than five minutes. Once dry, the coating needs no additional treatment. Dip coating is another evaporation process in which the part to be coated is entirely dipped into a liquid.

These processes can have very high deposition rate but a poor line-of-sight coverage on complexly shaped objects. The adhesion of the coating to the substrate may also be critical.

2.1.3 Chemical processes

This category contains a variety of Chemical Vapor Deposition (CVD) processes. Thermal CVD and plasma assisted CVD are the two main ones. In both of them, a range of gases is fed into a reaction chamber from a gas handling manifold which monitors individual flow rates. The reaction occurs near the substrate so that a reaction product is deposited on the substrate. Gases are finally exhausted by means of a rotary pump. Some typical chemical reactions are listed below:

$AlCl_3 + CO_2 + H_2 \rightarrow Al_2O_3$

$TiCl_4 + H_2O \rightarrow TiO_2$

$SiH_4 + CH_4 \rightarrow SiC$

The equations do not show the intermediate reactions occurring during the process, e.g., hydrogen reductions convert SiH_4 and CH_4 into SiH_3^- and CH_3^-, which then react together near the substrate.

Thermal and plasma-assisted CVD processes are distinguished by the different ways of providing energy to the gases to bring them to a reaction point. In the case of thermal CVD, energy is brought to the substrate by heating it up. Gas particles dissociate when they hit the substrate. Plasma-assisted CVD activates the reaction between the gases by creating a plasma in the vapor phase. The plasma is normally created by one of the three following excitation sources: D.C., 13.5 MHz R.F., or 2.5 GHz Microwave. The activated gas atoms and molecules are far more likely to react near the substrate where the greatest electric field exists. The electric field follows closely the contours of the surface allowing uniform coverage over complexly shaped objects. In addition, samples can be coated by plasma-assisted CVD at low temperatures and with a wide range of materials.

2.1.4 Physical processes

Physical processes include all the technologies currently considered as Physical Vapor Deposition (PVD) processes. PVD process terminology is confusing since so many different processes are called PVD processes. In a broad sense, a PVD process consists of the creation of a vapor phase element, its transport from a source to a substrate, and finally a film growth on the substrate (1).

Ion sputtering illustrates these three steps in the formation of the coating: A high voltage is applied to a cathode, the target material. The reaction takes place within a chamber filled with an ionized gas, usually argon, at low pressure (50 milliTors). The gaseous ions bombard the target and sputter atoms of target materials through momentum transfer processes. The escaping atoms can be transported by magnetic forces in order to reach a cool substrate and condense on it.

Ion beam deposition is another example of a PVD process, in which a beam of ions is generated to impinge and deposit on the substrate.

PVD processes give very low levels of contamination in the coating. However, the range of ceramics achievable by these processes is limited by the variables of the materials, and the fact that ceramics may depend on a gas in the chamber to produce a reaction, e.g., gaseous nitrogen fills the chamber to react with titanium atoms issued from the target and give titanium nitride, $N2 + 2Ti \rightarrow 2TiN$.

2.1.5 Thermal spraying processes

Thermal spraying processes contain deposition technologies in which a material is heated to near or above its melting point. Particles are then sprayed onto a substrate and on impact form a multi-layer coating consisting of overlapping thin lamellar particles. Processes differ from one another in material form (powder or wire), and in the way energy is provided to the particles. The following techniques will be reviewed: powder flame spraying, wire flame spraying, electric arc spraying, detonation gun, and plasma spraying.

Powder flame spraying

Powdered materials are fed onto a gun, carried in an oxy-acetylene gas stream and passed through an intense combustion flame. The fine powder particles are melted almost instantly and sprayed on the substrate where they solidify. The resultant coating offer high quality properties. However, the characteristics of the coating are sensitive to the process parameters and provide bad reproducibility in some cases.

Wire flame spraying

Wire flame spraying uses materials in wire form to create surface coatings. The wire is introduced in the gun and guided into the center of an oxy-acetylene flame. When the tip of the wire melts, atomized particles are propelled to the surface by the velocity of the gases. Using ceramic rods will produce ceramic coatings. The process is easy to transport and is preferred when coating areas are difficult to reach. However, wire drawn materials have limited availability and the process is difficult to automate since the rigid wires must be fed manually into the gun.

Electric arc spraying

Two wires converge into two copper electrodes. An electric arc is generated at their intersection point, where the high temperature melts the material. As with the wire flame spraying process, the molten particles are atomized by a high velocity gas stream and then deposited onto the substrate. The process was developed primarily for rapid, economic coatings, and has been successful with the application of high melting point metals. However, electric arc sprayed coatings are generally porous and the method includes the evident drawbacks considered for wire flame spraying.

Detonation gun

Detonation gun mixes a measured amount of powder injected in a water-cooled barrel about 3 feet long with a mixture of oxygen and acetylene. When the gas is then ignited, the explosion within the chamber causes the powder to heat up close to its melting point. The plasticized particles are propagated through the shock wave, and are imbedded in the surface of the substrate. After the powder has exited the barrel, a pulse of nitrogen purges the barrel. The process is repeated 4 to 8 times per second (2). Detonation gun coating is particularly useful for depositing hard materials, such as chromium carbide and tungsten carbide, which produce very dense, wear-resistant coatings. This technique also minimizes the residual stress that results from substrate heating. However, this method is available only as a service from Union Carbide, i.e., the process is patented and the equipment is not sold. In addition, the report of the gun makes the process extremely noisy.

Plasma spraying

The plasma is a gas stream, mainly argon or nitrogen, which is heated to temperatures as high as 30,000°F by an electric arc to partially ionize the gas and cause it to become electrically conductive (3). Powdered materials suspended in a carrier gas stream are injected into this plasma. Particles are instantly melted and propelled as a high velocity spray onto the substrate. Upon impact with the cold surface, particles are flattened out and cooled down by transfer of heat to the substrate. The plasma spraying process is illustrated on Figure 1. The electrodes

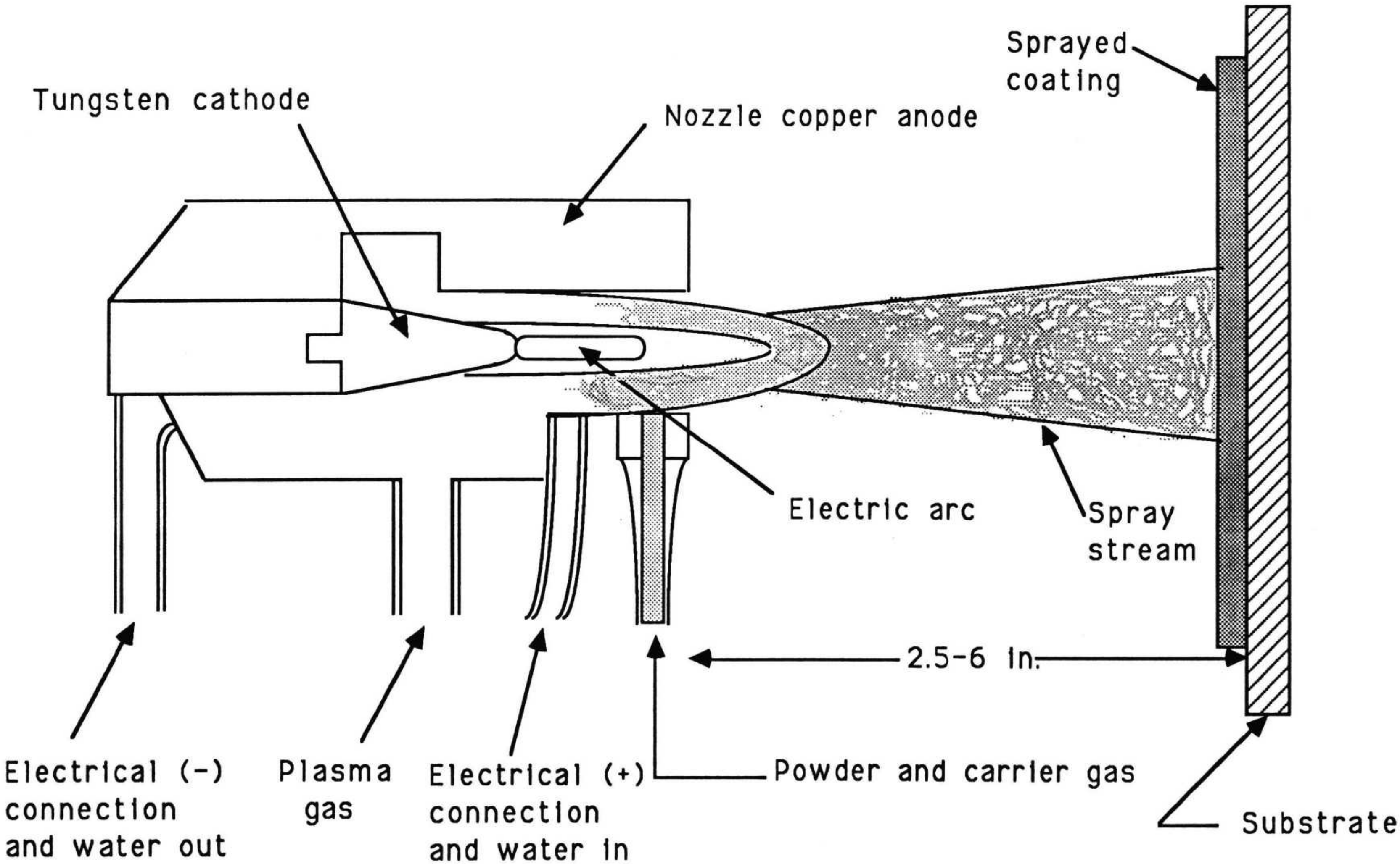


Figure 1. Plasma-Spray Deposition

which create the plasma are contained in the gun. The arc gas, carrier gas, powder feed material, D.C. power, and water coolant are all introduced through different orifices.

The plasma spraying process produces coatings with very good adhesion to the substrate. The coatings adhere mainly by mechanical bonding and through different types of chemical binding forces. Moreover, high coating densities are generally achieved. But the major advantage of the plasma spray technology is the variety of materials achievable, as almost all materials which can be melted without deterioration can be plasma-sprayed. Ceramic materials, however, do not melt completely due to the extremely short time particles remain in the plasma. Therefore, deposition efficiencies are relatively low when compared to other processes, leading to a substantial waste in materials.

The short dwell time of the particles in the plasma limits oxidation by surrounding air. Nevertheless, if oxidation needs to be completely avoided, the process must take place in a vacuum chamber filled with an inert gas, where lower pressure can also be achieved. As a consequence of the low pressure, the plasma jet increases from around 5 cm up to 50 cm and particle velocities reach values of 600 m/sec. Opponents of vacuum plasma spraying claim it shows the same disadvantages associated with spraying in the atmosphere. Moreover, the plasma has a lower energy density and additional power is required to melt the particles. Finally, gases which fill the chamber must have a very high level of purity, over 99.99%. Vacuum plasma spraying equipment is expensive, and performance evaluations have not proven yet if the technique is worth the extra cost.

Plasma spraying was the process chosen to assess economically the potential for ceramic coatings. The reasons for this choice are threefold:
1. The technique offers a wide range of ceramic materials applications to be studied,
2. Many of the ceramic applications are already commercialized,
3. The possibilities of this technique are probably not yet completely discovered.

2.1.6 Comparative analysis

This chapter will define some important criteria used to select a particular coating process, and will point out the incompatibility of some coating features with specific processes, i.e. ceramics coatings cannot be achieved by electrodeposition. Table 2 investigates the range of possibilities of four coating processes (Electrodeposition, CVD, PVD, and plasma spray) in terms of:

- Achievable materials.

Metals, metal alloys, oxides, borides, nitrides, cermets, or a mixture of the above are materials that can be coated through different processes. Some processes are limited to certain categories. For example, nitrides and borides have not been successfully plasma-sprayed in the past. However, an analysis that compares only categories of materials is misleading, since one may think the range of achievable materials is more limited for plasma spray than for PVD or CVD. In fact, the contrary is true. Within a category, the process can be applicable or not to a large number of materials. Thus, plasma spray has a wider range of achievable ceramics than CVD, and CVD than PVD.

- Substrates.

The substrate must be heated during CVD. On the other hand, heat-sensitive substrates must be cooled for rapid deposition in the case of PVD. It is

Table 2. Processes Comparison

Process	Materials	Substrates	Surface Area	Coating Thickness
Electrodeposition	Metals, alloys, cermets.	Metals, composites, ceramics.	10 sq. meter to 1sq. mm.	1 mm.to 0.001 mm.
CVD	Metals, alloys, oxides, cermets, nitrides, borides.	Metals, composites, ceramics.	10 sq. mm. to 0.01 sq. mm.	0.1 mm. to 0.001 mm.
PVD	Metals, alloys, oxides, cermets, nitrides, borides.	Metals, composites, ceramics.	10 sq. meter to 0.01 sq. mm.	1 mm. to 0.001 mm
Plasma-Spray	Metals, alloys, oxides, cermets.	Plastics, metals, wood, composites, ceramics.	10 sq. meter to 0.001 sq. mm.	10 mm. to 0.001 mm.

these thermal constraints that prevent application to many plastics and other materials. Under appropriate process conditions, plasma-sprayed coatings can be applied to a spectrum of substrates going from plastics to ceramics.

- Surface area.

The plasma spray technique offers the ability to coat large surfaces (10 square meters) to small surfaces (10^{-3} square millimeters). The other processes are more limiting because of the nature of the deposition technology and some engineering design constraints, e.g., CVD occurs in a vacuum chamber.

- Coating thickness

Here again plasma spray has the wider range of possibilities. CVD coating thicknesses are limited by the chemical reaction which takes place near the substrate.

The rate of deposition is also a crucial economic factor. Process time has a substantial impact on the overall coating cost. Sputtering occurs at a very low rate (0.01 in./hr). CVD has up to 10-fold advantage over PVD in the rate of deposition in some cases, though it still remains limited to 0.1 in./hr. Plasma-spray technology has much higher deposition rates depending on the characteristics of the material (flowability, melting point,...).

For some applications, the choice of the process can be determined by the desired microstructure of the coating. Different deposition technologies give different coating microstructures. PVD coatings have a columnar structure as plasma-sprayed ones are composed of a superposition of lamellar particles. Moreover, the nature of the bonding between particles can be very different: CVD coating particles are chemically bonded, and plasma-sprayed ones are mainly mechanically linked.

Finally, ecological considerations may decide on the choice of the process. Electroplating technologies have been regulated by the Environmental Protection Agency (EPA) for the past few years. But electrodeposition is not the only polluting technology. Plasma-spray produces large quantities of dust, and detonation gun is a very noisy process even if Union Carbide, the sole user of this deposition method, uses sound-proof booths.

Coating technologies are so numerous, no single company is capable of using all different kind of techniques. Therefore, coating manufacturers market their technology by over-estimating its benefits and ignoring the benefits of the others. The techniques should be compared at the same time. The choice of the optimal deposition technology for a specific application should be made by eliminating techniques that do not meet the engineering or/and economic criteria.

2.2 Coatings applications

The coating improves the engineering performance of parts by coupling a substrate bulk material with a surface coating material. Originally, coatings were applied to rebuild worn parts or to repair a failed component. Coatings are now used to obtain a combination of properties that would not be possible with homogeneous materials. The following analysis divides coating applications into four generic areas, based on the coating's function. Table 3 illustrates these four categories.

