

*A Study of Electrostatically Applied Powder Paint  
in the Automotive Industry*

by

James Edward Beuerle, Jr.

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Signature of Author \_\_\_\_\_

James Edward Beuerle, Jr.  
MIT Sloan School of Management  
Department of Chemical Engineering  
May 10, 1996

Certified by \_\_\_\_\_

Stephen Graves  
Professor, Management

Certified by \_\_\_\_\_

John Lienhard  
Professor, Mechanical Engineering

Certified by \_\_\_\_\_

T.A. Hatton  
Professor, Chemical Engineering

Accepted by \_\_\_\_\_

Jeffrey Barks  
Associate Dean, Sloan Master's and Bachelor's Programs

Accepted by \_\_\_\_\_

Robert Cohen  
Chairman of the Graduate Committee, Department of Chemical Engineering



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**ABSTRACT**

The U.S. Automotive industry is struggling with the adoption of a solvent-free powder coating technology as a replacement for traditional liquid painting technology which is considered to be environmentally harmful. The Low Emission Paint Consortium (LEPC) was formed by Chrysler, Ford, and General Motors to tackle many of the technical issues that are associated with bringing a new technology into practical use. Additionally, there are managerial and manufacturing issues which will need to be addressed before powder coating can be fully implemented in auto assembly plants. Understanding the implications and potential effects of both the managerial and technical issues are a prerequisite to the successful introduction of a new painting technology.

Studies performed by the LEPC have shown that powder transfer efficiency, film build, and film build uniformity are dynamically affected by the powder material and the specific set of applicators being used to deposit that powder. A thorough technical analysis which incorporates models portraying particle motion in an electric field, along with the effect of powder material properties, indicates many areas for technical improvement including revised application procedures and tightly controlled particle size distributions. Extensive experimental designs need to be run that account for product and site specific application requirements.

While the LEPC was formed for environmental reasons, costs will ultimately affect the timing that determines the implementation of powder technology. Cost models can be used to establish the effect of various application measurements and parameters on the overall cost of a paint facility. These models provide incentive to focus technical efforts on cost saving items that will strongly impact the bottom line.





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I would also like to thank my classmates who have assisted me on countless issues and taught me far more than I could ever have expected to learn in a classroom. Finally, I wish to thank my parents who have sacrificed much to help keep my life in order during the past two years.



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## **Chapter One -Introduction**

My thesis is based upon a seven month internship with the Chrysler Corporation where I served as a representative to the Low Emission Paint Consortium (LEPC), which is made up of Chrysler, Ford, and General Motors as voting members with ABB Paint Finishing acting as the Design and Construction partner. The automotive painting industry is under pressure to reduce volatile organic compound (VOC) emissions. Traditional automotive painting systems use organic-based solvents as carriers for the solid paint particles. As the paint cures, however, the solvent evaporates creating VOC emissions which contribute to the formation of lower atmospheric (tropospheric) ozone. In 1991, the EPA reported that 1.86 million metric tons of VOCs were emitted by industrial surface coating operations. Industrial surface coating operations account for approximately 25% of all VOC emissions.<sup>1</sup>

Numerous alternative painting technologies exist, but the LEPC has indicated that they will pursue the use of both electrostatic powder paints and waterborne coatings to replace the existing solvent-based systems. These technologies, along with some of their alternatives, will be discussed momentarily. The thrust of my project was to look at various applicator systems for the electrostatic application of powder-based paints. This will be discussed in detail in the next chapter. Additionally, I looked at certain material properties and their effect on the application process, including powder particle size and material electrical resistivity. Finally, I developed a model that allows cost comparisons to be made between powder-based paint systems and the traditional organic-based solvent paint systems.

### **1.1 - Problem Statement**

The LEPC was formed to tackle many of the technical issues that are associated with bringing powder paint technology into practical use within the automotive industry.

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<sup>1</sup> B. Bonifant, "Competitive Implications of Environmental Regulations in the Paint and Coatings Industry," *Management Institute for Environment and Business (MEB), Washington, DC 1994*

Given that each company has individual methods for evaluating application performance, common measurements were needed to align LEPC efforts. Furthermore, a common approach needed to be developed so that different applicator systems and materials could be effectively compared. Other technical concerns have been aroused, including the effect of particle size and electrical resistivity on application performance.

While the LEPC was formed for environmental reasons, the full implementation of powder technology will eventually depend on cost issues. It is difficult to predict what levels of transfer efficiencies can be expected or what material costs will be when powder technology is in full use. A cost model, along with a sensitivity analysis, will be a useful tool for management decision making.

## **1.2 - Low Emission Paint Consortium**

The Low Emission Paint Consortium (LEPC) was formed in February, 1993, but talks had begun between the Big Three as early as 1991 when it became clear that the 1990 Clean Air Act (CAA) Amendments would require the EPA to begin enforcing reductions in VOC emissions within the automotive painting industry. Ettl<sup>2</sup> discussed the formation of the LEPC and some of the key issues that were faced early in its existence. Over 80% of all pollution resulting from automobile manufacturing results from painting and coating processes in final assembly.

The formation of the LEPC was allowed under the auspices of USCar and various legislation that permits cooperative research and industrial collaboration in areas that are considered non-competitive. Any particular competitive advantage derived from the technical advance in paint would be short lived because none of the Big Three auto suppliers make paint or paint systems. Most of the competitive advantage in the industry is based on new product introductions. Therefore, pooling resources made sense from two

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<sup>2</sup> J.E. Ettl, "The Low Emission Paint Consortium (LEPC)," *University of Michigan Business School*, October 1995

perspectives. First, it allowed the Big Three to minimize development costs by sharing existing resources and knowledge. Second, the paint supplier community (both materials and applicators) would be much less apprehensive about developing new systems if each member of the Big Three was supporting it, rather than if only one automaker was pursuing it. Since most paint suppliers served several plants for each automaker, the suppliers could justify the resources and costs that a new paint technology would require.

Officially, the mission of the LEPC is as follows:

*“To conduct joint research and development programs on paint-related technologies to reduce or eliminate solvent emissions from automotive painting systems and to accelerate the availability of low emissions painting technology, thereby making the U.S. automotive industry a more highly coordinated and more powerful resource in the achievement of a cleaner environment while remaining competitive in world markets.”*

The LEPC aspires to this mission by pursuing the following five goals:

1. *Test and evaluate paint materials, painting equipment, and facilities with low emission potential.*
2. *Develop and demonstrate new painting equipment and facilities and new painting process technology with low emission potential.*
3. *Develop and demonstrate low emission painting technologies with high process capability.*
4. *Establish a common industry database of low emission painting and technical information.*

5. *Focus initially on powder painting technology developments in materials, processing, equipment, and facilities.*

While the LEPC decided to pursue powder technology early in their development, as evidenced by their fifth goal, there are numerous options available that would result in potentially reduced VOC emissions. Some of these technologies are described here:

- **Waterborne:** These coatings have been under considerable development for automotive base (color) coat applications, as will be discussed shortly. Waterborne coatings, however, have been found to be unacceptable for clear coat applications. Like solvent-based coatings, waterborne coatings provide for quick color change capability, but with lower levels of VOC emissions.
- **Powder Slurry:** Powder slurry is considered an excellent alternative to pure powder-based coatings. The liquid slurry is simply a water or solvent-based coat with a high percentage of solids and feels granular in nature.
- **High Solids:** Traditional solvent-based coatings are typically 40% resin, pigment, and additives, with 60% solvent. High solid coatings can contain as much as 70% solids with only 30% solvent. Further reduction is limited due to performance problems and handling issues.<sup>3</sup>
- **Supercritical Fluids:** Union Carbide has introduced a system that uses supercritical carbon dioxide to replace 70-80% of the solvents in industrial painting operations. There have been efforts within the auto industry to commercially apply this technology with limited success.<sup>4</sup>
- **UV-Cure:** UV-cure is VOC free with good appearance and excellent performance properties. It can, however, pose a safety hazard to workers and its usefulness is limited to line-of-sight application which allows it to be used only in the coating of simple, flat shapes.<sup>5</sup>

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<sup>3</sup> T. Triplett, "Resin Manufacturers, 'Struggling for Answers'." *Industrial Paint & Powder*, November 1994

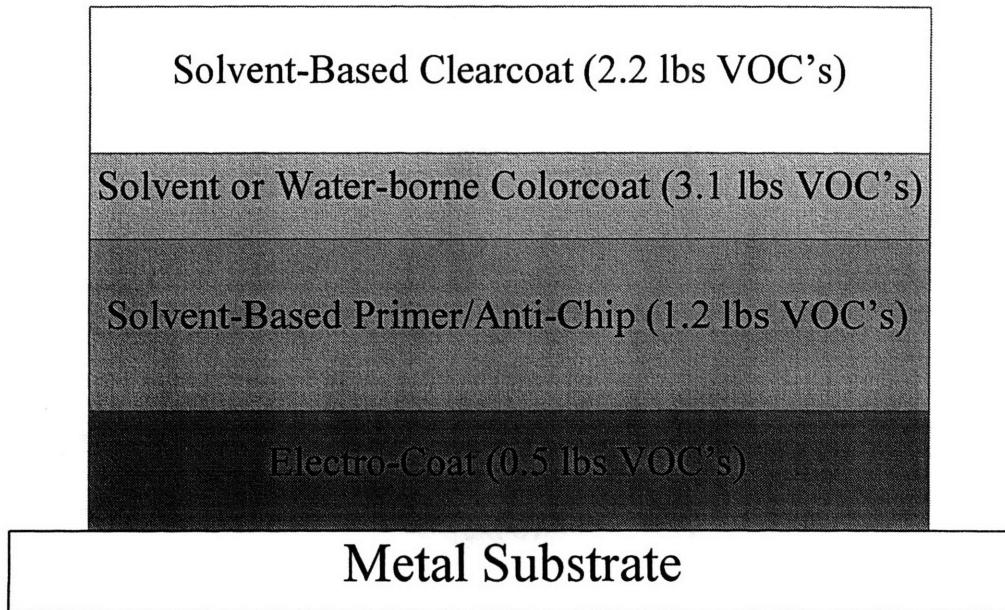
<sup>4</sup> J. Schut, "Novel Low VOC Paint Technology," *Plastics Technology*, March 1991

<sup>5</sup> Triplett



The coats that typically cover the metal substrate on an automobile are shown in Figure 1-1 with the indicated amount of VOC emissions per automobile:

**7.0 lbs VOC's per Car  
Automobile**

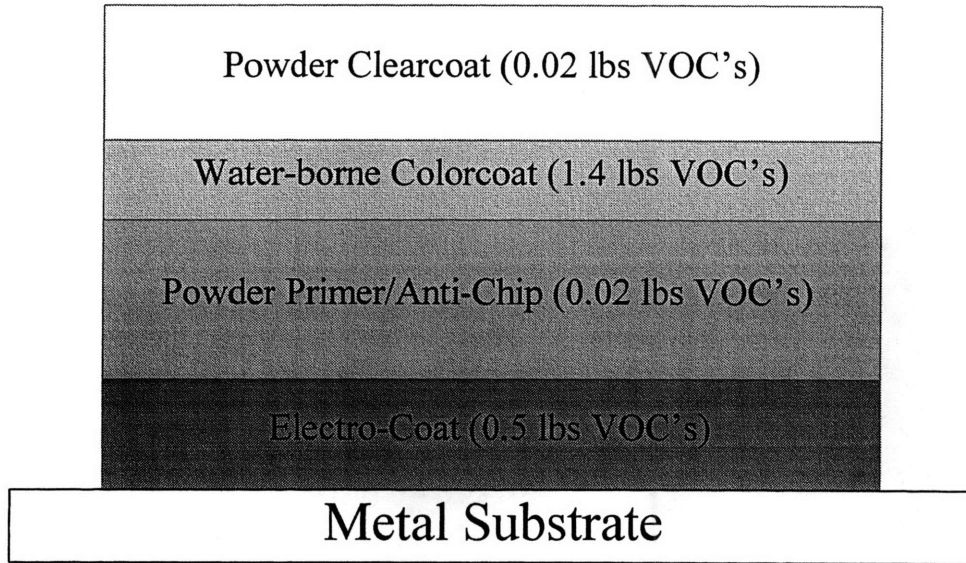


**Figure 1-1**

The metal substrate is cleaned and pre-treated before entering the coating process. The electro-deposition, or E-coat, process applies a corrosion resistant coating by dipping the entire vehicle into the coating solution. The E-coat is then baked in an oven before going to the next step. The second coat is traditionally a solvent-based primer coat which serves as an anti-chip protection layer. This material is typically a soft polyester or acrylic that absorbs the shock from stones that hit the vehicle. Before going to the color coat, the primer coat is fully cured by running the auto body through an oven. The color coat, also known as the base coat, provides the color that people are familiar with. Often, metallic flakes are dispersed within the liquid paint solution to provide a metallic effect. Before applying the clear coat, the color coat is passed through a flash heater so that the color coat becomes tacky. The final layer in the coating process is the clear coat which provide durability, UV light protection, and a high gloss finish. This coat is applied over the color coat which is still wet before proceeding to the final oven for a full bake.

Early in the existence of the consortium, the LEPC agreed to pursue the development of a coating process that looks as follows:

### **1.9 lbs VOC's per Car**



**Figure 1-2**

The proposed system has the same E-coat but uses a powder-based primer to replace the solvent-based primer coat. Actually, both Chrysler and General Motors are already using powder-based primer in several of their assembly plants. The primer coat has been considered to be non-critical to the overall appearance of a paint finish because it is disguised by the color and clear coat. In truth, however, waves or defects that appear in the primer coat will generally appear in the final finish. Powder cannot be used on the color coat because of the desire for a metallic finish and a method has not been developed yet that will allow its use. Waterborne color coats exist, however, which allow for a metallic finish similar to that for solvent-based color coats. These color coats are in use in many of the Big Three's assembly plants. Most of the LEPC's efforts have revolved around the development of powder-based clear coat. The clear coat is critical to the final finish as any defects will be visible to the naked eye. Clear coat has never been applied commercially to a surface as large as an automobile, though companies (such as Harley-Davidson on their gas tanks) have used powder clear coat in other applications.

Another one of the early decisions made by the LEPC involved the development of a powder-based clear coat technology prove-out facility to duplicate a production environment at assembly line speeds. This facility would allow the LEPC to evaluate various applicators and materials under actual plant conditions on full size automobiles. Furthermore, the prove-out facility will allow the LEPC to evaluate the strengths and weaknesses of the design and construction performed by ABB Paint Finishing. This design can be used as a basis when constructing future powder facilities. The General Motors Technical Center has a powder spray booth that allows for some testing to be done, but a considerable amount of speculation must be made when transferring laboratory experiments to a full size facility. Sharing the cost between the Big Three and various suppliers is an attractive scenario. The cost of such an effort had prevented the development of such a facility in the past, and there was always a significant amount of concern associated with a technology change going into an assembly plant. Powder-based clear coat will be one of the biggest technology changes faced by automobile paint experts. After some deliberation, it was decided that the technology prove-out facility would be built at Ford's Wixom assembly plant. The \$20 million Wixom prove-out facility comes on line in the spring of 1996. DeWitt and Etlie discuss the LEPC in more detail.<sup>6,7</sup>

### **1.3 - Powder Coating**

Powder coating is an environmentally friendly alternative to the traditional solvent-based paint systems used in many applications. The dry powder, with the look and feel of baby powder, serves as a substitute for liquid paint. The paint material suppliers mix the base resin (epoxy, polyester, or acrylic) with a number of additives then extrude the mixture to form sheets of the brittle material. The material is then sent through a grinder to break the material into tiny particles (with a typical target of 20-40 microns) before being sent

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<sup>6</sup> DeWitt, Charles M., "A Holistic Approach to Automotive Powder Coating," *Massachusetts Institute of Technology*, June 1995

<sup>7</sup> Etlie

to a cyclone where the smallest and largest particles are removed. Sieves are sometimes used to remove the largest particles.