Table 3. Ceramic Coatings Applications

FUNCTION	PURPOSE	EXAMPLES OF APPLICATIONS
Optical	- Reflection and anti-reflection. - Laser optics.	- Mirrors - Lasers
Electrical	-Electrical insulation and conduction. -Dielectric strength	- Wires - Superconductors - Electronics
Mechanical	- Abrasive wear resistance - Galling wear resistance	- Cutting tools - Rolls in textile industry - Screws in plastics industry
Chemical	- Environmental corrosion. - Hot corrosion. - Thermal Barrier Coatings.	- Aircraft parts - Furnaces - Diesel engine components, blades and vanes of gas turbines.

2.2.1 Optical function

Thin coatings, often referred to as films, are used in various optical applications. Different kinds of mirrors (home mirrors, automotive rear view mirrors,...) have been coated for years to give them reflective or anti-reflective properties. More recent applications are found in the laser optics industry where surface properties are changed to improve transmission and reflection of light beams. Solar panels are another example of optical applications: M.I.T solar house windows are coated with a film of indium-tin oxide or copper-tin oxide which give selective solar absorbent properties to the glass.

2.2.2 Electrical function

Coatings may provide improved electrical conductivity to a component. For example, research conducted on coating the tungsten filament on a light bulb demonstrates both decreased energy use and a substantial life-extension of the light bulb. Beyond conductivity, a great deal of excitement has surrounded the area of high temperature superconducting ceramics. Professor Herbert Herman, State University of New York, and his associates have produced plasma-sprayed coatings of Y-Ba-Cu-Oxide, and characterized their superconducting properties by resistivity measurement analysis. Superconductors can be developed commercially in the future, as semi-conductors have been in the past twenty years. Ceramic coatings have also been used in this last technology. For example, photovoltaic solar cells have been produced by CVD processes.

Insulation is the most important electrical application for ceramic coatings judged by market size. Ceramic powders like aluminum oxide and magnesium aluminate provide electrical insulation even at the high temperatures where plastics fail. In an electrical system, for example, the current jumps between two narrow coils, resulting in electric arcs. A thin coating of Al_2O_3 prevents the spark and increases the life of the induction coil.

The electronics industry uses aluminum oxide coatings to give high dielectric strength to critical areas. Electronic components also face special wear problems due to their speed of operation, a type of problem that occurs to electronic chips as well as to the tooling equipment that manufactures them. The problems can be solved by coating the parts with ceramics which have both wear resistance and electrical properties. In the same way, fast moving computer cards and tapes wear out computer peripheral parts. Chrome plated parts wear after processing less than 40,000 cards; chromium oxide plasma-sprayed coatings show no measurable wear after processing 1.5 million cards (4). This last set of applications combine wear resistance and electrical coating properties.

2.2.3 Mechanical function

The major mechanical property achieved through ceramic coatings is wear resistance. Overall, wear resistance applications represent the largest market for ceramic coatings. For example, coatings of carbides or aluminum oxide can enhance substantially the useful life of high speed steel cutting tools. In 1983, annual sales of coated cutting tools accounted for about $1 billion (5). Moreover, it has been found that the addition of TiO_2 to alumina results in considerable improvement in the mechanical properties of plasma-sprayed coatings. After impact on the substrate, the titania remains in a molten state because of its lower melting point. It then fills gaps between solidified particles, and reduces the coating porosity (6).

Wear resistance coatings have many other applications, including mining drills, main rotor shafts in helicopters, pumps and compressors in the petroleum industry. An important distinction should be made, however, between abrasive wear resistance and galling wear resistance. Abrasion occurs when abrasive particles erode a part, and galling wear results from metal parts rubbing against each other.

Ceramic coatings are not used only on cutting tools to protect from abrasion. In the textile industry, nylon and polyester fibers wear parts in direct contact with yarn, resulting in the frequent replacement of machinery parts, or, even worse, the degrading of yarn quality (7). Other typically coated parts are pumps, handling slurries and liquids containing abrasive particles.

Galling wear is encountered in many different industries: ceramic coatings may provide wear resistance to steel mill rolls, and to different types of screws in the plastics industry. Even after the wear has occurred, worn components can be restored if damages are not terminal. Ceramic coatings may thus offer an extension of service life at a lower cost than part replacement.

2.2.4 Chemical function

A corrosive environment can be hostile to materials, causing the part to fail after a certain time of service. Figure 2 shows how coatings can provide a long-lasting, productive solution to the problem: the coating material degrades at a lower rate than the substrate material. However, when the coating is penetrated, a coated and an uncoated part have the same corrosion resistance to the environment.

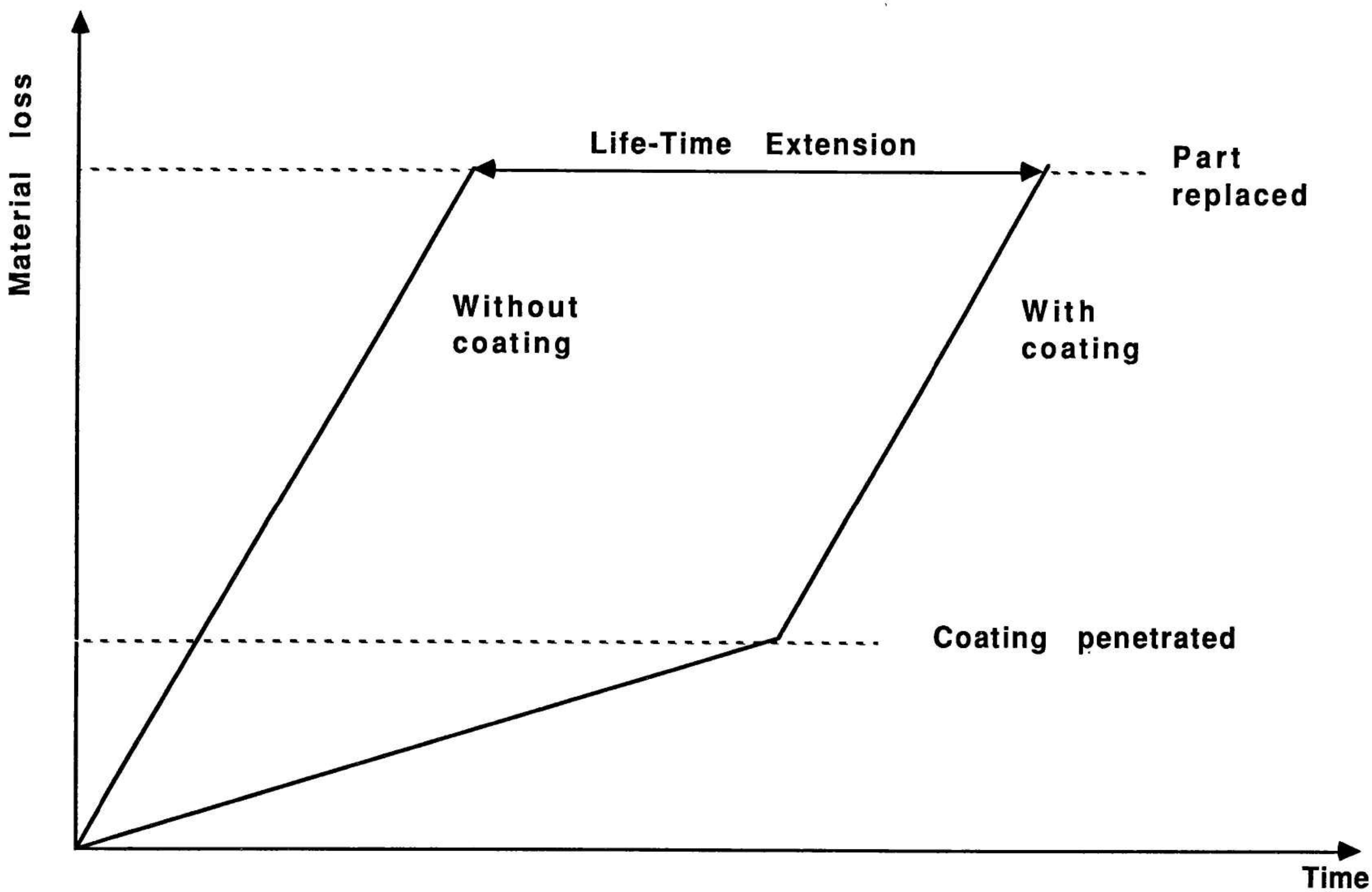


Fig. 2. Schematic comparison of corrosion resistance of a coated and an uncoated part.

Corrosion can occur over a wide range of temperatures. Environmental corrosion covers all types of chemical deteriorations at ambient temperatures. For example, coatings have been applied on commercial and military aeronautical airframes to combat air corrosion. In this case, coatings must feature light materials. For the protection of large areas subject to environmental corrosion, galvanization remains the number one process since it is a low-cost, mature technology.

Ceramic coatings are now being successfully used in elevated temperature applications. Car engines are equipped with plasma-sprayed sensors which control the exhaust gases, i.e., the combustion. The coatings are permeable to the gases but give sufficient corrosion protection to the active layers of the sensor. Ceramic coatings are used also for metal and refractories on burning equipment. Silica-alumina coatings are sprayed at room temperature on furnace walls, and increase service life from 50 to 700 percent (8). By increasing the radiating effect inside furnaces, substantial energy savings are achieved as well.

Coatings for high temperature applications may serve as both thermal barriers and corrosion resistant coatings. Zirconium oxide-yttrium oxide composite materials are plasma-sprayed on gas turbine engine parts like fan blades, turbine blades, and seals to achieve good thermal and chemical stability up to 3,000°F. Such powders also produce high temperature thermal barrier coatings resistant to thermal cycling stresses on diesel engine parts such as valves, liners, and piston heads. This last application will be thoroughly analyzed in the case study following chapter 3.

2.2.5 Conclusions

Even though this chapter has made generic distinctions, a ceramic coating can combine the above functions. More research should be conducted to investigate the potential of composite materials for multi-functional applications.

Many applications have not been mentioned in this analysis. One can envision a great future for many that are now in their development stage. Ceramic coated biomedical implants are one of them.

Finally, the actual or future value of the market for ceramic coatings cannot be easily assessed for the following reasons:

- The range of applications is extremely wide.

- There is no general agreement on the definition of a ceramic coating application, e.g., is the bathtub's enamel a ceramic coating?

- Many applications are in their development stage, and used only for research experimentation.

3. COST MODELING - PLASMA-SPRAYED COATINGS PRODUCTION

3.1 Model development

Chapter 3 offers to explain the cost model's mechanisms through the structure of the flowsheet as presented in the appendix.

The appendix only shows results, and does not reveal the underlying calculations. If inputs definitions are clear to the user, the model can be run by ignoring the calculations. However, a better understanding of the computations may help to introduce consistent inputs.

Finally, this chapter analyses the plasma-spray process step by step, and emphasizes the future technical developments that will bring improved quality to the coating.

To sum up, each feature in the plasma-spray process is discussed to give:

- its definition, e.g., what is the overspray?
- its reason, e.g., why is there an overspray?
- its influence on the cost, e,g., how to include the overspray in the calculations?

3.2 Factor prices

Electricity is the only source of energy in the process. Its primary function is to provide energy to the gas and create a plasma.

The model provides a list of ten materials including ceramics, carbides and metals. This list could be extended infinitely since any powder which does not sublime at high temperatures can theoretically be plasma-sprayed. The user may add the name and characteristics of a new material if needed.

The cost of the material must be based not only on the powder's composition, but on its specifications, e.g., pure aluminum powders can have different levels of quality,ranging from $0.60 to $12 per pound. It must be noted that powders with identical characteristics may be sold at very different prices depending on where you buy it. Powder manufacturers have substantially lower prices than plasma-spray equipment manufacturers which may be powder retailers.

The particle size and the particle size distribution are two major factors. If the powders were monosized, particles would be injected in the center of the plasma and would be melted uniformly. In reality, powders are a blend of particles with different sizes, and you end up with partially melted particles mixed with totally melted ones. These differences can result in low rates of deposition, or, even worse, in poor quality coatings. Therefore, powders must be carefully differentiated on the basis of their composition, degree of contamination, particle size, and particle size distribution. Other factors may also intervene on the final choice, but the above four criteria should be sufficient to compare powders from different sources.

The gas functions as a carrier gas and as a plasma gas. As a carrier, the powder is suspended in a carrier gas stream, and introduced into the plasma where the particles are melted. A minimum carrier gas flow rate minimizes cooling effects on the arc gas.

The plasma gas is introduced directly through the gun between an anode and a cathode where it becomes ionized and highly energetic. Typical primary gases used are argon and nitrogen. A priori, nitrogen appears to have an advantage over argon. However, argon is a monoatomic gas whereas nitrogen is a diatomic one. This difference is significant to the plasma-spray operation, and the following factors should be taken into consideration(9):

- Nitrogen requires approximately 50% more arc power than argon;

- Under normal spray conditions, 50% more nitrogen than argon is consumed;

- A diatomic gas like nitrogen causes more erosion in the gun nozzle than a monoatomic one like argon. Thus, the use of argon increases the nozzle life by a factor of five;

- Even though externalities other than air pollution have no direct economic bearing on the plasma-spray process model, it must be remarked that nitrogen produces higher noise levels than argon.

When reviewing all the above facts, argon appears as a better choice from an economic point of view. Nevertheless, the user can choose, and see the economic consequences throughout the computations.

It is sometimes desirable to add a mixing gas to the plasma gas. Hydrogen, for example, can increase the power level in the plasma, resulting in increased temperatures. Helium when mixed with argon gives substantially higher particle velocities. The model offers the opportunity to mix a desired percentage of helium and hydrogen with the primary gas.

The cost of labor should include the wage of the worker, but also his risk insurance, taxes, and the safety equipment necessary to the accomplishment of his work. The $/man-hour value indicated in the model should be adapted to the specifications of the working environment.

The "others" category regroups four important items which will be used later in the model:

- The plasma-spray process consumes large quantities of air. The air coming in should be sufficiently clean to avoid contamination and oxidation of the coating. The air coming out should have a reasonable concentration of pollutants. The cost of clean air includes both the cost of cleaning the air for the process, and the social cost of pollution. The cost is practically reflected in the use and replacement of air filters and stacks.
- Nozzles are worn out by the plasma gas and must be replaced frequently.
- The grinding operation considers the use of diamond wheels which are more appropriate to remove hard ceramic materials than carbide wheels. The specifications of the wheel are introduced in the grinding step.
- Powders are stored in canisters and dispensed to the gun through a powder feed unit. Each powder must have its personal canister in order to avoid mixtures and contamination.

Finally, the accounting assumptions are related to the capital investment charges. The equipment is paid back on the basis of a given interest rate, i.e., the cost of capital, over a certain period of time, i.e., the years to recover investment. In addition, the maintenance rate evaluates the percentage of the initial capital investment which should be replaced every year.

3.3 Capital investment calculations

The equipment is distributed among the five step categories: substrate preparation, coating, grinding, quality control, and storage. Each step can be operated at different levels of automation and sophistication. The user can choose the equipment as a function of his needs.

Substrate preparation equipment

The substrate preparation includes four distinct operations: masking, degreasing, grit-blasting, and preheating. The masking step is entirely manual and needs no equipment. The part can be preheated also, using the hot plasma without powder fed into the gun; no additional equipment is needed.

If impurities lay on the substrate, they prevent the coating from adhering to the substrate. The degreasing step rids the substrate of contaminants. This can be achieved either by wiping the part manually with a degreaser solvent, or by vaporizing the same solvent on the substrate. The second option requires the use of vapor degreasing equipment.

Various methods have been developed to improve mechanical interlocking between coating and substrate. The most commonly used technique is surface abrasion by grit-blasting. The equipment consists of an air compressor apparatus which can be automated by the means of belt-conveyors.