The powder painting process is analogous to the solvent-based process that is traditionally used. The powder is kept dry and cool so that it fluidizes easily without clumping together. The powder is kept in a fluidized hopper just outside the paint booth. A jet pump delivers the powder from the hopper to a number of applicators inside the paint booth. An applicator creates an electric field through which the fluidized powder flows. The powder picks up a charge as it passes through the electric field which allows it to stick to the grounded metal car body as it passes by. This process will be discussed in detail in the next several chapters.

The powder that does not stick to the car body will fall through grates in the floor which lead to a reclaim system. The material in the reclaim system can be either recycled or disposed of. Electrostatic forces on the powder material will hold most of the powder on the car body while the car is transferred to the oven. In the oven, the parts are heated to approximately 300° F where they are held for 20-30 minutes. The heating process allows the particles to flow, creating a smooth surface. As time progresses, the polymers begin to cross-link resulting in a finish of high quality and excellent durability.

#### **1.4 - Thesis**

This document contains information and actual data on several issues that are of concern to the LEPC. Chapter two looks at the theory behind powder applicators and considers the effect of physical and operational variables, and looks at data from actual LEPC experiments. Chapter three considers the effect of powder particle size and how it can affect particle trajectories, particle charging and transfer efficiency. Chapter four looks at the effect of powder material's electrical resistivity and how this influences particle charging, transfer efficiency, and film thickness. Chapter five compares equipment and facility cost differences for liquid and powder systems, plus the operational cost differences between liquid and powder paint systems. Finally, chapter six makes

recommendations regarding additional work that should be considered by the LEPC.



## **Chapter Two - Applicators**

### **2.1 - Introduction**

This chapter will look at the effect of electrostatic powder applicators and the effect of physical and operational variables on their performance. This was the main thrust behind my internship where I was charged with evaluating and comparing various applicator systems at the General Motors Technical Center powder spray laboratory. The LEPC's technology prove-out facility at Ford's Wixom Assembly Plant will be the sight of future applicator evaluations. The LEPC will use some of the conclusions and methodologies developed during my internship to thoroughly and effectively evaluate the performance properties of various applicator systems and make appropriate comparisons for industrial use.

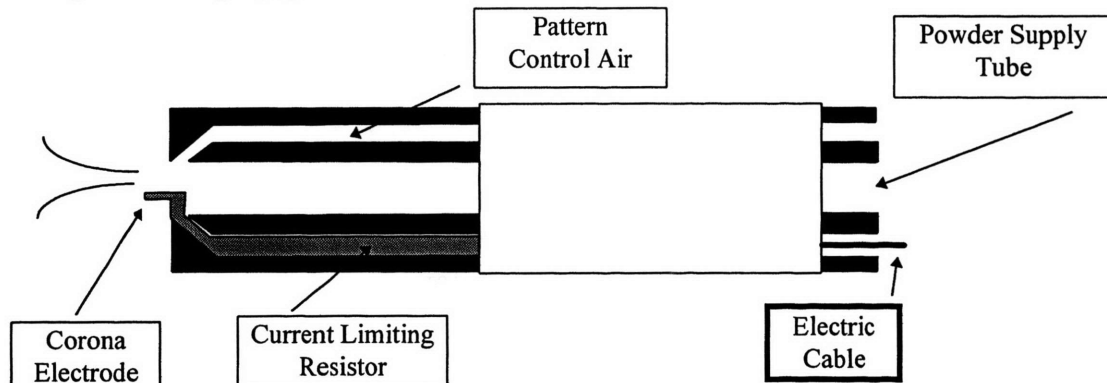
Section 2.3 of this chapter will look at the theory behind the applicators themselves. There is a considerable amount of overlap between the issues discussed in this chapter and the next two chapters. Where appropriate, the other chapters will be referred to. This chapter will also consider the effects of numerous physical and operational variables in section 2.3. The effects on application performance for several of these variables will be shown in actual studies that were performed on different application systems in section 2.4. For proprietary reasons, the actual suppliers will not be listed and the data will come from a conglomeration of studies. Furthermore, some of the measurements that were used in the evaluation of these systems will also be explained and some of the tests that were performed will be discussed. Lastly, recommendations will be made regarding future applicator system studies.

### **2.2 - Theory Behind Applicators**

Applicators can typically be classified into one of two categories; corona charging and tribocharging. For reasons discussed in the next chapter, only corona charging will be considered in this chapter. A corona charged applicator is usually referred to as a spray

gun. Powder is fed pneumatically from a fluidized bed or vibrating hopper to the spray gun through flexible tubing. The powders are sprayed out of a spray gun and charged by the ions produced from a corona which is generated by an applied voltage on an electrode located at the outlet of the spray gun. The charged particles are then attracted to and deposited onto a grounded substrate. The theory behind particle charging will be discussed in considerably more detail in the next chapter.

A negative voltage is typically applied to the electrode tip of the spray gun to produce a negative corona. Thus, the positive terminal is connected to the substrate through grounding (i.e., an infinite supply of positive ions are available through the grounding wire). Negatively charged particles tend to deposit more evenly due to the greater propensity for electric breakdown of a positively charged powder layer. The attractive forces acting on the particles both in the air and subsequent to deposition are discussed in the next chapter. The spray gun is shown here:



**Figure 2-1**

A resistor is used in the gun as a safety device. As the gun is brought near a grounded substrate, the voltage will decrease and current will increase so that energy output remains the same. This prevents high energy sparking which could result in explosion (given that powder can be flammable given the appropriate conditions). The corona electrode is typically a pointed wire that lies in the path of the powder supply tube. Spray guns are being developed that will place the electrode outside the spray path of the powder. Deflectors can be put around the electrode that shape the flow pattern of the powder. Finally pattern control air can be used to further change the spray pattern .



The electric field between the spray gun and the grounded substrate arises from two sources; the applied voltage to the electrode tip and the space charge due to the cloud of charged powder particles. This electric field, along with the aerodynamic forces imparted to the conveyed particles and the induced charge that develops on the grounded substrate cause the charged powder particles to migrate toward the grounded substrate. This is discussed in more detail in the next chapter where an iterative technique uses several equations to converge on an electric field calculation. In general, however, the electric field drops off quickly as the distance between the spray gun and the grounded substrate increases. The following drawing shows the effect:

### Electric Field vs. Distance to Job

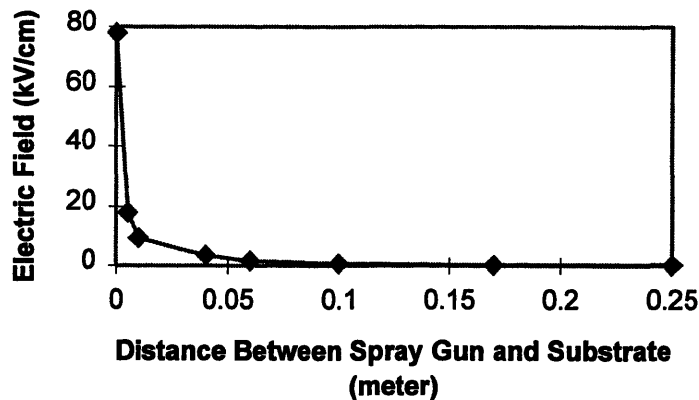


Figure 2-2

Near the electrode (less than 0.05 meters), the electric field results mostly from the applied voltage. Near the substrate surface, however, the space charge contributes about seven times more than the electric field.<sup>8</sup>

For powder particles to become charged, it is critical that the particle be exposed to free ions. This requires that the phenomenon known as corona generation be achieved. A