Coating equipment

The basic coating equipment is illustrated in Figure 3. From left to right, the power supply unit delivers electricity to the system through the plasma arc

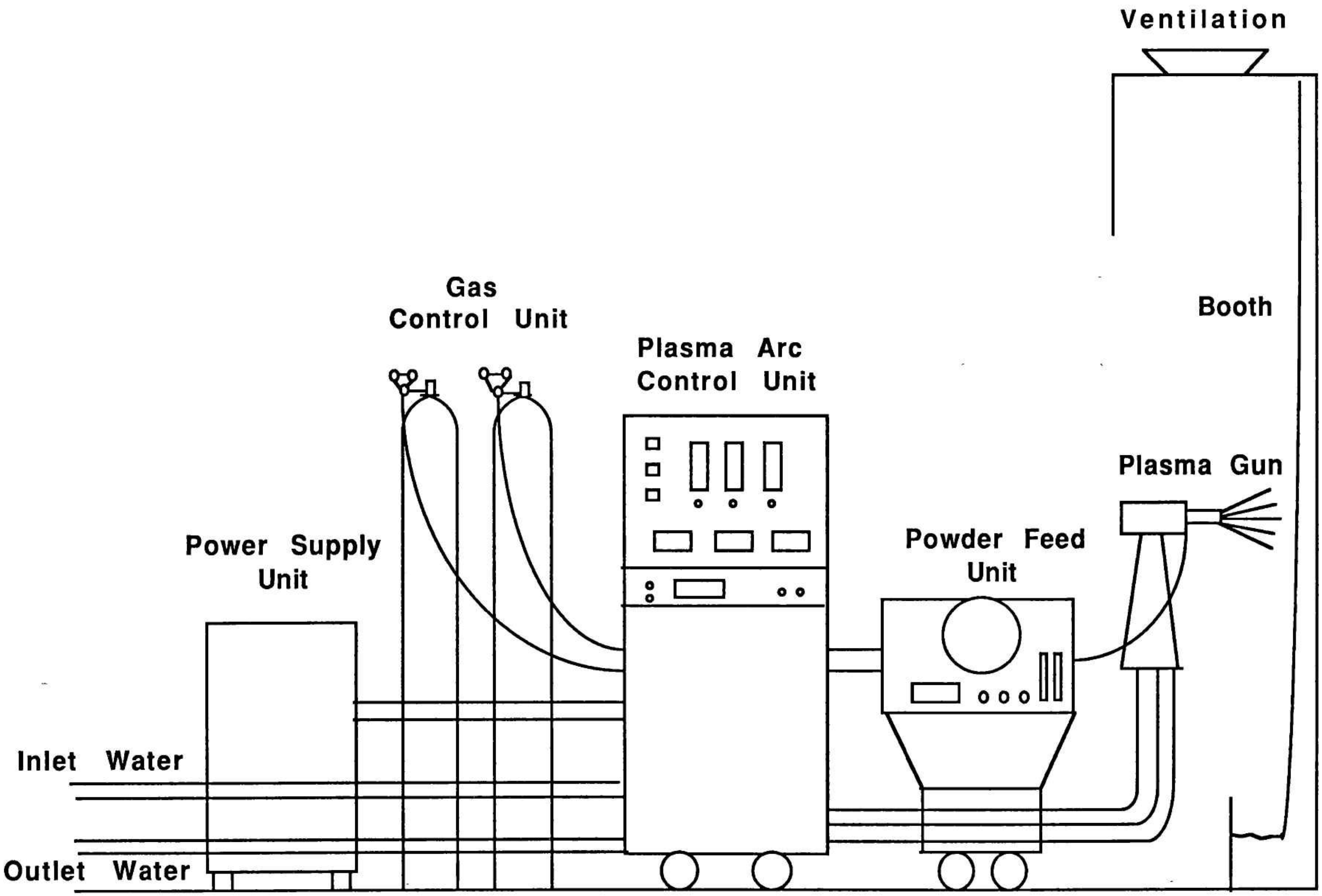


Figure 3. Typical Plasma-Spray Equipment

control unit which determines the power level. The arc gas flow rate and the cooling-water flow rate are also controlled by this last unit.

Figure 3 does not show the water chiller located at the edge of the inlet and outlet water pipes. A water chiller can recycle the water used to cool the gun nozzle. Indeed, the cathode in the gun is thermodynamically emitting and the cooling of the anode (nozzle) can be critical.

The powder must be distributed uniformly at a constant rate in the plasma stream. The powder feed system generally has its own control system over the carrier gas flow rate and the powder injection rate.

The booth needs to be ventilated in order to suck out the air consumed during the process. Therefore, it is equipped with a ventilation system at the top. The wall facing the gun is also protected by a water curtain in order to wash out particles which have not reached their target.

The optional equipment improves the quality of coatings and increases productivity by means of advanced robotics and the computerized plasma-spray system. The first step in automation uses rotary tables and automated XY equipment which move the workpiece in one or two directions. However, this equipment does not remove the spray operator from the booth, and the quality of plasma-sprayed coatings remains largely operator dependent. Further automation demands the integration of a computer control with a robot operation. Plasma-spray equipment manufacturers deliver a plasma-spray package in which the robot can be integrated. The spray-gun is controlled by a computer interfaced 5-axis manipulator with X, Y, Z, Oyz, and Ozx degrees of freedom. Part configuration data is programmed into the computer (10). In view of potential productivity improvements and substantial cost savings, automated systems are being implemented increasingly.

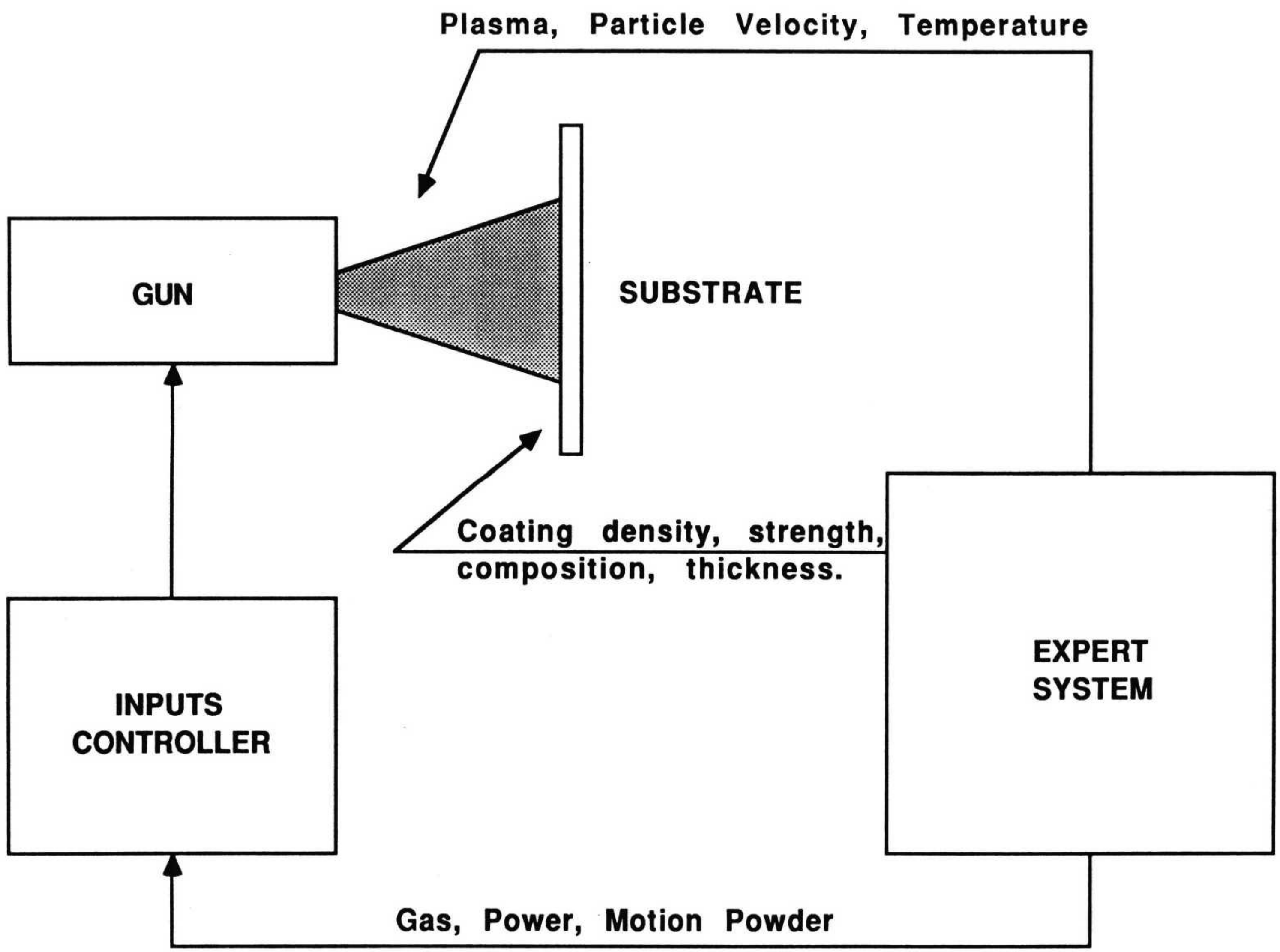
Ultimately, the plasma-spray process will be automated using the closed loop feedback control system described in figure 4. An expert system establishes a minimum level of control on process parameters that permits variations in the parameters within a tolerance range to improve process stability. Such a system would yield the following benefits:

- identification of poorly performing parts,
- closer dimensional control, resulting in material savings and lower machining costs,
- increased productivity.

The closed loop systems currently under research will render the plasma-spray technique more of a science than an art.

Grinding equipment

The grinding equipment is composed mainly of high speed rotating machine tools. Generally, ceramics require machines with consistent grinding forces and power (11). In addition, the use of a coolant becomes critical with ceramics to prevent thermally induced cracks. A liquid coolant is often not practical or desirable. An air compressor gun is used to direct a low-pressure, cold air stream to the precise point of heat buildup. The cold air system may eliminate microcracks in the coatings induced by grinding, and extend the wheel life as well.



<u>Figure 4. Closed-Loop Feedback Control System</u>

Quality control equipment

The choice of quality control depends on the coating specifications. Some tests may not be necessary under certain circumstances, e.g., an electrical insulator coating may not need any mechanical test if external forces are not applied to it during operation. Nevertheless, plasma-spray coating manufacturers generally recommend a close look at the surface microstructure. A computer enhanced metallograph gives appropriate cross-sectional pictures of the coating, revealing its composition and porosity content.

In many cases, dimensional control is also required to check if the coated part is staying within a tolerable range of sizes. The model offers two degrees of sophistication in the control: mechanical and electronic.

Storage equipment

Coated parts are easily stored on racks with no further protection. On the other hand, powders stored in containers should be kept in a refrigerated area to prevent agglomeration and deterioration.

3.4 Preliminary questions & Data base tables

The model asks the user six essential questions. The first three are related to coating characteristics: surface area, thickness, and density. Answers should be be given in a reasonable range, given the possibilities of the plasma-spray technique. The model has no "engineering common sense" and will not analyze the practicability of the value introduced. For example, full coverage of the substrate cannot be achieved with a coating thickness inferior to .007 of an inch. The model can calculate the plasma-sprayed deposition cost for any thickness whether the material deposited forms a coating or not.

Moreover, the model assumes all surfaces can be treated as planes. The surface area is actually the developed surface of the part. For example, the cost of coating a cylinder will not differ from that of coating a plane sheet as long as their surfaces are equal.

The last three questions enquire about specific procedural matters. The coating may need to be partially masked, or ground at a precise dimension. Finally, the production volume is determined to compute the cost equipment amortization, and to give total costs for all the parts.

This set of questions is followed by two data-base tables that report powder characteristics and powder spray conditions. When materials are purchased, no specification is generally given on the particle size distribution, the powder flowability... Therefore, spraying parameters must be tailored to individual powders. Those tables intend to establish the optimal powder feed rate, gas rate, and energy required during the process. For example, one may want to increase the gas flow rate to improve the deposition efficiency although, generally, the cold part of the plasma is enlarged without improving results.

The deposition rate is 25% to 50% inferior to the powder feed rate. For technical reasons, all the powder is not properly melted and applied to the substrate. Therefore, a substantial amount of material is lost in the process. A narrow particle size distribution is desirable. The additional cost of sizing the powder is at least partially recovered in higher deposition efficiency and better coating quality.

The information gathered through the questions and tables permits computation of two fundamental values: the amount of material consumed, and the deposition time. The following chapter examines those calculations, and explains how the inputs are coordinated to evaluate the costs.

3.5 Production input factors

3.5.1 Substrate preparation

In the model, substrate preparation includes four steps in the following order: masking, degreasing, grit blasting, and preheating.

a) Masking

Some part areas may need protection from plasma arc and powder deposition. Therefore, two types of masks are applied to them:

- Primary masks withstand long stand-off in front of the plasma torch. Silicone coated fiberglass / silicone adhesive tapes are generally used to cover the area to be protected (12). They withstand abrasion of grit blasting and are easily removed without breaking.

- Secondary masks protect parts located far from the plasma jet. They usually consist of metal sheets, and are called hard masks.

Masking is a timely and costly operation to be avoided if possible. Silicon-fiberglass tapes are more expensive than hard masks since they are not recoverable. However, they allow more precise protection, and coverage of small areas. Tape masking is a time consuming process that is necessarily manual. In the model, the high values in the ratios of masking time to coating time illustrate this fact. For certain aircraft engine parts, it may take longer to tape the part than to plasma-spray it.

If coatings are produced on a large scale and masking is necessary, other options for protection should be considered, such as easy-to-remove plastic films.

b) Degreasing

Organic chemicals are passed over the substrate to remove any contaminants, particularly oils. The cheapest degreaser commonly used is the solvent 1.1.1. Trichlorethylene. Vapor degreasing is more effective and less labor-intensive than liquid degreasing. However, degreasing may not be necessary if the part is assumed to be already clean.

Other cleaning technologies are under research. Ultrasonic cleaning is effective at removing contaminants in difficult-to-reach locations.

c) Grit blasting

The roughened substrate surface the plasma-spray process requires to improve mechanical bondings between coating and substrate particles can be achieved by methods such as chemical etching and lathe turning.

The most frequently used technique is grit blasting. Abrasive grit is applied to the substrate by means of pressure blast equipment, and produces surfaces with roughened textures. Grit blasting parameters are time, pressure, distance, angle, and blasting media. The geometric parameters can be adjusted as a function of the substrate parameters. The optimum angle, based on observations, seems to be somewhere between 60° and a normal angle.

The choice of the blasting media is an important feature of the process. Angular steel grit has been used for numerous substrates in the past. For harder substrates, however, special grits like alumina and silicon carbide have better cutting action. They also remain sharp for a longer period and do not rust. In many applications, alumina is preferred to silicon carbide because it produces less warpage and less substrate contamination. Moreover, low-grade alumina powder is cheap and available.

The blasting media must be renewed approximately every three hours because it becomes contaminated by substrate particles and loses its cutting efficiency. The coating should be applied as soon after grit blasting as possible to insure a clean, active surface.

If the process is automated, the amount of blasting media used will represent the major cost of the operation in the model. Grit blasting is a mature technique whose cost cannot be fundamentally decreased.

d) Preheating

It is advisable to warm the substrate surface by induction heating or by passing the plasma jet without powder. The reasons for preheating are two-fold:

- to prevent stress on the coating while the substrate expands;
- to remove any absorbed gases from the surface.

Preheating has no harmful effect unless the substrate cannot take heat, and is advisable if the weather is cold and humid because particles may solidify without bonding to the substrate.

The operation is always short. The two major inputs in terms of dollar value are gas and labor.

3.5.2 Coating

The coating operation is the central part of the model. The process has been divided into production inputs: powder, labor, energy, gas, nozzles, and air.

a) Powder

This part asks the user to estimate the overspray percentage, i.e., the percentage of powder lost from the substrate by manipulation. The value input will vary according to the operator's skills, or on the control of the robot. Small parts and complexly shaped objects can also have substantial higher overspray factors.

Thus, the model possess all the information to compute the amount of powder consumed per coated part:

$$\text{Powder} = \frac{\text{Volume} \times \text{Coating density} \times \text{Powder density} \times (1+\text{Overspray})}{\text{Deposition efficiency}}$$

where Volume = (Surface - Masking area) × Thickness ,

and $\text{Deposition efficiency} = \dfrac{\text{Deposition rate}}{\text{Powder feed rate}}$

The powder cost per part is then obtained by multiplying the amount of powder by its cost per pound.

These calculations demonstrate the effect of deposition efficiency on the powder cost for the coating.

b) Labor

The traverse speed of the gun is not a critical parameter though it should be adjusted to permit a uniform rate of deposition. The rate of powder deposition is rather the limiting factor in the model. In other words, a limited amount of powder is deposited per hour, regardless of the number of gun passes on the substrate.

In addition, the gun must be cleaned for about ten minutes every hour, a time loss characterized by the downtime percentage.

Finally, the coating time per part can be calculated:

$$\text{Coating time} = \frac{\text{Powder consumed}}{\text{Powder feed rate}}$$

The time actually spent by the operator in the booth, i.e., the worktime, is different from the coating time. Automation of the process and downtime affect the calculation of the worktime and not that of the coating time. Automation is shown in the model by the ratio of worktime to coating time, e.g., if the operator watches the robot spraying during half of the coating time, the ratio is equal to 0.50. All the time ratios found in the other process steps are based on the same principle, e.g., if preheating the part takes one second and coating twenty seconds, the time ratio is equal to 1/20, or 0.05.

c) Energy

Plasma-spraying is not an energy-efficient process. The electrical efficiency of the equipment ranges from 23% to 60%, whereas the overall energy efficiency of the process remains between 15% to 20%. A large part of the energy in the plasma is not utilized to melt the particles, and, therefore, is wasted. However, when compared to other inputs, electricity is cheap, and accounts for a small part of the overall coating cost.

d) Gas

The second data base table provides the gas feed rate for the material used. Multiplying this rate by the coating time gives the volume of gas consumed, even considering the effect of different gas choices; for example, 50% more nitrogen than argon would be used for the same operation.

e) Nozzles

The lifetime of the nozzles depends on the nature of the gas used in the process. The model determines the number of nozzles worn out during the operation, and calculates their costs.

f) Air

The volume of air consumed is estimated. The plasma stream acts as an aspirator, sucking up air from the surrounding environment. The air must be relatively clean so as not to oxide the powders. Besides, the air used in the grit blaster should also be purified so as not to corrode the substrate. The cost of clean air is insignificant but is taken into account as an externality.

Adding up all the above inputs gives the overall cost of the coating step.

3.5.3 Grinding

After being manufactured, numerous and various engineering parts are finished to maintain close dimensional tolerances. Plasma-sprayed ceramic coatings, however, are a unique family of materials, and their finishing has very specific features. Ceramics are very hard materials, and produce heat intensively when rubbed against other hard materials.

Finishing can be defined as the action of shaping by the friction of machining or grinding. Although the processes are fundamentally similar, a part is machined when the tool is almost fixed and the workpiece rotates at high speed, whereas the workpiece is fixed and the tool rotates when the part is ground. Grinding gives a better response for ceramic coatings since it is often easier to control the movement of the workpiece against a wheel turning at high speed. Moreover, machining removes around four times more material at each pass than grinding. When precision is wanted, grinding is definitely preferred.

Different wheels are designed to meet the needs of specific applications. For example, grinding wheels are narrow for electronic applications. The grinding equipment should also be compatible with the process requirements, e.g., adequate rotating speed and power.

Engineers and scientists involved in ceramics finishing activities emphasize the grinding wheel material. In the past, a wide spectrum of abrasive materials from carbides to diamond was offered. Silicon carbide was eliminated since it tends to burnish and deteriorate ceramic coatings (13). Cubic boron nitride (BZN) has very good abrasive properties but is more expensive than diamond.

Ultimately, diamond wheels appear to be the favorite candidate to grind hard ceramic coatings.

The cost modeling of grinding is similar to that of coating, except that the material is removed instead of being deposited. The model computes the total volume of coating material to be removed, given the grinding depth introduced in the preliminary questions. The grinding time is established by the following equations:

$$\text{Grinding time} = \frac{\text{Volume of coating ground}}{\text{Removal rate}}$$

where Removal rate = Width of wheel × Depth removed × Traverse rate

An additional time for loading the part is reported, comparable to the downtime of the coating step.

The wheels wear out gradually while the coating is ground. For X cubic inches of coating particles removed, Y cubic inches of the diamond wheel are worn out. The coating to wheel removing ratio represents Y over X. The model calculates the usable diamond volume given the geometric characteristics of the wheel. Assuming a value R for the coating to wheel removing ratio, the maximum volume of coating ground per wheel is computed:

Maximum volume of work = R × Volume of wheel

The number of wheels needed for the operation can then be inferred.

Adding up labor, energy, and wheels costs give the cost of grinding step per part. Note that this part of the model can evaluate the cost of grinding parts other than coated parts. If materials were changed, the coating to wheel ratio would vary accordingly.

3.5.4 Quality control

Quality control can be a very time-consuming and costly operation if every coating has to be checked. The first goal is to establish the level of quality required. No coating should be of poor quality, but some may be downgraded more rapidly than others, depending on the operational surroundings. For example, a ceramic coating in an aircraft engine is exposed to a very hot and corrosive environment. If the coating detaches from the substrate, the ceramic material may damage other parts in the engine. Furthermore, the no longer coated part itself may not have sufficient thermal resistance and break. This specific ceramic coating cannot afford to fail, and, therefore, needs stringent quality control.

In order to avoid a systematic checking of the parts, research is conducted to establish predictive correlations between plasma-spray factors and the properties of coatings. The final goal is to assess the minimum level of control over the process to ensure the required level of quality. In addition, a high degree of automation of the plasma-sprayed process can be achieved, so that the reproducibility of coatings is assured.

Fortunately, many coating depositions are straightforward, simply because the level of quality achieved is sufficient for the applications requirements. Coating samples are generally tested before production. If it is established that they are reliable, the production can start. Coatings can be checked later on from time to time.

Labor is the only input cost of this process step. This chapter showed that the amount of time spent on quality control can vary greatly, depending on the requirements of the application.

3.5.5 Storage

Ceramic coated parts are usually wrapped up and stored on racks.

3.6 Recycling option

The plasma-sprayed coating would never damage the part itself. If the coating has failed, parts can be recovered by grit blasting. The defective coating is removed from the substrate, leaving the part uncoated as it was before. However, the ceramic coating particles contaminate the blasting media which then must be changed more frequently.

Scrap rates are usually less than 2%. These failing parts will go again through the entire plasma-spraying operation, skipping the masking stage. Therefore, the cost of recycling the part is equal to the cost of coating again:

Cost of recycling = Scrap rate $\times$ Cost of coating

3.7 Cost of capital

The method used in the model is derived from standard financial calculations.

A percentage of equipment utilization is calculated by the ratio of the time spent on a specific piece of equipment over the yearly total productive time. The method assumes non-dedication of the equipment, i.e., the equipment is also utilized out of the plasma-spray operation. This assumption tends to under-estimate the equipment cost, and further work on optimization of equipment use should be conducted. However, one may over-evaluate the equipment price to overcome this problem.

Capital charges are based on an amortization of investment capital to be paid back over a certain period and the interest rate fixed by the user.

Cost of capital = % Utilization × @PMT(Investment, I.R, Term),

where Investment is the investment capital; I.R. is the periodic interest rate; Term is the number of payment periods (# of years).

@PMT computes the amount of the periodic payment on a loan. The installment loans are computed like ordinary annuities, in that payments are made at the end of each payment period (14). @PMT uses this formula:

$$\text{Investment} \times \frac{\text{I.R.} \times (1 + \text{I.R.})^{\text{Term}}}{(1 + \text{I.R.})^{\text{Term}} - 1}$$

In addition, the maintenance cost is calculated, and added to the total equipment charges.

3.8 Recapitulative tables

The cost distribution is presented in two ways:

- The first table lists the repartition of costs per inputs. Those inputs are provided in the following order: powder, process materials, labor, gas, energy, and capital cost. Each cost is retrieved from the model, and added in its category.

Process materials define all the production inputs that are different from the others listed, e.g., wheels, blasting media.

-The second table reviews the cost of the process steps: substrate preparation, coating, grinding, quality control, and storage.

Results are given in terms of costs per part, total costs, and percentages.

3.9 Further work and conclusions

This model will not give a 100% perfect cost estimation of a coating operation. It has not been designed for a particular coating application, and certainly suffers from a lack of specific inputs. On the other hand, it can be used over a wide range of materials, substrates, and spraying conditions. The user can adapt most of the applications reviewed in chapter 2.

Moreover, the model does not consider certain important features like insurance and labor space costs. The insurance cost can be included in the labor cost. The complete coating operation can take place in a space smaller than 1,000 square feet. The booth itself occupies almost 100 square feet. The coating equipment may be installed in a limited space in a plant at no additional cost, i.e., plumbing and ventilation expenses are already included in the model.

Fusing may well be an additional step in the process. The substrate is heated up with a torch to allow it to fuse with the coating. When red heat can be seen through the coating, the part needs to be slowly cooled down to avoid thermal stresses. The coating may lose up to 20% of its thickness, and substantially increase in density.

Finally, the model not only estimates a cost but may also help to figure out the organization of a production line. For example, the total amount of labor time involved in each process step is reported. Given a typical coating operation, a non-automated line may need about 5 people: 1 masking + 1 blasting + 1 coating + 1 grinding + 1 controller (inputs, inventory, quality). An automated process may bring the number of persons needed up to 2.

The following chapter gives some indication of how to use the model for a specific application.

4. CASE STUDY: THERMAL BARRIER COATING OF A DIESEL PISTON CAP

4.1 Definitions

Chapter four investigates the potential of using plasma-sprayed ceramic coatings on a diesel piston head to provide thermal insulation and corrosive protection. This study focuses on diesel pistons for two major reasons:

- Hitherto, engineers have researched the application of ceramic coatings on the tops of diesel pistons.

- Because the heat flow through the piston is critical, it is a priority candidate for thermal insulation.

It should be noted, however, that to insulate a diesel engine effectively, Thermal Barrier Coatings must be applied to other components.

4.1.1 Diesel engine

The fundamental difference between the diesel and the gasoline engine is the combustion process. The gasoline engine compresses the charge of fuel and air in the piston's upward stroke, and then ignites it with a spark from the spark plug; the diesel engine uses twice as much compression to heat the charge, which ignites because of the sharp increase in temperature.

In addition, the diesel engine demonstrates numerous economic advantages. It uses a variety of fuels with a higher thermal efficiency, it delivers from 25% to 40% better fuel mileage than a gasoline engine of comparable power, it lowers exhaust emissions, and it requires less adjustment because of the elimination of an ignition system.

During combustion in a diesel engine, heat is exchanged from the pistons, valves, and liners to the cooling system. Around one fifth of the energy which is produced goes to the coolant. Figure 5 shows the energy balance of a cylinder unit.

Energy is saved directly by thermal insulation of the hot parts, because more of the energy produced is mechanically used. Indirectly, the increased heat in the exhaust gas is transformed into additional power by turbocompounding. Ultimately, engine manufacturers would like to design an adiabatic turbocompound engine without a cooling system.

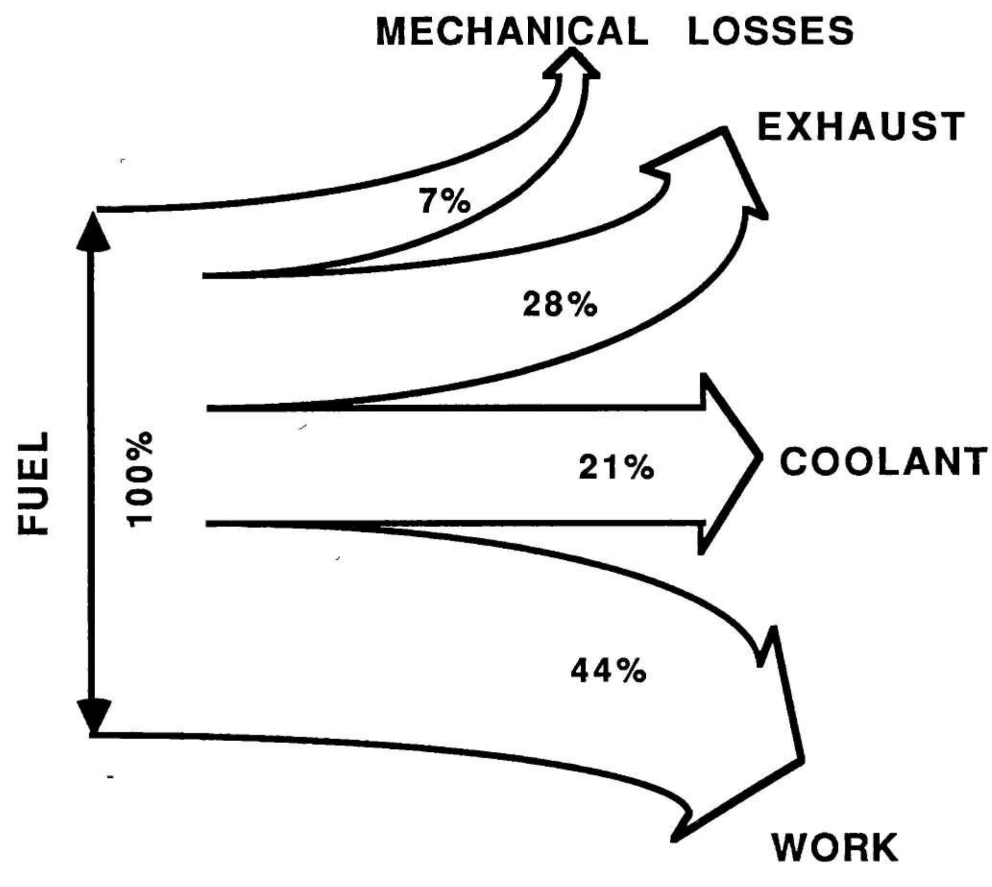


Fig. 5. Cylinder Unit Energy Balance.

4.1.2 Thermal Barrier Coating

In the Mercury Space Capsule Program of the 1950s, N.A.S.A introduced Thermal Barrier Coatings (TBC) to heat shields and rocket engine parts. The technology was pursued in applications to military aircraft and land-based industrial turbines. However, the emergence of competing technologies, including structural ceramics, had slowed the development of TBC in the past ten years. Only recently, with research programs like the study of plasma-sprayed ceramic coatings at the NASA Lewis Research Center in Cleveland, Ohio,(15) has the technology regained the interest of researchers.

Most TBCs consist of a two-layer system composed of an insulative ceramic coating attached to an underlying metallic bond coating. The thickness varies from 0.012 inch (0.3 mm) up to 0.25 inch (6.4 mm) for ultra-thick TBC. State-of-the-art thickness for diesel engine coatings ranges between 0.039 to 0.15 inch (1 to 3.8 mm). One fifth of the coating thickness is composed of a metal bond which functions primarily to avoid a thermal expansion mismatch between the oxide coating and the metal substrate. In addition, the bond coat must be oxidation and corrosion resistant at the metal operating temperature.