<sup>8</sup> Souheng Wu, "Electrostatic Charging and Deposition of Powder Coatings," *Polymer-Plastics Technology and Engineering* Vol. 7, No. 2, 1976

high electric field is produced in a small region near the electrode as shown in the diagram above. A self-sustaining electrical field breakdown, known as corona, will occur when the field strength reaches a critical value which is characteristic of the gas medium. Before the onset of corona, the electrical current from the electrode is negligibly small, but once corona begins the current will be significant and will increase as applied voltage is increased. Peek<sup>9</sup> calculated the corona onset voltage by combining

$$E_c = 30fs \left( 1 + 0.30 \sqrt{\frac{s}{b}} \right)$$

with

$$E_o = \frac{V_o - V_p}{b \ln(L/b)}$$

where

$E_c$  = corona onset field in kV / cm

$f$  = roughness factor for the electrode

$s$  = relative air density =  $(T_o / T)(P / P_o)$

$T_o = 293K$

$P_o = 1 \text{ atm.}$

$T, P$  = actual temperature and pressure

$b$  = electrode radius in cm

$L$  = distance from spray gun to substrate

$E_o$  = electric field on the surface of the electrode

$V_p$  = voltage on the powder layer

Letting  $E_o = E_c$  and  $V_o = V_c$ , it is possible to calculate the corona onset voltage as;

$$V_c^o = V_p + 30fs \left( 1 + 0.30 \sqrt{\frac{s}{b}} \right) \ln(L/b)$$

These equations show that the generation of corona depends very little upon temperature and pressure (within reasonable ranges), but is very dependent on the condition of the electrode tip. It should not be surprising that application performance will change over time as powder is scraped against the electrode tip. As the tip becomes rougher and the

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<sup>9</sup> Peek, F.W. Jr., "Dielectric Phenomena in High Voltage Engineering," 3rd ed., McGraw-Hill, New York, 1929

diameter is eroded away, the critical corona generation voltage will increase. The value for the corona generation voltage is typically -20 to -30 kV, but this number can easily double as the electrode tip changes. As will be shown later in this chapter, and in chapter three, this type of effect can result in significant transfer efficiency and application performance changes as the charge to mass ratio changes.

The space charge generated by the corona can significantly affect application performance. The electrons generated near the electrode tip will quickly attach themselves to electronegative gas molecules (in air this is oxygen, but not nitrogen). In turn, some of these ionic molecules will attach themselves to powder particles (discussed in the next chapter) to form negatively charged powder particles. The electric current from the electrode tip to the substrate is carried by both the ionic gas molecules and the charged powder particles. Measurements show that the ionic gas molecules carry about 90% of the electric current, which indicates that most of the ions generated at the electrode tip are not actually used to charge the powder particles. Wu<sup>10</sup> showed, however, that because of the ionic gas molecules high mobility and the low mobility of the charged particles, the ionic gas molecules contribute only about 7% of the total space charge. Given that the space charge is much more significant near the substrate than the applied voltage is (as discussed earlier in this chapter), this would indicate that the ionic gas molecules are not as much of a problem as some suspect.

### **2.3 - Effect of Physical and Operational Variables**

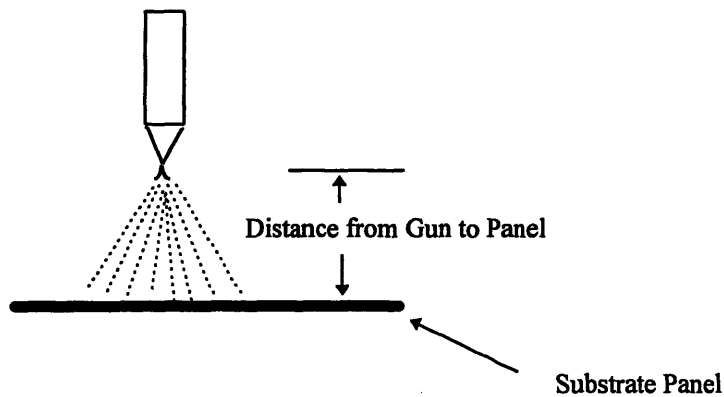
Several physical variables are believed to have significant effects upon application performance. Some of these variables include the material properties of the powder itself, the powder particle size and the humidity and heat associated with the coating environment. Material properties, including electrical resistivity and the dielectric constant of the material, will be discussed in more detail in chapter four. In general, it is believed that the electrical resistivity of a material plays a very important role in the

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<sup>10</sup> Wu

adhesion of the powder particles. The next chapter is dedicated to the effect of particle size on application performance. It seems as if adhesion and appearance tend to conflict with one another with regard to particle size. Larger particles tend to have higher transfer efficiencies, but the appearance is worse as the large particles tend to create a surface that appears lumpy. Humidity and heat can cause powder particles to cluster and cake which results in poor fluidization. For this reason, great effort is expended to ensure that powders are not exposed to excessive heat or humidity during transportation and storage. In chapter four, however, it will be shown that humidity can affect the electrical resistivity of a powder particle. Wu<sup>11</sup> shows that powder electrical resistivity seems to decrease slightly as relative humidity is increased.

Numerous operational variables affect the application performance of powder particles. Applicators are typically oriented such that the spray pattern is vertical, such as onto the hood or roof of a car, or horizontal, such as onto a door or quarter panel. The automobile then moves in one direction as the guns stay in a fixed position (or are allowed to oscillate in a direction perpendicular to the direction of the car's movement). This chapter will only consider applicators that are applied vertically as shown in this picture:



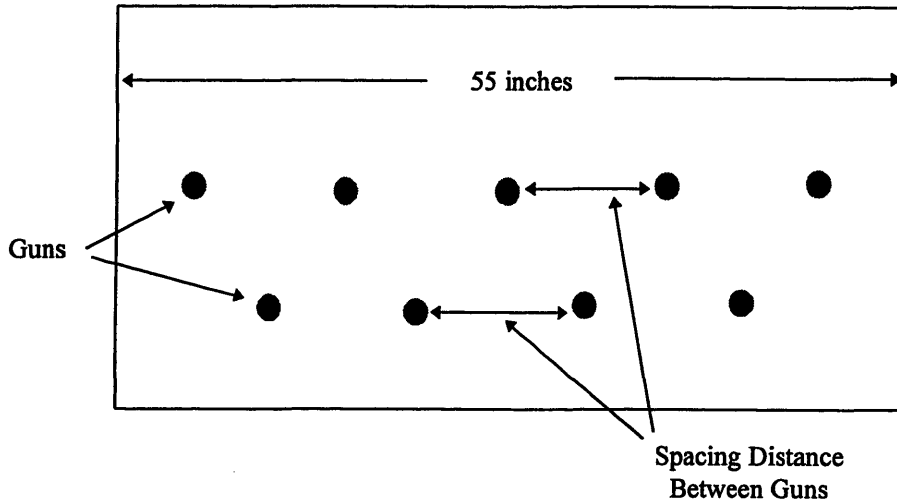
**Figure 2-3**

The width (as defined later in this chapter) of most gun's spray patterns are typically 5-9 inches while the average automobile hood is approximately 55 inches from one side to the other. Thus, it is necessary to use as many as 11 guns to spray an entire hood. The

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<sup>11</sup> Wu

guns are typically offset into two rows with the guns spaced evenly and offset between the two rows. Taking a top view of the guns, they would appear as follows:



**Figure 2-4**

The two rows are typically offset by enough distance such that electric field interactions between guns are not a concern as they can be between guns in the same row. The spacing distance between guns is important for numerous reasons, however, including the electric field interactions that occur between guns.