The ceramic coating is 10% to 15% porous to accommodate changes in the coefficient of thermal expansion, and to give increased thermal barrier efficiency. Figure 6 shows the insulative nature of a TBC: since the temperature drops in the ceramic layer, thermal stresses in the metal component are reduced. The engine can be operated at higher combustion temperatures, which significantly increases the thermodynamic efficiency of the system. The TBC protects the metallic component from the corrosive environment of the engine. Protection is twofold:

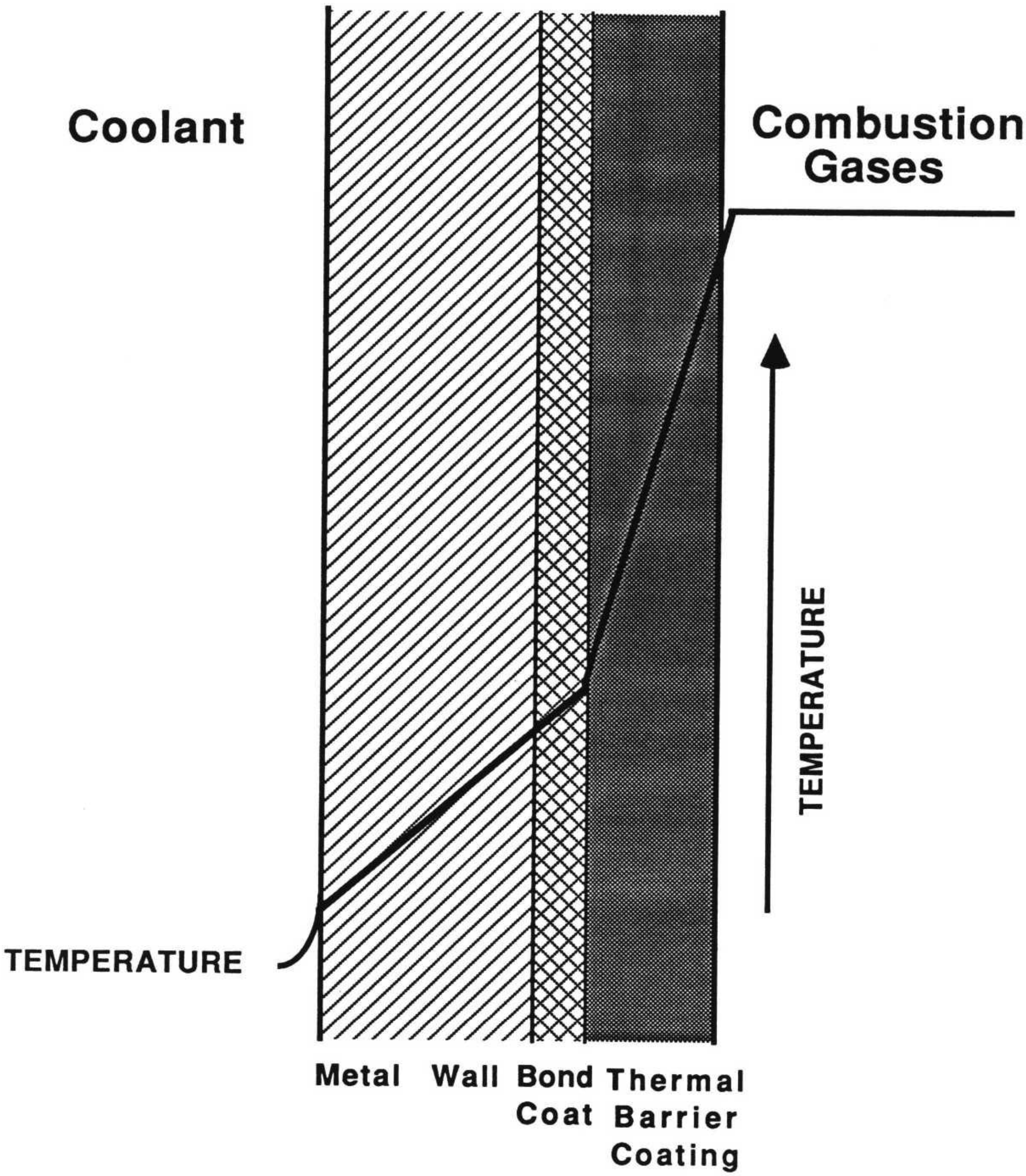


Fig 6. Schematic Representation Of A TBC- Bond Coating System, Indicating The Temperature Profile On An Air-cooled Engine Component.

the ceramic coating not only acts as a barrier to the corrosives, it also lowers corrosion rates by lowering metal temperatures.

4.2 Applicability of the Plasma-Spray Technique to Thermal Barrier Coatings

4.2.1 Material Properties

The use of ceramics to overcome the problem of oxidation has been promoted for high temperature applications. However, not all ceramics meet this criterion, and materials scientists are now choosing from the large category of oxides. High thermal resistance is another constraint that limits choice. Other fundamental requirements (16) of the material used for the thermal barrier are as follows:

- sufficient inertia,
- adequate mechanical strength,
- similar thermal expansion coefficients with the adjoining metal,
- high resistance to thermal variations.

Zirconia is preferred over materials such as silicon carbide and silicon nitride. Tungsten carbide demonstrates excellent abrasion resistance up to 1500°F, but the different coefficients of expansion between the ceramic layer and the metal induce failure at high temperatures. The development of TBC has been 90% based on plasma-sprayed ZrO_2-base materials, which have been successful because of their low thermal conductivity and relatively high coefficient of thermal expansion.

The three phases that pure zirconia exhibits (monoclinic, cubic, tetragonal) depend on temperature. Changes in volume, which go as high as 10% in the transformation between the phases, induce major flaws in the material and spallation of the coating. This problem can be avoided by doping the zirconia with CaO, MgO, or Y_2O_3. TBC technology recognizes yttria as the state-of-the art additive, and the optimum amount of stabilizer is thought to be around 8% mole. The material finally obtained is Partially Stabilized Zirconia (PSZ).

If ceramicists want to achieve high quality coatings, they must be very attentive to the powder specifications of the material they have chosen. The following powder properties must be considered:

- particle size and shape,
- chemical composition including contaminant concentration,
- flowability,
- moisture content.

Ceramists are more and more concerned with the microstructure of powders. Commercial users of ceramic coatings seem to share the same interest, since it has been demonstrated that coating reliability depends greatly on control over material properties.

4.2.2 Substrate preparation

Before coating the part, the substrate surfaces are degreased and blasted with Al_2O_3 grit. Unlike other plasma-sprayed coatings, TBC uses an intermediate bond coating between the substrate and the ceramic layer. The bond coat is typically composed of a MCrAlY alloy , where M = Ni, Fe or Co. The bond coats can either be sprayed like the ceramic, or applied in a low-pressure vacuum chamber. The low-pressure method achieves higher coating densities and prevents the particles being sprayed from oxidizing. This process costs more in equipment and gas; it is debatable whether or not it is worth the extra cost. The computerized cost model avoids this problem by including the bond coat as part of the ceramic coating. A 4 mm PSZ coating on top of a 1mm MCrAlY bond coat is converted to a 5 mm PSZ coating. Since the alloy powder and zirconia are about the same price, the extra cost of low-pressure plasma-spraying as well as the downtime between the two different processes are neglected in this simplification. For a more detailed cost evaluation, one can run the program twice, adding optional equipment to each, e.g., one run for the 4 mm PSZ coating, and one run for the 1 mm MCrAlY bond coat with optional vacuum chamber.

4.2.3 Coating

The characteristics of a TBC are created by adjusting the deposition parameters. The porosity, for example, is controlled by varying inputs such as powder feed rate, gas flow rate, the temperature of the substrate, and other parameters influencing the coating properties. Experimental plasma-sprayed samples are needed to determine the optimal deposition parameters; only then can production start.

4.2.4 Finishing

Grinding the ceramic coating to the 5 micron range gives a polished surface to the component, and helps to meet the dimensional tolerances of the part, particularly for components like pistons with binding requirements. The grinding step may also be motivated by aesthetics: engineers like components polished even if no engineering value is added to the part! However, one must be careful not to introduce unwanted microcracks in the finishing stage of coating.

4.2.5 Fabrication feasibility

Once the optimal spraying parameters are set, the emphasis is on the reproducibility of the process. Two types of equipment achieve better reproducibility:

- Closed-loop systems that control inputs both in the process and coating parameters;

- Robot-aided plasma-spraying equipment that prevents process interruptions and coating failures due to operator fatigue.

The coating is a two-part component integrating a ceramic layer and a metal substrate. Even if the thermal mismatch discussed earlier can be overcome, sudden changes in substrate geometry must be avoided. Sharp corners, edges, and deep pockets may subvert uniformity in the ceramic coating. A rule of thumb states the cavity interior can be reached if its depth is equal to its diameter (17), i.e., angle of impact of 45°. In the case of the piston cap, the rather flat geometry of the top part avoids this problem -- though it is advisable to consider the piston top periphery as a critical edge.

Finally, materials scientists recommend a diagnosis of the coating microstructure. TBCs require the right amount of porosity to establish a trade-off between thermal insulation and microcracks. A close look at the microstructure can help to define the porosity content and its distribution.

Unfortunately, no remedy has yet been found to solve the major problem with TBC, hot corrosion. The coating can degrade as a result of dissolution of the yttrium stabilizer from the presence of vanadium oxide (V_2O_5) in the fuel, which causes a destabilization of the PSZ ceramic (18). Moreover, recent work conducted by S.L. Shinde et al. of Lawrence Berkeley Lab, Materials Div. shows that TBC failure is generally due to oxidation of the bond coat, leading to the coating failure near the ceramic-bond coat interface. Now that the location and the reasons for chemical degradation have been determined, oxidation resistance needs to be developed in the materials. For example, the NASA Lewis research center has substituted ytterbia for yttrium in the ceramic top coat and ytterbium for yttrium in the bond coat, reporting a doubled-life improvement (15).

The reliability of the coating is crucial, because if the coating fails, the component itself may break. This consideration is discussed in the following chapter.

4.3 Engineering Analysis

4.3.1 State of the technology for pistons

A properly designed piston can contribute significantly to efficiency. Pistons are commonly made of alloys such as aluminum and silicon, and they are usually cast in a mold, a process that has been used for years. The advantages of aluminum-based materials can be described in terms of castability, machinability, density and thermal conductivity. The choice of aluminum is not purely a matter of reducing weight and inertial forces, important as these are in fast-running engines. The higher thermal conductivity of aluminum, about 117 W/mK compared to 20 W/mK for gray iron, allows a better heat flow through the piston, and reduces the temperature of the material by 200°C compared to a ferrous component. However, aluminum strength falls off rapidly above 390°F and at 900°F the aluminum alloy has little strength (19).

In addition, when an aluminum piston runs in a ferrous bore, its higher thermal expansion may present another drawback: the coefficient of thermal expansion of aluminum alloys varies from 19 to 25×10^{-6} per °C, whereas that of cast iron is 11×10^{-6} per °C . Therefore, lightness may be sacrificed to ensure both mechanical strength at high temperatures and thermal expansion compatibility. A stronger cost-effective design may be needed. The other approach to the problem would be to coat a ferrous piston with ceramic in order to:

- give mechanical strength to the bulk material,
- avoid a thermal expansion mismatch within the engine,
- restrict the heat flow from the combustion gases into the piston without dangerously increasing the metal temperature.

4.3.2 Coating technical performance criteria

Coatings must perform many functions to increase engine efficiency and reliability. Typical functions include thermal insulation, erosion and corrosion resistance, and coating adherence.

a) Thermal insulation

The ceramic material must combine a low thermal conductivity with great resistance to thermal shock. Stabilized zirconia has unique properties as a thermal insulator, because ceramic silicon nitride can have a coefficient of thermal expansion as high as 20 W/mK, while plasma-sprayed PSZ is measured to about 1.5-2.4 W/mK (20). Moreover, the coating is exposed to thermocycling due to the interrupted combustion process occurring in diesel engines. The ceramic must withstand both variations in temperature of some 10 °C and pressure that can range up to 2000 psi. Resistance to thermal shock can be reached by controlling the plasma-spray deposition parameters and thus achieving a satisfactory microstructure of the coating.

b) Erosion and corrosion resistance

The gas stream can mechanically wear out the ceramic coating, but hot corrosion is still the number one problem for TBC. During the combustion process, the ceramic coating is surrounded by fuel with higher corrosive content than gasoline. As discussed previously, yttria in the stabilized ceramic is attacked by impurities such as vanadium. In addition, the presence of different impurities in the fuel may breed synergistic corrosion, e.g., vanadium in combination with sodium presents a potentially serious problem. Since scientists have demonstrated that the primary failure occurs by oxidation of the bond coat, thicker coatings in diesel engines minimize the corrosion problems.

c) Coating adherence

Most TBC research has been developed in the aircraft and gas turbine industry. Aircraft turbines can afford intensive overhaul every 3000 hours of operation. As soon as failure between the aluminum part and the ceramic layer is detected, the part is coated again. Little research has therefore been conducted on long-term ceramic coating adherence for aluminum-based substrate. Adherence can be easily and quantitatively evaluated by a simple bend test. The data base for aluminum users is insufficient compared to the amount of information on the adherence of ceramic coatings to steel that is available to gas turbine manufacturers. Reliability is imperative for the ceramic coating, because if the TBC detaches from the coating, the part underneath may weaken and break, leading to severe damage to the engine itself.

4.3.3 Utility definition

The following analysis not only attempts to review the range of advantages of a TBC on a piston cap, but investigates whether this is an economically desirable solution, compared to redesigning or replacing the piston more frequently.

The manufacturer will judge the relative importance of the advantages offered by an insulating layer, based on the priorities in the diesel engine. The benefits of insulation are listed below:

- Better fuel economy

In a joint program of the U.S Army Tank Automotive Command and Cummins Engine, pistons as well as valve heads and cylinder liners of a 5-ton Army truck were coated with fully stabilized zirconia. The engine proved to run successfully over 15,000 km. Assuming reliable performance, almost 5,600 gallons of fuel could be saved over a lifetime in 2,500 hours of operation per year, according to Cummins Engine. On the other hand, Ford Motor Co. developed an experimental single-cylinder engine in which heat loss was reduced by 30%. The study also demonstrated a drop in fuel consumption of 9%.

A simple calculation evaluates potential fuel savings from adiabatic diesel trucks in the U.S, given the following assumptions:

U.S truck production: 3,207,000 units per year.(21)

Percent penetration of adiabatic diesel on new trucks: 5%.

Time of operation per year: 2,500 hours.

Average speed: 55 mph.

Energy intensity: 13,439 BTU/vehicle-mile (22).

Diesel oil energy content: 138,000 BTU/gallon

Percentage savings in fuel consumption per engine: 9%.

The computation shows 1205 gallons of fuel saved per year per new adiabatic diesel truck. On a global basis, 193 million gallons of diesel fuel would be saved per year in the United States. The result, however, should be viewed as a rough estimate, given the uncertainty on fuel consumption savings and market penetration of adiabatic diesel engine. In addition, the analysis makes no distinction between heavy and light trucks. This figure gives magnitude to fuel consumption savings, on both a national and unit scale.

- Increased power output

Engine manufacturers do not agree on how much power is generated from increased temperatures in the combustion chamber. On the one hand, Toyota Motor Corporation claims an increase in the temperature of the combustion chamber from 925°C to 975°C raises the power output by 10%. And on the other, J.M. Guillemot et al.(2) reports that with 100% insulation the direct increase in efficiency is approximately 1%, the greater part of the energy gained being transferred to the exhaust gas. The most profitable solution would be to recover the energy contained in the exhaust gas by turbocompounding, assuming the cost-effectiveness of the investment. In this way, an improvement of up to 7.5% in overall efficiency could be achieved.

In my opinion, increased operating temperatures can do no harm to the overall efficiency of the engine, and may even bring substantial improvements under certain conditions. However, better engine output should not become a priority goal for thermal insulation.

- Smaller cooling system

A smaller cooling system not only reduces the fabrication cost of the engine, but the lower weight saves fuel. The Cummins Army truck was designed without a cooling system; no doubt the elimination of an apparatus that is often unreliable during tactical exercises presented a major incentive to the use of a 100% insulated engine.

- Less corrosion

For years, corrosion in energy systems has been a major concern for engine manufacturers. Gas turbines and diesel engines present arduous conditions for metals. One way of retarding hot corrosion and/or oxidation is to plasma-spray a ceramic layer of an appropriate thickness. Stabilized zirconia TBC demonstrably extends the component lifetime. The ceramic protection makes the engine less sensitive to fuel quality, and fuels containing larger amount of impurities can be used. In the long run, TBC technology may even meet the technical criteria for the use of alternative fuels, such as powdered coal or blends of ethanol with gasoline.

- Lower emissions

Few quantitative data are available on carbon monoxide and noise emissions when the operating temperature increases. It is a common thought among engineers to reduce the CO concentration in the exhaust gas. However, the noise problem has not been investigated clearly. Moreover, NOx concentrations seem to increase at the higher exhaust gas temperature. Although the literature and engineering reports agree on the overall benefits, the precise relationships between burning fuels at higher temperatures and reduction in toxic emissions should be assessed.

- Metal substitution

Economically, the ceramic coating is strictly value-added to the overall cost of the piston. However, if one considers the coated piston as a two-part system, this extra cost may be partially recovered by using a cheaper bulk material in the part. Chapter 4.3.1 showed material substitution from aluminum to iron makes sense from an engineering point of view. The following table evaluates a material substitution in the heavy duty diesel piston, the one used in the cost model, from the viewpoint of potential dollar savings:

Metal	Aluminum	Grey iron
Cost	$0.90/lb	$0.22/lb
Density	0.10 lb/cu.in.	0.28 lb/cu.in.
Part volume	74 cu.in.	74 cu.in.
Scrap rate	10%	10%
Total metal cost	$7.32	$5.01

Chapter 4.4.3. will compare the importance of these material savings to the cost of coating.

All the benefits should not be taken in an absolute sense, but rather compared to alternative solutions. Replacing the part is one of them. The common argument against part replacement is that it is often cheaper to recoat a worn part than to replace it. In some cases, a new design of the component may, in fact, be more effective than ceramic coatings.

New process technologies should be also considered. The squeeze casting of metal matrix composites is an example of a new technology competing with TBC in diesel piston applications. Potential gains from materials reinforcement overlap many of those stated in this chapter, e.g. wear resistance, thermal conductivity, thermal expansion, etc.(23)

4.4 Cost estimation

4.4.1 Overall cost calculation

The appendix contains a hard copy of the Lotus 123 spreadsheet representing the cost model. Inputs are differentiated from results by bold characters.

The model estimates the cost of coating a heavy duty diesel piston with a diameter of 5.5 inches, which is the type utilized on the large trucks that represent a high volume market for diesel engines. Preliminary questions will define characteristics of the coating, such as its surface area, thickness, and density. These inputs were chosen in a conservative way, given the usual features of a TBC, i.e. 1mm thick and 10% porosity.

In addition, the model asks the user the number of parts to be coated, and whether masking and finishing are needed. In order to use the coating equipment at full capacity, the number of parts was limited to 80,000 pistons which is a fair number to start a prototype production using only a single manufacturing line. If larger production volumes are needed, one can purchase an additional set of plasma-spraying equipment but keep the other pieces working at higher rates. Thus, economy of scale for capital investment could be achieved by increasing equipment utilization.

Given the specifications of the part, masking is not necessary on a piston cap. Masks are used essentially to protect specific areas from the ceramic powder and from being warmed up by the plasma gas. In this case, TBC would cover the entire surface and no protection seems to be needed. If a masking step were required for other coated parts in diesel engines, there would be substantial additional costs for labor and process materials. However, the model includes a finishing step: the amount of ceramic material removed to meet the dimensional criteria is equivalent to 1% of the overall coating thickness.

The other inputs are distributed all over the spreadsheet and can be divided in 3 categories:

- Capital and process materials costs, as collected from plasma-spray equipment manufacturers.

- Inputs imposed by specifications of the powders and equipment, e.g. powder feed rate.

- The last category includes the inputs that relate to the specific application, left to the judgment of the user.

Work-times for the different operations are proportional to coating time by a factor defined as the ratio of operating time to coating time. In other words, the user evaluates how much time a worker should spend at a specific stage of the process, compared to the time it takes to coat a part. Because of TBC thickness, coating time is relatively long. Therefore, time ratios in steps other than coating are low. The time needed for grit blasting the substrate is independent from the coating thickness. Thus, the ratio of blasting time to coating time is equal to 0.2, but should approximately double if the coating thickness is halved. On the other hand, the ratio of work-time to deposition time should be rather high during the coating step. Even if the process is fully automated, an operator must definitely allocate 50% of his time to control the process.

Given the technical statistics available, the user must estimate the percentage of parts rejected. Those parts will be grit blasted and coated again. Therefore, the additional cost of the recycling option is proportional to the percentage of rejected parts. It may appear difficult to assess such a number since TBCs have not yet been manufactured on a large scale. However, rejection rates inferior to 1%. are reported for the the majority of plasma-sprayed ceramic coatings in other applications. The model considers a conservative figure which equals two times the value of what is commonly estimated as an upper limit.

Once the inputs are properly introduced, the model computes an overall cost of $8.35 per part. However, this value synthesizes the cost of a wide range of inputs, and they need further analysis to get a better understanding of their share in the overall cost.

4.4.2 Cost distribution

The piechart presenting the repartition of cost per process step leads to several comments:

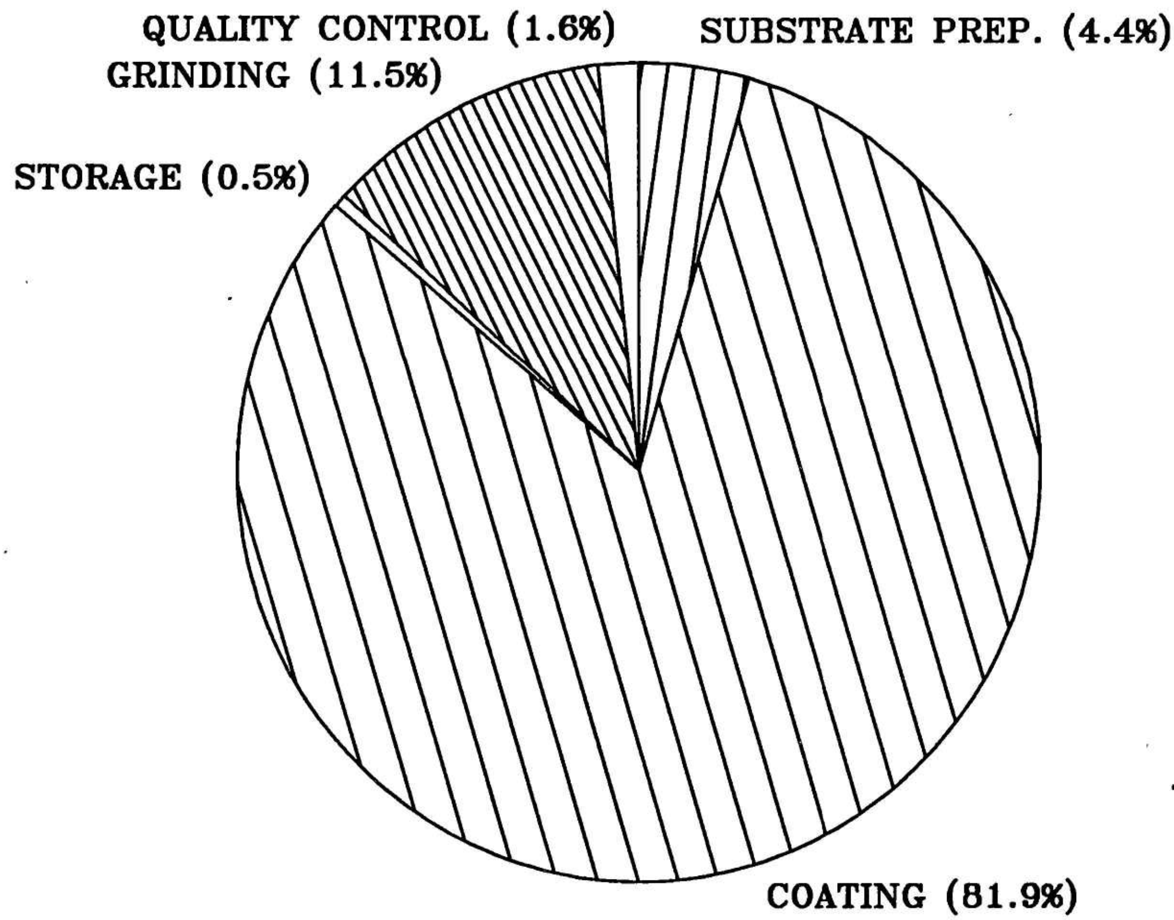
- The coating stage accounts for more than 80% of the overall cost. Even though the other steps are fundamental to achieve coating reliability, they do not account for a large share in the overall cost. As plasma-sprayed coatings manufacturers are very cost-conscious, they focus on coating stage efficiency. Thus, their efforts are directed towards improvements in equipment reliability and ceramic powder properties. The coating stage includes the entire cost of inputs such as powders and gas. In addition, a fair amount of labor is needed to control inputs and coating characteristics during the process.

- The dollar value of process steps like substrate preparation and quality control may seem underestimated. None of them actually is. Substrate preparation assembles two steps, vapor degreasing and grit blasting, that are straightforward and relatively inexpensive compared to masking. On the other hand, quality control contains expensive labor and equipment costs, but no input factors. Therefore, the costs are rapidly paid off on a large production scale.

- Grinding accounts for 11.5% of the total cost. This step appears to be compulsory for the piston to reach dimensional tolerances but may well be optional for other parts of the engine. Manufacturers may envision automation of the grinding step for potential labor savings.

REPARTITION OF COST PER PROCESS STEP

Plasma–sprayed TBC



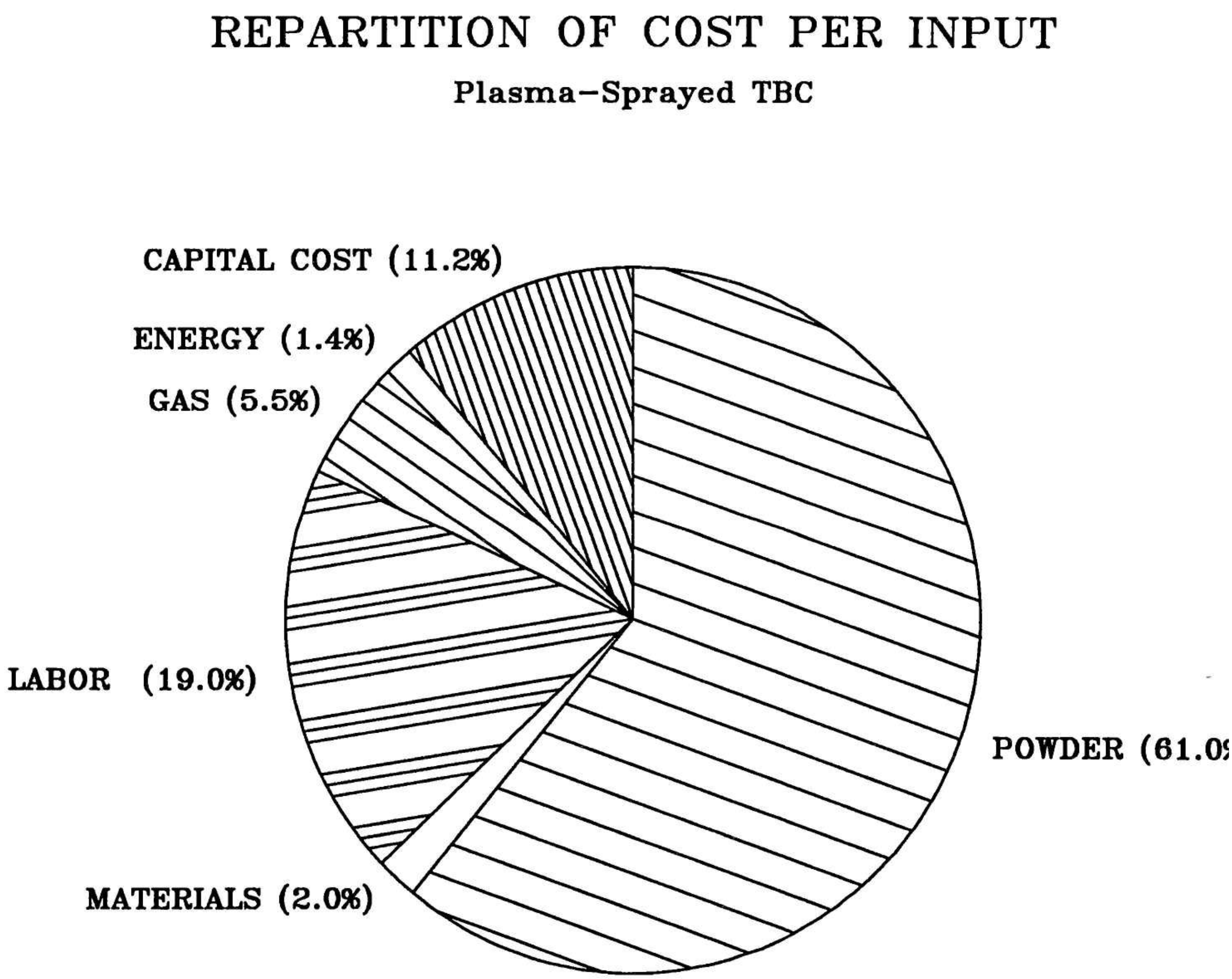
The piechart describing the repartition of cost per input is, in many ways, illuminating:

- As far as inputs other than powder are concerned, costs as estimated in the model are reasonable. Since the process is globally semi-automated and composed of many different steps, it seems difficult to imagine labor cost under the computed value of \$1.59 per part. Nevertheless, complete automation of the process remains a future, workable project which would bring about both labor savings and process reliability.

Energy, gas and process materials account for \$0.73 altogether. The plasma-spray process has the advantage of being less energy-intensive than structural ceramics forming processes, which include a sintering step. Even though almost 4 cubic feet of gas per part are used to carry the powder and create a plasma, argon is cheaply available.

Finally, capital costs account for less than \$1, given the accounting assumptions of the model. However, this value may be underestimated because the % utilization of quality control and substrate preparation equipment is low. In other words, the model assumes this equipment may be used in a different manufacturing line during operation time. This may not be the case, though, and the total equipment cost may be reevaluated up to 50% of its current value. In the worse case, this would mean less than a \$0.50 increase in capital cost.

- Powder cost is, by far, the largest input in terms of money value. Three fundamental reasons that ceramic powder accounts for 61% of the total cost are:


REPARTITION OF COST PER INPUT
Plasma-Sprayed TBC
CAPITAL COST (11.2%)
ENERGY (1.4%)
GAS (5.5%)
LABOR (19.0%)
MATERIALS (2.0%)
POWDER (61.0

1) TBC are very thick ceramic coatings,

2) Deposition efficiency is relatively low for Partially Stabilized Zirconia (more than 35% of the powder is not deposited onto the substrate).