Some of the key operational variables that were studied will be mentioned here and explored in detail in the next part of this chapter as some actual applicator studies are reviewed. The critical distance between the gun and the substrate panel (also known as gun to job distance) is shown above. The crucial spacing distance between guns is also shown above. The applied voltage is another important operational variable which can be controlled. The flow rate of powder is important in controlling the thickness of each film layer. Just as important, however, is the shape of the spray pattern which is controlled by the amount of shaping air that is used along with the fluidizing air. The use of various sized deflectors will also affect the shape of the spray pattern. Finally, oscillation of the guns will also affect the uniformity of the film build. The guns are mounted on an

overhead rack that will oscillate back and forth in a direction perpendicular the direction of the car's movement.

#### **2.4 - Actual Studies**

The following excerpts are from various reports presented to the LEPC that were used in evaluating various application systems. Some changes have been made so as not to reveal the supplier system being evaluated. These studies were performed using an acrylic primer powder. The tests were performed to expedite future tests on powder clear coat materials which are now available. For comparison purposes, however, it was decided to use an acrylic primer since powder clear coat was not available for some of the earlier tests and it provided the only way of making an historical comparison. It is expected that powder clear coat will be an acrylic material very similar to the acrylic primer used in these tests.

Several critical measurements were considered in evaluating various applicator systems. Transfer efficiency is important from a cost and process efficiency standpoint. Transfer efficiency refers to the percentage of powder sprayed that adheres to the metal car body and is discussed later in this chapter. High transfer efficiency will both minimize the costs associated with recovering and/or disposing of powder, and eliminate the need to use recovered powder which is a potential source of appearance problems. A certain film build (paint film thickness) is necessary for performance purposes. A target film build of 2.5 - 3.0 mils was considered optimal from a cost and performance standpoint. At the same time, film build uniformity across the panel is critical from an appearance and cost standpoint. Poor uniformity requires excess powder to be used so that thin film areas will be eliminated. A small standard deviation in film build allows for the minimization of powder being applied. Orange peel (a measurement of coating waviness), Distinctiveness of Image (DOI - correlates to the reflectivity of the paint job), and other measurements are considered necessary for evaluating a coating job, however, these are considered to be more functions of film build, film uniformity, and, more importantly, the material being

applied than they are functions of the applicator being used.<sup>12</sup> Therefore, only transfer efficiency, film build, and film uniformity were evaluated in this study. The calculations for these measurements are discussed momentarily.

This study was conducted to provide a “robust” starting point for the LEPC prove-out facility. As will be discussed, there are certain payoffs between transfer efficiency and film build/uniformity. Providing for a “robust” design means to develop an experiment that allows for slight variations in process parameters while minimizing the effect on performance measurements. At the same time, it is understood that there may be more than one goal. Transfer efficiency can be maximized or film build standard deviation can be minimized. Unfortunately, both of these cannot always be achieved under the same conditions. For this reason, this study was kept broad to allow for more than one goal.

As mentioned above, the main goal of this study was to find the operating conditions that provided a cured film build of 2.5 - 3.0 mils of acrylic powder while maximizing transfer efficiency and minimizing film build standard deviation (maximizing film uniformity). In order to accomplish this, it was decided to begin by spraying a single gun under an array of conditions (based on an experimental design matrix). After statistically analyzing the results from one gun, five guns would then be sprayed to test the interaction of some of the important, controllable variables. Based on the experimental results and their analyses, nine guns were then to be set up on an automatic overhead spray machine. Another set of experiments would then be run with the results being an optimal set of spraying conditions for the overhead application system.

It was hoped that the single gun spray patterns could be extrapolated to a multiple gun system just by overlapping a series of single gun charts. Unfortunately, it was found that interactions between guns make the multiple gun set up much more complex. Since five guns could be set up and changed more quickly than nine guns, it was decided to do most

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<sup>12</sup> DeWitt

of the experimenting with the five gun set up and then use the nine gun set up to “fine tune” the key variables that needed to be evaluated still. The details of this set up will be discussed as this chapter progresses.

### 2.4.1 Calculations

Three calculations were used throughout the analysis; average film build, film build standard deviation, and transfer efficiency. Film width calculations have been used historically on single gun tests but were not used here for reasons discussed below. Orange peel was also considered in early studies, but it was soon decided to forego this test because it is almost a direct function of film build and the material being used (and is difficult to measure when film uniformity is poor).

#### 2.4.1-1 - Film Width

The spray pattern from a single bell or gun gives a film build very similar in distribution to that of a normal curve. By numerically integrating the area underneath the curve, a mean distribution and standard deviation can be calculated. It was decided to compare profiles sprayed under different conditions by defining for each pattern a film width equal to 2.36 times the standard deviation calculated from the normal curve description. A wide spray pattern seemed desirable for numerous reasons including the need for fewer guns and the fact that guns placed further apart will interact less. It is not known why 2.36 times the standard deviation was originally chosen other than the fact that this is a number that contains approximately 90% of the area underneath a normal curve.

While interesting, this film width calculation was not as helpful when looking at a multiple gun set up. First of all, the single gun’s spray pattern does not often resemble a normal curve. Besides, a wide spray pattern from a single gun does not matter much if it cannot be used with other guns to spray a large car hood. While conditions that gave wide single gun spray patterns were eventually used in the multiple gun set up, this was not emphasized or sought exclusively since the single gun spray patterns were only a



small part of the final modeling. For these reasons, film width was not used in evaluating application system performance.

#### ***2.4.1-2 - Average Film Build***

A film build of 2.5 - 3.0 mils was targeted across the middle 54 inches of a 70 inch panel. Each set of panels were measured at one inch intervals across the center of the panel with a calibrated film build gauge. The data was then downloaded to an Excel spreadsheet for analysis. Typically, the middle 54 inches were averaged, but the overhead system was sometimes moved during gun adjustments causing the guns to be off center in which cases a judgment call was made as to which 54 inches of the panel were to be measured.

#### ***2.4.1-3 - Film Build Standard Deviation***

Similar to the average film build, film build standard deviation was measured across the middle 54 inches of a 70 inch panel. Plants typically see standard deviations in the neighborhood of 0.5 inches. The minimum film build is of paramount importance in determining performance characteristics of a paint coat, as it is the minimum film thickness that determines the likely spots where underneath coating exposures will take place - which is what leads to problems. A lower standard deviation allows for less paint to be used since the mean film build can be targeted closer to the minimum thickness.

#### ***2.4.1-4 - Transfer Efficiency***

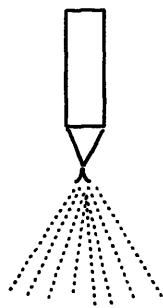
Transfer efficiency is a frequently used term in the powder world. While simple in concept, actually measuring it is somewhat more challenging. In words, it is the percentage of powder sprayed at a target that actually sticks to the panel. DeWitt<sup>13</sup> used a complex formula that took film area, powder density, line speed, and flow rate all into account. It may seem to make more sense to simply measure the weight of powder that

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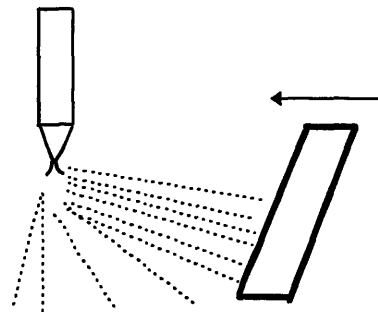
<sup>13</sup> DeWitt

stuck to the panel and divide by the weight of powder that should have been sprayed while the panel passed underneath the guns. Surprisingly, however, this method gives transfer efficiencies above 100% on some of the panels. By taking a side look at the spray pattern it can be realized that the leading edge of each panel was being sprayed well before the panel passed underneath the gun because the charged powder was strongly attracted to the closest grounded object. This hypothesis was tested by measuring the film build at the leading edge of the panel and comparing it to the rest of the panel. Sure enough, the film build at the leading edge is sometimes as much as a mil thicker than are similarly positioned points on the rest of the panel. Powder is deposited onto the panel before the panel actually passes underneath the spray gun which result in transfer efficiencies that are higher than is theoretically possible. The effect is shown here:

Normal Spray

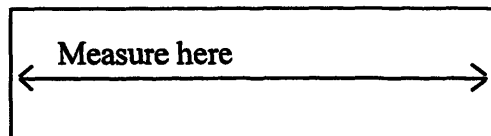


Spray as a Grounded Object Approaches



**Figure 2-5**

In order to be consistent with previous work, the film build method of measuring transfer efficiency, as conceived by DeWitt, was chosen. Though DeWitt never defined his method of measuring transfer efficiency, the following equations seem to match his experimental data. Transfer efficiency is simply calculated by measuring film build laterally across the center of the panel.