3) Ceramic powder producers charge high prices for zirconia powders because of the low volume of manufacture.

The total cost of the TBC has been detailed in order to investigate which improvements will lead to significant savings.

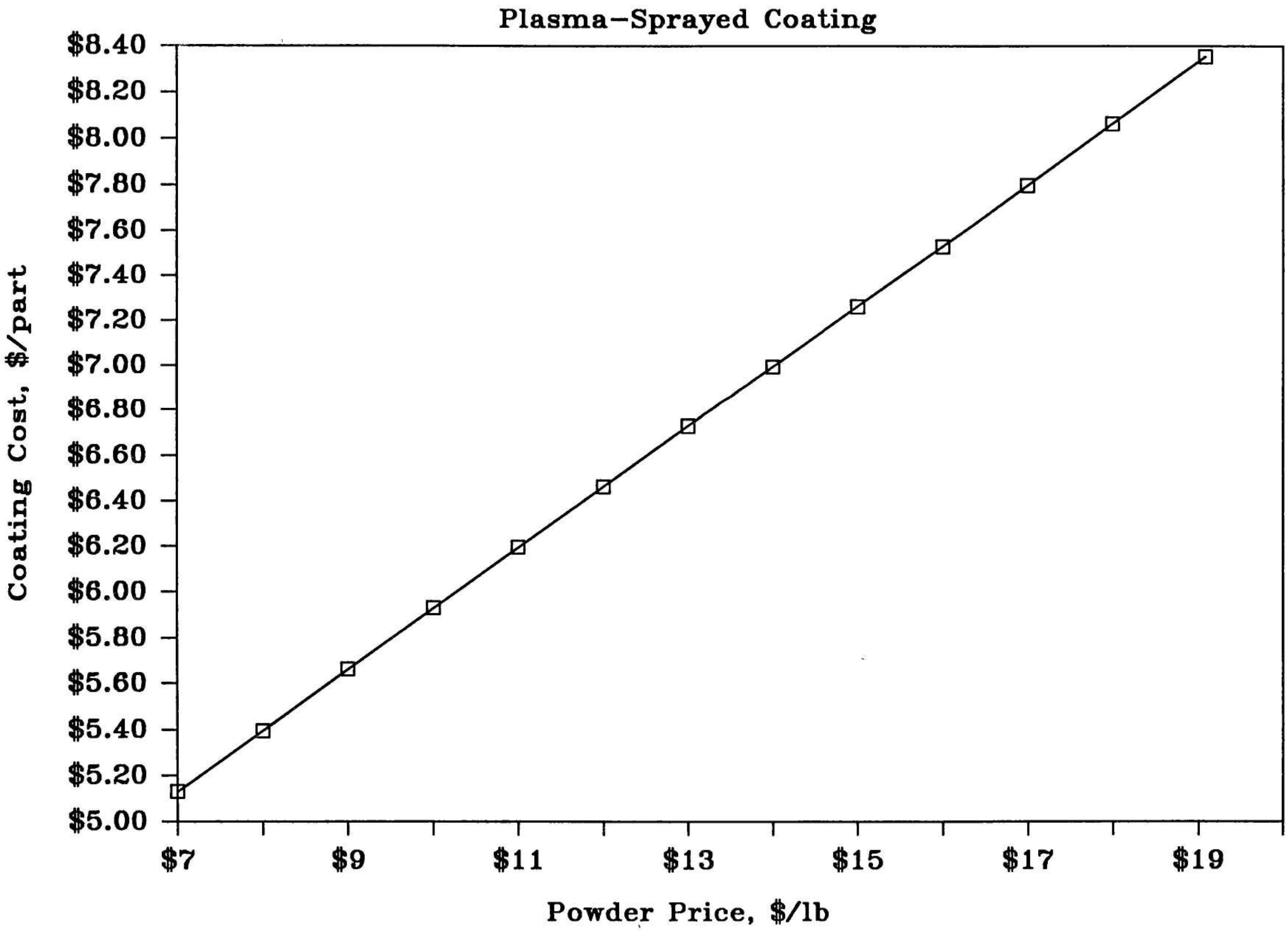
4.4.3 Possible improvements

As mentioned above, PSZ price per pound would drop if large amounts of this powder were produced, but the current market for zirconia powder is limited to niches. Those powder manufacturers who make zirconia agree that cost could be decreased up to 50%. If we assume a conservative diminution of PSZ price by 40% ($11/lb instead of $19/lb) the graph presented on the next page shows TBC costs go down to $6.20, a drop of 26%.

Chapter 4.3.3 reports that a material substitution from aluminum to gray iron in pistons may be appropriate if the component is properly insulated, to create a $2.31 savings per part. Therefore, one could achieve a 27% reduction by including these savings in the coating cost calculation.

Increasing the degree of automation in the process can yield better productivity while providing improved quality in the coatings. Both labor and ceramic material is saved by reducing overspray, which causes a 5% loss in

TBC COST VS. ZIRCONIA POWDER PRICE



material. The current deposition yield (64.7%) may also be improved through better regulation of the inputs flow.

All the above improvements may not be reached simultaneously but are more effectively implemented on a large scale production line. The total cost of a TBC computed by the model should not be taken for granted since significant cost savings can be achieved.

4.5 Applications

4.5.1 Market assessment

The current market for TBC in diesel engines cannot be assessed. Ceramic coatings applications for thermal insulation are limited to aircraft engine and gas turbines. The implementation of TBC may be slowed down by the technical problem of achieving 100% reliable ceramic coatings. Besides, TBC will be opposed by competing alternatives that use alloys with intrinsic resistance. Moreover, TBC should be used after a cost-benefit analysis to compare it with more frequent component replacement.

Prospects are optimistic because numerous programs on TBC are at work all around the world. Australians recently have run busses powered by diesel engines with critical parts that have been plasma-sprayed with ceramics. Many people seem excited by TBC applications in diesel engines, feeling that ceramic coating technology will reach full maturity. According to Charles Kline & Co, Fairfield, N.J., the automotive engine market for ceramic coating materials is expected to grow annually by 25% over the next ten years. It would thus be one of the largest application for ceramics. Regardless of reports that may look too optimistic, everyone seems to agree that ceramics have a great future in engines.

Problems arise when one investigates the respective market shares of ceramic coatings and monolithic ceramics.

4.5.2 Ceramic coatings vs. structural ceramics

A school of thought among ceramic scientists states that coatings are transitory and structural ceramics are the preference for the future. The argument goes: coatings are not as impermeable nor thermally shock resistant as monolithic ceramics; weight reduction cannot be achieved in engines since the bulk material of the coated part remains metallic (monolithic ceramics are a definite advantage in turbochargers).

These remarks are arguable in a technical sense, but must be revised when it comes to economic considerations. The coated metal part can trade its lower thermal shock resistance for a higher strength and toughness. Monolithic ceramics would hardly find a market where impact damages may cause catastrophic results. Using coatings gives better control of final dimensions, while variable shrinkage occurs during sintering of the all ceramic part, which then requires a costly machining step. Moreover, Julie M. Schoenung (24) showed lower raw ceramic powder prices are required to reduce costs if structural ceramics are to become competitive. Materials accounted also for a large share of the total TBC cost. However, structural ceramic parts contain more expensive ceramic materials than the identical metallic component coated with a 1 mm thick layer. Structural ceramics suffer from the material cost comparison with metals, but ceramic coatings do not.

For all the above reasons, ceramic coatings should find earlier commercial applications than monolithic ceramics; a significant market already exists for applications in aircraft engines and gas turbines. On the other hand, structural ceramic applications in engines require a long-term commitment. Going first for ceramic coatings does not preclude, however, the advance of structural ceramic forming technologies. On the contrary, commercial development of ceramic coatings should be taken as a learning phase towards complete understanding of ceramic powder properties.

4.5.3 Implementation of fuel economy regulations

1In the early 1960s, the automobile industry was virtually an unregulated industry. Public awareness of energy consumption problems arose after the 1973 oil crisis. All American automobile firms agreed on the President's plan to increase fuel economy, although they did not anticipate that the government would set efficiency standards for automobiles. The Energy Policy and Conservation Act of 1975 set a goal of 27.5 miles per gallon for average fuel economy of new automobiles by 1985, and gave the Secretary of Transportation the responsibility of establishing the "maximum feasible average fuel economy standards for 1981-1984 cars" taking into consideration:

1) the technological feasibility,

2) economic practicability,

3) the effect of other Federal motor vehicle standards,

4) the need of the Nation to conserve energy.

First, the auto industry down-sized cars: by 1984, cars were 67% more energy-efficient than the average car on the road in 1973 (8). Though this has been a tremendous achievement for American automobile manufacturers, improvements are still necessary. In most cases, it is now technically more difficult to achieve significant energy savings. The automobile industry finds an escape in the economic practicability clause, which takes into consideration economic costs and benefits, effect on R&D in the automobile industry, and effects on competition.

Moreover, consumers do not act as an active interest group in the issue because they fear the cost of making more energy-efficient cars may be passed on in the form of higher prices and higher taxes.

As well, politicians will not seize on the old issue of energy conservation and make it their own. They prefer more appealing issues where media attention has not faded away. As James Wilson points out (25), it is not because of the incompetence of the regulators that regulations imposed on American business fail, but because of the political system constraints placed on the regulators. The political system is dominated by interest groups which do not have strong incentives for making more energy-efficient cars.

4.6 Conclusions and Future Developments

The prevailing approach of the U.S. automobile industry is to wait and see if a market niche for ceramics develops before investing heavily in this technology. Meantime, the Japanese incorporate structural ceramics in prototype engines. The auto industry might be persuaded to believe in TBC as a long-term alternate to structural ceramics. Work on ceramic coatings is in its infancy compared to the amount of effort that has been expended on metallic coatings. Current technical problems, particularly in TBC self-reliance, could be overcome with proper R&D programs.

This chapter has evaluated the cost of using TBC on large diesel pistons. It shows that, even though it appears as an expensive value at first sight, the total cost can be significantly reduced. In order to achieve a complete cost-benefit analysis, further work could assess quantitatively the benefits of insulating engine parts. Thus, automobile manufacturers would have useful elements to judge whether TBCs are worthwhile.

The automobile industry should be a major participant in the development of TBC technology but not the only one. In order to help commercialization of ceramic coating technology, the government could fund R&D programs or subsidize implementation of TBC in car engines. In the top industries, you find that automobile industries and oil companies are both concerned with energy consumption. One can envision a joint program where not only investment but experience in fuel-burning engine technology would be shared.

5. CONCLUSIONS

The proposed methodology included:

- An overview of the coating technologies, and their applications.
- An explanation of the plasma-spraying process and an evaluation of its cost by means of a computerized model.
- An analysis of the implementation of plasma-sprayed TBC on top of a piston.

Even though the specifications of the application greatly influences the choice of the deposition technology, plasma-spraying can apply a variety of materials on almost any substrate, and provides high rate of deposition and good coating to substrate adherence. However, the development of plasma-sprayed ceramic coatings has been largely empirical over the last thirty years, as an understanding of the chemical and mechanical phenomena involved with the process is lacking (26). Relationships between factors of the plasma-spray process and properties of coatings need to be established. Plasma-sprayed ceramic coatings are still in their infancy compared with the development of metallic coatings. Thus, intensive fundamental research programs must be conducted if plasma-sprayed ceramic technology is to emerge from art to science.

If the process is feasible, the cost model is a useful tool to view the economics of plasma-sprayed coatings. The plasma-spray industry testified that costs were difficult to determine at best, and that a common practice is to rely on rules of thumb to approximate processing costs. The model not only provides the overall cost but also the distribution of cost per input, and per process step. The analysis reveals that the process is in many ways labor intensive, and emphasizes the need for automation to reduce processing costs and improve coating quality.

Another major cost on top of labor is raw materials. Many of the powders are produced in small volumes, resulting in high selling prices. However, a recent trend towards lower powder prices may encourage the development of ceramic applications. The relatively low deposition efficiency of the plasma-spray process contributes to high powder costs as well. More than one-third of the powder is usually wasted. Increasing the spraying efficiency while maintaining the coating quality should be a high priority to achieve cost effectiveness.

In addition to primary fabrication costs, the model evaluates the costs of the grinding and masking operations, which may be used in conjunction with other processes.

Thermal Barrier Coatings currently experience failures due to oxide-layer growth near the bond-coat/ceramic coating interface. Technical problems could be overcome with proper R&D programs. Benefits from insulating an engine component with a ceramic coating have been demonstrated, but further work is needed to assess quantitatively those benefits. Because TBCs are essentially thick, to use ceramic materials is not cost-effective. TBC may be an opportunity for automobile manufacturers interested in ceramics, which are conscious of the risks comprised in structural ceramic development programs. Research on ceramic coatings may also yield a better understanding of brittleness in monolithic ceramics.

Nevertheless, the results of this case study should not preclude investigation of thinner coating applications, some of which have already demonstrated their cost-effectiveness. Many others are under development, and future markets like superconductors, biological implants, and engine applications will offer a high-technology future to plasma-sprayed ceramic coatings.

BIBLIOGRAPHY

1. "Deposition Technologies: An Overview," Rointan F. Bunshah; Deposition Technologies for Films and Coatings edited by Robert C.Tucker. Noyes Publications.

2. "Plasma and Detonation Gun Deposition Techniques and Coating Properties," Robert C. Tucker; Deposition Technologies for Films and Coatings. Noyes Publications.

3. "Functionally Effective Coatings Using Plasma Spraying," M. Villat. Sulzer Technical Review 3/1986.

4. METCO Plasma Spray Coatings Applications, Bulletin 267.

5. Department of Commerce, Bureau of the Census, Census of Manufacturing, Fuels, and and Electric Energy Consumed (1984).

6. "Plasma-Sprayed Alumina-Titania Composite," G. Durmann and F. Longo; American Ceramic Society Bulletin, 48 (2).

7. "Union Carbide Coatings - Service for Industry " Bulletin.

8. "Sprayed-on Ceramic Coatings Increase Furnace Life and Efficiency," John C. Hellander, Energy Management Technology, March 1986.

9. "Plasma Gas Facts," George M. Herterick; Product Data Sheet No ES-2, Bay State Abrasives/Dresser; Westborough, Massachusetts.

10. "Automation of the Thermal Spray Process," S.G. Lee and S. Safai; Advances in Thermal Spraying, p.197.

11. "Machining of Advanced Ceramics," Laurel M. Sheppard; Advanced Materials & Processes, Volume 132 Issue 6, December 1987.

12. Pressure Sensitive Industrial Tapes. T & F Division of CHR Industries, Inc. Rolling Meadows, Illinois.

13. " Diamond Wheel Grinding of Thermal Spray Materials," Robert B. Massad. Paper presented at the 1984 ASM Thermal Spray Conference; Long Beach, California.

14. 1-2-3, Lotus Reference Manual. Lotus Development Corporation, Cambridge, Ma.

15. "NASA Lewis Research Center Studying Plasma-Sprayed Ceramic Coatings," Metal Working News; September 21, 1987.

16. "Diesel Engine Combustion Chamber Insulation by Ceramic Plasma Spraying," J.M Guillemot et al., Materials Science and Engineering, 1987.

17. "Thermal Barrier Coatings for Reciprocal Engines," Doug Harris, APS-Materials Publication; Dayton, Ohio.

18. "Role of Coatings in Energy-producing Systems: An Overview," John Stringer, Materials Science and Engineering, 1987.

19. "Piston Design Plays Major Role in Fuel Economy," SAE paper, Automotive Engineering; December 1983.

20. "Coating of Diesel Engine Components," Ingard Kvernes; Coatings for High Temperature Components, edited by E. Lang, Applied Science Publisher; 1983.