Transfer efficiency is then calculated as:

$$\text{Transfer\_Efficiency} = \frac{\text{Amount\_on\_Panel}}{\text{Amount\_Sprayed}} * \text{Unit Conversion Factor} * 100$$

where

$\text{Amount\_on\_Panel} = (\text{Area\_Under\_Curve}) * (\text{Panel\_Width}) * (\text{Powder\_Density})$  and

$$\text{Amount\_Sprayed} = \frac{(\text{Flowrate}) * (\text{Panel\_Width})}{\text{Line\_Speed}}$$

with the variables defined as follows:

*Area\_Under\_Curve* - The integrated two-dimensional area across the entire panel determined by measuring the film thickness (in mils) at one inch intervals. Units are mils-inches.

*Panel\_Width* - This was always 12 inches, though it is canceled out by the *Panel\_Width* used in the *Amount\_Sprayed* calculation.

*Powder\_Density* - A density of 1.1 g/cc for DuPont acrylic powder has been historically used (and was used in this test). In reality, however, this density is actually 1.17 g/cc, but a number of 1.1 g/cc was used for historical comparisons. This should be considered if a different material is being compared. For example, when a powder with a density of 1.3 g/cc is being compared, the final transfer efficiency number should be multiplied by the ratio 1.3/1.17. This will allow for a relative comparison to tests done with the DuPont acrylic material.

*Flowrate* - This was determined by placing the hopper on a scale and by using a stopwatch to determine the flow for every panel that was sprayed. We measured this by recording the weight change and time while the gun(s) was spraying. This number will change slightly with hopper level and atmospheric conditions so it should be calculated for each panel. Units should be calculated in g/min.

*Line\_Speed* - This was assumed constant at 24 ft/min.

If *line\_speed* and *powder\_density* are assumed constant, transfer efficiency can be calculated simply by determining the *area\_under\_curve* and *flowrate*. Including the unit conversion numbers, transfer efficiency can be calculated as follows:

$$\text{Transfer\_Efficiency} = \frac{\text{Area\_Under\_Curve}(\text{mil-in.}) * 519.1}{\text{Flowrate}(\text{g/min})}$$

#### 2.4.2 - Statistical Tools

Statistical analysis tools can be helpful when considering the effect of multiple factors on particular outcomes. Knowledge of experimental design (DOE's) and response surface analysis can save time and money by focusing efforts. MINITAB® Statistical Software was used in analysis where appropriate. For example, when looking at distance from gun to job, analysis done with statistical software can be used to show how transfer efficiency improves as the guns are placed closer to the substrate. At the same time, however, the analysis will show that film uniformity becomes worse. The software allows for the quantification of these two responses and the user can then determine where the guns should be placed or further studies can be performed under different conditions. This will be discussed more later.

#### 2.4.3 - Results

This section and the following sub-sections will look at some of the tests that were run and the results that were found. Single gun tests were run first to look at the effects of certain properties and the different deflectors. 'Five gun' experiments were then studied in more detail and finally 'nine gun' experiments were evaluated on longer panels, similar in width to an automobile hood. Several problems were found that should be considered when performing future studies with this system and they will be discussed here as well.

##### 2.4.3-1 - Single guns

Single gun experiments should not occupy much time when evaluating different applicator systems. Previous work by the LEPC has focused mostly on single gun test results which are extrapolated for multi-gun setups. Single gun tests should be used to

focus on the consistency between guns and the effect of operational parameters, along with equipment modifications such as deflectors or different tips. Deflector tips, for example can significantly affect the spray pattern as shown here:

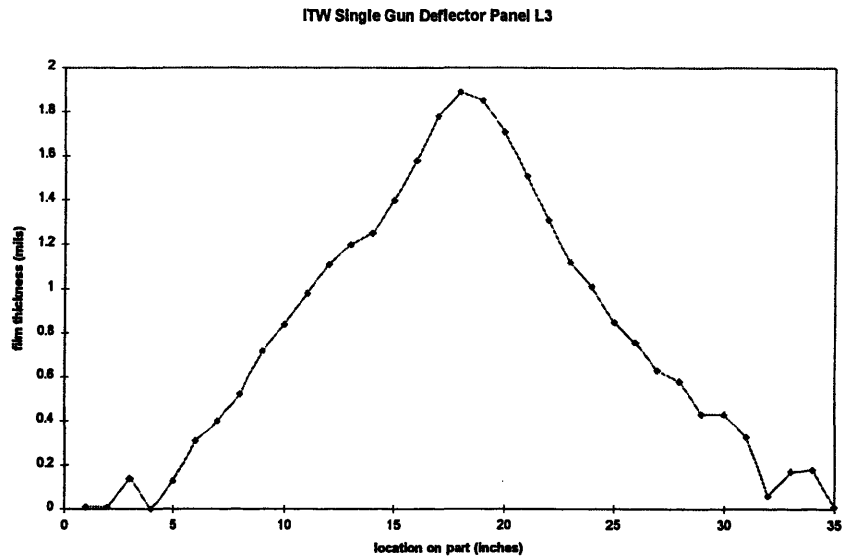


Figure 2-6

On the other hand, a narrow pattern (also using the 15/16" deflector) might look more like this (applied voltage, distance from gun to job, and powder flow differ for the two graphs):

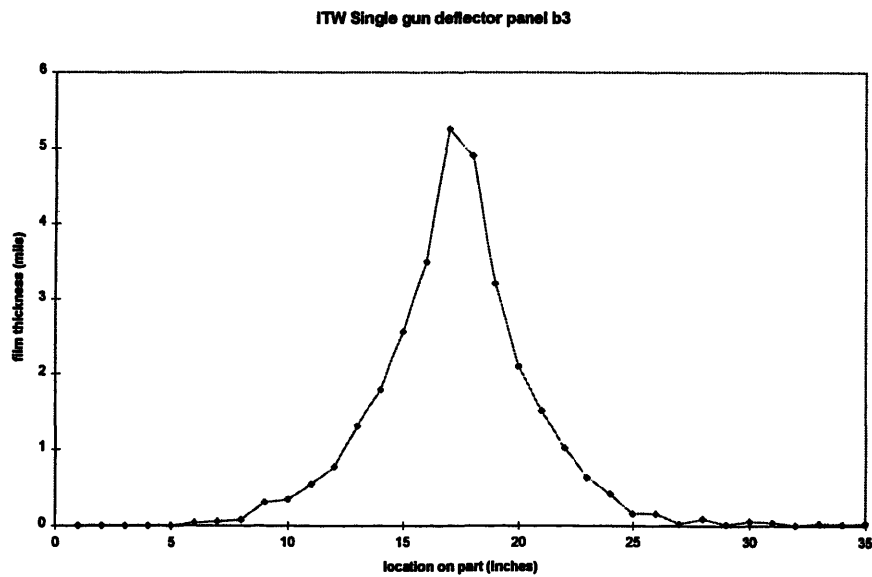
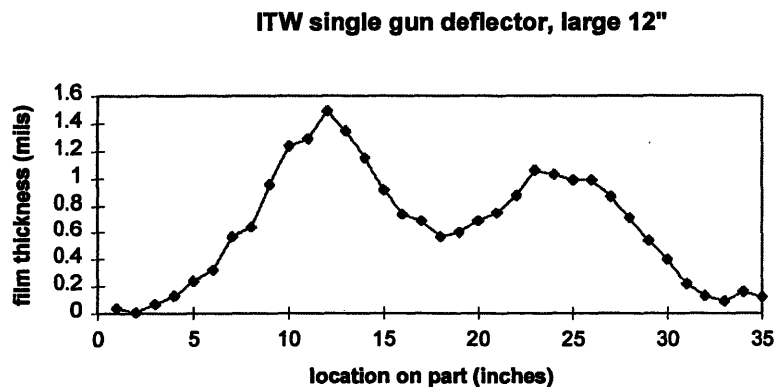


Figure 2-7

These graphs can be used to simulate a multi-gun experiment by overlaying the graphs at certain intervals. Unfortunately, the interaction effects between guns when they are sprayed at the same time are such that much of the work performed in single gun experiments are worthless.

The single gun experiments did allow comparison between the different deflector sizes provided by the gun suppliers. The smallest (3/8" diameter) deflector provided a narrow, spiky pattern that would require the use of 11 or more guns to spray a hood (we only had nine guns on the overhead). Compared with the medium sized (15/16") deflector, the smallest deflector did not allow for better transfer efficiency, while the medium deflector displayed a much wider, more uniform pattern. Lastly, the largest deflector (1.5"), showed a significant drop in transfer efficiency because the powder flow is directed in a path parallel to the job rather than at it. It also showed a bimodal pattern that provided for electrostatic interference problems when the multiple guns were arranged. The bimodal display (for the 1.5" deflector) is show here:



**Figure 2-8**

Experience shows that the single gun experiments do not accurately reflect how the multiple gun systems will perform. Several conclusions were drawn from the single gun experiments, however. It seems that the addition of shaping air only hurts transfer efficiency without improving film uniformity by misdirecting the powder flow. If atomizing air (additional air added to the fluidized powder flow) is not added, the powder flowrate will be very high and come out in clumps. Small adjustments within the

manufacturer's recommended range do not affect performance characteristics. The extensive analysis performed on single gun tests will not be reviewed here because of its limited usefulness.

#### 2.4.3-2 - Five Guns

Because it takes quite a bit of time to setup the gun spacings, distances, flowrates, voltages, and other operational parameters, it was decided to look at five guns before going to nine. Previous work by LEPC and GM personnel indicates that this incremental approach is not without flaws. A set of conditions that works well for five guns may perform much differently for nine guns. For this reason, it was desired not to spend an excessive amount of time looking at five guns if the work would not translate to the full gun system. The following test matrix (with the given results) was performed using the five gun setup:

| Test # | Spacing(in) | kV  | Distance(in) | Flowrat | Mean | Film   | TE   |
|--------|-------------|-----|--------------|---------|------|--------|------|
|        |             |     |              |         | Film | St.Dev |      |
| psi1   | 14          | 90  | 12           | 675     | 2.44 | 0.37   | 65.7 |
| psi2   | 14          | 50  | 12           | 682     | 1.84 | 0.24   | 49.1 |
| psi3   | 14          | 90  | 8            | 701     | 2.46 | 0.73   | 63.7 |
| psi4   | 14          | 50  | 8            | 692     | 2.41 | 0.66   | 63.2 |
| psi5   | 10          | 90  | 12           | 678     | 2.44 | 0.77   | 65.5 |
| psi6   | 10          | 50  | 12           | 702     | 2.12 | 0.75   | 54.8 |
| psi7   | 10          | 90  | 8            | 705     | 2.91 | 0.94   | 75.1 |
| psi8   | 10          | 50  | 8            | 710     | 2.82 | 0.83   | 72.1 |
| psi9   | 12          | 70  | 10           | 721     | 2.63 | 0.68   | 66.2 |
| psi10  | 12          | 70  | 10           | 722     | 2.52 | 0.59   | 63.4 |
| psi11  | 12          | 100 | 10           | 721     | 2.93 | 0.61   | 73.8 |
| psi12  | 12          | 40  | 10           | 721     | 2.26 | 0.65   | 57   |
| psi13  | 16          | 70  | 10           | 682     | 2.02 | 0.62   | 77.8 |
| psi14  | 8           | 70  | 10           | 712     | 2.76 | 1.25   | 70.5 |

**Table 2-1**

This test matrix followed earlier tests that were used to approximate the flow and atomizing air pressures that would give a film build in the 2.5-3.0 mils range. The first test run in the matrix was performed with 14" spacing between guns (offset in two rows such that the guns in the second row are spaced halfway between the guns in the first row), 90 kV applied voltage, and 12" distance to the job. The film build across the panel appeared as follows:

Guns 3,4,5,8&9 - Spacing=14", kV=90, Distance=12"

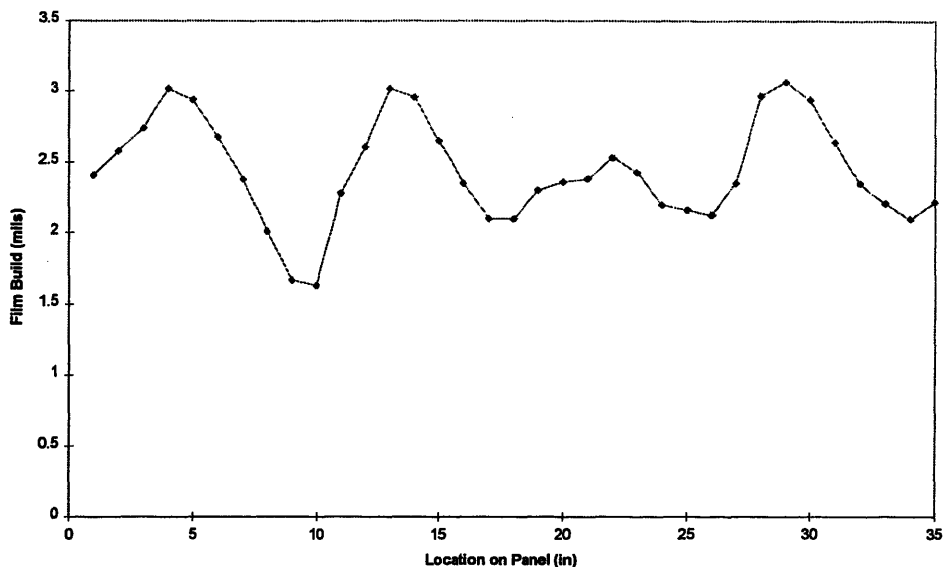


Figure 2-9

The design shown in the matrix above is referred to as a “star central composite.” It requires that all input factors (spacing, kV, or distance) are run at five levels each. Unfortunately, it was not practical to run distance at five levels, so the experimental design was modified slightly for this factor. A response surface analysis was performed using MINITAB. The results are shown as follows:

| Estimated Regression Coefficients for TE |        |         |         |       |  |
|--|--------|---------|---------|-------|--|
| Term                                     | Coef   | Stdev   | t-ratio | p     |  |
| Constant                                 | 194.54 | 95.6193 | 2.034   | 0.081 |  |
| Spacing(                                 | -5.68  | 7.1272  | -0.797  | 0.451 |  |
| kV                                       | -0.65  | 0.9107  | -0.712  | 0.500 |  |
| Distance                                 | -13.17 | 8.1408  | -1.617  | 0.150 |  |
| Spacing(*kV                              | 0.01   | 0.0580  | 0.182   | 0.861 |  |
| Spacing(*Distance                        | 0.46   | 0.5800  | 0.793   | 0.454 |  |
| kV*Distance                              | 0.07   | 0.0580  | 1.287   | 0.239 |  |

s = 6.562    R-sq = 64.5%    R-sq(adj) = 34.0%

| Analysis of Variance for TE |    |         |         |        |      |       |
|-----------------------------|----|---------|---------|--------|------|-------|
| Source                      | DF | Seq SS  | Adj SS  | Adj MS | F    | P     |
| Regression                  | 6  | 547.152 | 547.152 | 91.192 | 2.12 | 0.174 |
| Linear                      | 3  | 447.404 | 127.566 | 42.522 | 0.99 | 0.452 |
| Interaction                 | 3  | 99.748  | 99.748  | 33.249 | 0.77 | 0.545 |
| Residual Error              | 7  | 301.421 | 301.421 | 43.060 |      |       |