21. Automotive News, p 47; November 2, 1987.

22. "Learning about Energy," David J. Rose, Plenum Press; 1986.

23. "Techno-economic Assessment of Metal Matrix Composite Piston Processing," Jeffrey E. Jacob, SM in Technology and Policy, M.I.T; June 1987.

24. "An Engineering and Economic Assessment of the Potential for Ceramics in Automotive Engines," Julie.M Schoenung, PhD Thesis in Materials Science, M.I.T; June 1987.

25. "The Politics of Regulation," James Q. Wilson in James McKie ed., Social Responsibility and the Business Predicament.

26. "Thermal Spraying Technology: From Art To Science," Edward J. Kubel Jr.; Advanced Materials & Processes, Metal Progress. December 1987.

Attendance to the 1987 National Thermal Spray Conference and Exhibition, Lake Buena Vista, Fla., 14-17 September, 1987.

APPENDIX

INSTRUCTIONS

* Select one option on the menu displayed in the control panel either by typing the first letter of the option, or by highlighting the option and pressing return.

* Press return to move on in the CMD mode.

* Change the inputs distinguished by bold characters, if wanted.

* Press Alt I if you want to come back to the Menu after you choose the Quit option.

Have fun!

COST MODEL FLOWSHEET

------->
FACTOR PRICES

Energy
Powder
Gases
Labor
Others

------->
CAPITAL INVESTMENT CALCULATIONS

1. Substrate Preparation
a) Vapor degreasing equipment
b) Grit blasting equipment

2. Coating
a) Basic equipment
b) Optional equipment

3. Grinding

4. Quality Control

5. Storage

------->
PRELIMINARY QUESTIONS

Surface area coated?
Coating thickness?
Coating density?
Surface area masked?
Number of parts?
Grinding depth?

------->
POWDERS CHARACTERISTICS

1.
Price
Density
Powder feed rate
Powder deposition rate

2.
Energy
Gas flow rate

------->
PRODUCTION INPUT FACTORS

1. Substrate Preparation

a) Masking and demasking
b) Degreasing
c) Grit blasting
d) Preheating with gun

COST MODEL FLOWSHEET

==

------->
PRODUCTION INPUT FACTORS

2. Coating

a) Powder
b) Labor
c) Energy
d) Gas
e) Nozzles
f) Air

------->
PRODUCTION INPUT FACTORS

3. Grinding

Labor
Energy
Wheels

------->
PRODUCTION INPUT FACTORS

4. Quality Control
Labor

5. Storage
Labor

------->
RECYCLING OPTION

------->
COST OF CAPITAL

------->
RECAPITULATIVE TABLES

Table 1: Repartition of cost per input.

Table 2: Repartition of cost per process step.

FACTOR PRICES

==

	Units	$/Unit
==========> ENERGY		
Electricity	Kw	**$0.0650**

	Units	$/Unit
========> MATERIALS		
1. Zirconia powder	lbs	**$14.60**
2. Partially stabilized zirconia powder	lbs	**$19.09**
3. Ni Cr Al Mo Alloy powder	lbs	**$20.50**
4. Chrome oxide powder	lbs	**$20.75**
5. Aluminum oxide powder	lbs	**$5.00**
6. Titanium dioxide powder	lbs	**$9.50**
7. Tungsten carbide powder	lbs	**$35.30**
8. Chromium carbide powder	lbs	**$14.50**
9. Nickel powder	lbs	**$12.80**
10. Aluminum powder	lbs	**$11.80**
Choose powder type by number --------->	**2**	**$19.09**

GASES

WORKING GAS		
1. Argon	Cubic foot	**$0.10**
2. Nitrogen	Cubic foot	**$0.04**

Choose plasma gas --------------------->1 **$0.10**

MIXING GAS	% VOLUME		
Helium	**0%**	Cubic foot	**$0.16**
Hydrogen	**0%**	Cubic foot	**$0.09**

Total cost of gas per cubic foot ------> $0.10

LABOR

Labor	$/man-hour	**$18**

OTHERS

Clean air	lbs	**$0.00001**
Nozzles		**$60**
Diamond grinding wheels		**$2,500**
Canisters (10)		**$1,000**

ACCOUNTING ASSUMPTIONS

Years to recover investment	**5**
Cost of capital (% of initial investment)	**10.0%**
Maintenance (yearly % replacement)	**4.0%**

CAPITAL INVESTMENT CALCULATIONS
==

1. Substrate Preparation

a) Vapor degreasing equipment		$10,000
You have the choice between three options : "vapor degreasing", "hand degreasing" and "no degreasing". If you choose the "vapor degreasing" option, you must turn the highlighted cell ON. (ON = 1 ; OFF = 0)	1	$10,000
b) Grit blasting equipment		
1. Automated		$20,000
2. Manual		$10,000
3. No equipment		$0
Choose type by number ---->	1	$20,000
		========
Total investment for step:		$30,000

2. Coating

a) Basic equipment		
Plasma gun		$2,990
Cable kit		$550
Powder feeder		$4,370
Flow switch kit		$400
********************************		
BOOTH		
Floor area		
1. 4' 6" x 11'		$5,700
2. 11' 6" x 11'		$9,000
Choose size by number ---->	2	$9,000
Plumbing expenses		$1,000
Booth ventilation		$1,500
Water chiller		$12,000
********************************		

POWER SUPPLY		
1. 40 Kw		$8,600
2. 80 Kw		$13,900
Control consol		
1. 40 Kw		$3,400
2. 80 Kw		$5,300
Choose power by number ---->	2	$19,200

b) Optional equipment
For each piece of equipment
desired, put ON next column.
(ON = 1 ; OFF = 0)

Robotized plasma-spray system	1	$120,000
Automated XY equipment	0	$0
Rotating equipment	0	$0
Canisters (10)	1	$1,000
		========
Total investment for step:		$172,010

3. Grinding

Grinding equipment	$70,000
Air compressor gun	$500

4. Quality control

1. Computer enhanced metallograph		$100,000
2. Basic metallograph		$10,000
Choose metallograph type ---->	1	$100,000
Bend adhesion tester		$200
Bond strength tester		$10,000
Tensile shear tester		$10,000
Others		$0
1. Mechanical dimensional measurement		$500
2. Electronic dimensional measurement		$5,000
Choose measurement type ---->	2	$5,000
		========
Total investment for step:		$125,200

5. Storage

Storage racks	**$1,000**

TOTAL CAPITAL INVESTMENT:

1. Substrate Preparation	$30,000
2. Coating	$172,010
3. Grinding	$70,500
4. Quality control	$125,200
5. Storage	$1,000
	========
TOTAL	$398,710

PRELIMINARY QUESTIONS (TYPE Alt.G IF NOT IN MENU)	ANSWERS
A] What is the surface area to be coated (in square inches) ?	**24** sq. in.
B] What is the thickness of the coating (in inches) ?	**0.0390** in.
C] What is the coating density (in %) ?	**90** %
D] What surface area has to be masked (in square inches) ?	**0** sq. in.
E] How many parts will you coat ?	**80,000**
F] What depth of removal is required on each part to reach the finished size (in inches) ?	**0.0004** in.

POWDERS CHARACTERISTICS

POWDER	PRICE $/#	DENSITY g/cc	POWDER FEED RATE #/hr	DEPOSITION RATE #/hr
1 ZrO2	$14.60	**5.32**	**5.2**	**3.0**
2 PSZ	$19.09	**5.30**	**5.1**	**3.3**
3 NiCrAlMo	$20.50	**7.03**	**10.5**	**7.1**
4 Cr2O3	$20.75	**5.60**	**6.5**	**4.0**
5 Al2O3	$5.00	**3.75**	**2.0**	**1.0**
6 TiO2	$9.50	**4.60**	**6.0**	**3.7**
7 WC	$35.30	**13.20**	**6.0**	**4.0**
8 Cr3C2	$14.50	**6.27**	**6.6**	**4.7**
9 Ni	$12.80	**7.65**	**8.6**	**6.1**
10 Al	$11.80	**2.33**	**6.6**	**4.4**

POWDERS SPRAY CONDITIONS

POWDER	ENERGY Kw	GAS FLOW RATE CFH
1 ZrO2	**30.6**	**80.5**
2 PSZ	**30.6**	**80.5**
3 NiCrAlMo	**30.6**	**89.5**
4 Cr2O3	**30.6**	**82.5**
5 Al2O3	**30.6**	**120.6**
6 TiO2	**30.6**	**82.5**
7 WC	**29.3**	**119.6**
8 Cr3C2	**30.6**	**80.5**
9 Ni	**30.6**	**80.5**
10 Al	**18.8**	**80.5**

PRODUCTION INPUT FACTORS

1. Substrate Preparation

a) Masking and demasking

	Cost of masking material per square inch	Ratio of masking time to coating time
1. No masking	**$0.00**	**0.00**
2. Tape masking	**$0.02**	**1.00**
3. Hard masking	**$3.00**	**0.20**

CHOOSE OPTION BY NUMBER ------------------> 1

Materials ----------------> $0

Labor --------------------> $0

Cost of masking per part ----------> $0.00

TOTAL COST OF MASKING --------------------------------> $0

b) Degreasing (Vapor or Liquid)

	Cost of liquid ($/square inch)	Ratio of degreasing time to coating time
1.Vapor degreasing	**$0.001**	**0.20**
2.Liquid degreasing	**$0.001**	**0.40**
3.No degreasing	**$0**	**0**

CHOOSE OPTION --------------------------> 1

1. Vapor degreasing

Liquid ---------------------->		$1,920
Energy -------------->	Power in kw:**4**	$203
Labor ---------------------->		$14,067

2. Liquid degreasing

Liquid ------------------->		$0
Labor -------------------->		$0

Cost of degreasing per part -------> $0.20

=====

TOTAL COST OF DEGREASING -------------------------------->$16,190

c) Grit blasting

Lifetime of blasting media (hours) **3**	Ratio of blasting time to coating time
# of lbs per cycle **25**	1.AUTOMATED: **0.20** 2.MANUAL: **0.25** 3.NO BLAST: **0**
Cost of blasting media (Al2O3) per lbs **$0.60**	

OPTION ALREADY CHOSEN-->**1**. Automated

Blasting media (Al_2O_3)----->		$4,884
Labor ------------------>	AUTOMATED	$0
Energy --------------->	Power in kw:**4**	$203

Cost of grit blasting per part ----> $0.06

=====

TOTAL COST OF GRIT BLASTING ------------------> $5,087

d) Preheating with gun

	Ratio of preheating time to coating time **0.05**	
Gas ----------------------->		$1,573
Energy --------------------->		$389
Labor ---------------------->		$3,517
Cost of preheating per part ------->	$0.07	
		=====
TOTAL COST OF PREHEATING -->		$5,478
	=====	
Cost of substrate preparation per part -->	$0.33	
		=====
TOTAL COST OF SUBSTRATE PREPARATION -------------->		$26,756

PRODUCTION INPUT FACTORS

==

2. Coating

a) Powder

Overspray (percentage)	**5%**	
Deposition efficiency	64.71%	
Powder consumed per part	0.262 lbs	
Powder cost per part ------------>	$4.993	
TOTAL POWDER COST ------------------------>		$399,447

b) Labor

	Downtime (percentage)	Ratio of worktime to coating time	
	10%	**0.50**	
Coating time (hours)	3,907.4		
Worktime		2,149.1	
Labor cost per part ------------->		$0.532	
TOTAL LABOR COST ------------------------->			$42,552

c) Energy

Power (kwh)	119,666	
Energy cost per part ------------>	$0.097	
TOTAL ENERGY COST ------------------------>		$7,778

d) Gas

Volume (Cubic feet)	314,550	
Gas cost per part --------------->	$0.393	
TOTAL GAS COST --------------------------->		$31,455

e) Nozzles

Lifetime (hours)	**75**	
Price	**$60**	
Nozzle cost per part ----------->	$0.039	
TOTAL NOZZLES COST ---------------------->		$3,126

f) Air

Volume of air (cubic feet) 2,419,492,740

TOTAL AIR COST ---------------------------> $1,216

==========

Cost of coating step per part ---> $6.05

==========

TOTAL COST OF COATING STEP ----------------> $485,574

PRODUCTION INPUT FACTORS
==

3. Grinding

Volume of Coating Ground (cubic inches)	768.00	
Width of wheel (inches)	**1**	
Depth removed at each pass (inches)	**.0005**	
Traverse rate (inches per minute)	**10**	
Removal rate (cubic inches / minute)	0.005	
Grinding time (hours)	2560	
Time for loading per part (seconds)	**20**	
Labor cost per part ------------->	$0.68	
TOTAL LABOR COST -------------------------->		$54,080
Power of grinding equipment (kw)	**2**	
Energy cost per part ------------>	$0.00	
TOTAL ENERGY COST ------------------------->		$333

****

Wheels

Coating to wheel removing ratio	**50**
Depth of usable wheel rim (inches)	**0.125**
Wheel diameter (inches)	**20**
Volume of wheel (Cubic inches)	7.9
Maximum volume of work (cubic inches)	393
Maximum number of parts per wheel	40,906

Wheel cost per part ------------->	$0.06	
TOTAL WHEEL COST --------------------------->		$4,889
	==========	
Cost of grinding step per part.-->	$0.74	
		==========
TOTAL COST OF GRINDING STEP --------------->		$58,969

PRODUCTION INPUT FACTORS
==

4. Quality control

Ratio of quality control
time to coating time

0.10

Labor time ---------> 390.74

Cost of labor per part --------------> $0.09

TOTAL COST OF LABOR -------------------------------> $7,033

5. Storage

Ratio of storage
time to coating time

0.05

Labor time ---------> 195.37

Cost of labor per part -------------->$0.04

TOTAL COST OF LABOR ------------------------------> $3,517

RECYCLING OPTION

==

YOU HAVE THE OPTION OF RECYCLING COATINGS THAT HAVE FAILED DURING THE COATING STAGE. TO DO SO, ENTER 1 IN THE HIGHLIGHTED CELL ON THE RIGHT. OTHERWISE, ENTER 0 TO TURN OFF THE RECYCLING OPTION. **1**

PERCENTAGE OF PARTS TO BE RECOATED (%) ---> **2.0%**

	$/PART	TOTAL
COST OF RECYCLING OPTION	$0.15	$11,612

COST OF CAPITAL

Number of productive days	**250**
Number of hours per shift	**8**
Number of shifts per day	**2**
TOTAL PRODUCTIVE TIME PER YEAR	4000 hours

STEP PROCESS	% UTILIZATION	INVESTMENT CAPITAL	COST OF CAPITAL
Substrate preparation	24.91%	$30,000	$1,971
Coating	99.64%	$172,010	$45,212
Grinding	76.61%	$70,500	$14,248
Quality control	9.96%	$125,200	$3,291
Storage	4.98%	$1,000	$13
Maintenance			$9,816
TOTAL		$398,710	$74,552

RECAPITULATIVE TABLES

Table 1: Repartition of cost per input

	$/PART	TOTAL $	%
POWDER	$5.09	$407,436	60.96%
MATERIALS	$0.16	$13,157	1.97%
LABOR	$1.59	$127,261	19.04%
GAS	$0.46	$36,887	5.52%
ENERGY	$0.11	$9,084	1.36%
CAPITAL COST	$0.93	$74,552	11.15%
TOTAL	$8.35	$668,378	100.00%

Table 2: Repartition of cost per process step

	$/PART	TOTAL $	%
SUBSTRATE PREP.	$0.37	$29,561	4.43%
COATING	$6.84	$547,353	81.93%
GRINDING	$0.96	$76,557	11.46%
QUALITY CONTROL	$0.14	$10,964	1.64%
STORAGE	$0.05	$3,602	0.54%
TOTAL	$8.35	$668,038	100.00%