|  |         |          |          |          |       |       |
|--|---------|----------|----------|----------|-------|-------|
| Lack-of-Fit  | 6       | 297.357  | 297.357  | 49.559   | 12.20 | 0.216 |
| Pure Error   | 1       | 4.064    | 4.064    | 4.064    |       |       |
| Total  | 13      | 848.572  |          |          |       |       |
| Estimated Regression Coefficients for FBstdev (Standard deviation of the film build) |         |          |          |          |       |       |
| Term   |         | Coef     | Stdev    | t-ratio  | p     |       |
| Constant   |         | 0.34717  | 2.17076  | 0.160    | 0.877 |       |
| Spacing(<br>kV   | 0.07063 | 0.16180  | 0.436    | 0.676    |       |       |
| Distance   |         | -0.00061 | 0.02068  | -0.029   | 0.977 |       |
| Spacing(*kV  |         | 0.14094  | 0.18481  | 0.763    | 0.471 |       |
| Spacing(*Distance  |         | 0.00022  | 0.00132  | 0.166    | 0.873 |       |
| kV*Distance  |         | -0.01656 | 0.01317  | -1.258   | 0.249 |       |
|  |         | -0.00009 | 0.00132  | -0.071   | 0.945 |       |
| s = 0.1490 R-sq = 78.9% R-sq(adj) = 60.8%  |         |          |          |          |       |       |
| Analysis of Variance for FBstdev   |         |          |          |          |       |       |
| Source   | DF      | Seq SS   | Adj SS   | Adj MS   | F     | P     |
| Regression   | 6       | 0.580688 | 0.580688 | 0.096781 | 4.36  | 0.037 |
| Linear   | 3       | 0.544851 | 0.014768 | 0.004923 | 0.22  | 0.878 |
| Interaction  | 3       | 0.035838 | 0.035838 | 0.011946 | 0.54  | 0.671 |
| Residual Error   | 7       | 0.155347 | 0.155347 | 0.022192 |       |       |
| Lack-of-Fit  | 6       | 0.151297 | 0.151297 | 0.025216 | 6.23  | 0.298 |
| Pure Error   | 1       | 0.004050 | 0.004050 | 0.004050 |       |       |
| Total  | 13      | 0.736036 |          |          |       |       |
| Estimated Regression Coefficients for FBave (average film build across the panel)    |         |          |          |          |       |       |
| Term   |         | Coef     | Stdev    | t-ratio  | p     |       |
| Constant   |         | 8.4841   | 1.97589  | 4.294    | 0.004 |       |
| Spacing(<br>kV   |         | -0.3156  | 0.14728  | -2.143   | 0.069 |       |
| Distance   |         | -0.0251  | 0.01882  | -1.335   | 0.224 |       |
| Spacing(*kV  |         | -0.4981  | 0.16822  | -2.961   | 0.021 |       |
| Spacing(*Distance  |         | 0.0007   | 0.00120  | 0.626    | 0.551 |       |
| kV*Distance  |         | 0.0181   | 0.01199  | 1.512    | 0.174 |       |
|  |         | 0.0024   | 0.00120  | 2.034    | 0.081 |       |
| s = 0.1356 R-sq = 90.9% R-sq(adj) = 83.1%  |         |          |          |          |       |       |
| Analysis of Variance for FBave   |         |          |          |          |       |       |
| Source   | DF      | Seq SS   | Adj SS   | Adj MS   | F     | P     |
| Regression   | 6       | 1.28266  | 1.282663 | 0.213777 | 11.63 | 0.002 |
| Linear   | 3       | 1.15736  | 0.164400 | 0.054800 | 2.98  | 0.106 |
| Interaction  | 3       | 0.12530  | 0.125300 | 0.041767 | 2.27  | 0.167 |
| Residual Error   | 7       | 0.12871  | 0.128708 | 0.018387 |       |       |
| Lack-of-Fit  | 6       | 0.12266  | 0.122658 | 0.020443 | 3.38  | 0.394 |
| Pure Error   | 1       | 0.00605  | 0.006050 | 0.006050 |       |       |
| Total  | 13      | 1.41137  |          |          |       |       |

Table 2-2

Equations can be developed from this data that predicts the performance of the applicators under different operating conditions. For example, using the data for transfer efficiency (TE) in the coefficient column (Coef) in the above table, the following equation can be developed:

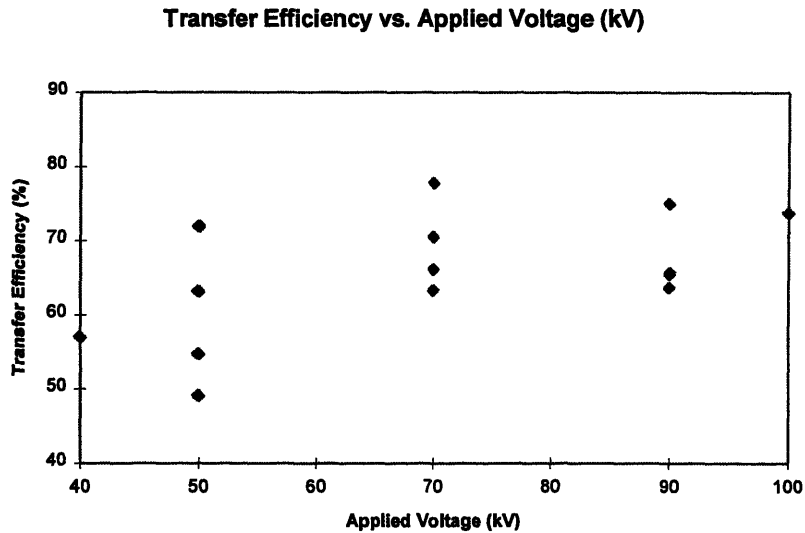
$$\text{TE} = 194.54 - 5.68*\text{Spacing} - 0.65*\text{kV} - 13.17*\text{Distance} + 0.01*\text{Spacing}*\text{kV} + 0.46*\text{Spacing}*\text{Distance} + 0.07*\text{kV}*\text{Distance}$$

As described below, however, not all of these terms may be significant. The less significant variables have a smaller influence, however, because their associated coefficients are smaller.

It is important to be very careful when analyzing these tables. Keep in mind that the input variables are only being evaluated over the experimental range. For example, the t-ratio and p value under the estimated regression coefficients table for transfer efficiency (TE) would indicate that increasing distance from gun to job will decrease transfer efficiency. The absolute magnitude of the t-ratio indicates the relative significance of one input variable compared with others (and interaction terms) while the p value indicates the probability that a certain input variable is NOT significant (thus a low p value indicates a strong correlation between that input and the measured output). This table says that the distance from gun to job seems to affect transfer efficiency in the distance range from eight to twelve inches. It is tempting to move the guns closer to improve transfer efficiency even more, however, the effect on other output variables must be considered. Furthermore, over a different range, the distance variable may not be significant and at some point, the impact of distance may reverse itself. For example, moving from eight to six inches may not improve transfer efficiency at all, and moving from six to four inches may make transfer efficiency worse.

Similarly, just because a variable (or an interaction term) does not significantly affect an output in a certain test or over a certain range does not mean that it has no effect on that output. For example, the regression coefficients for transfer efficiency would indicate

that applied voltage (kV) does not have a significant effect on transfer efficiency. Most people familiar with electrostatic powder coating would disagree with this, however. If one is to plot kV against transfer efficiency in the five gun experiment, the result is as follows:



**Figure 2-10**

This graph indicates that applied voltage has a non-linear effect, but there does appear to be a relationship between transfer efficiency and applied voltage. Under these experimental conditions, it appears that transfer efficiency does not improve (and might even get worse) as voltage is increased above 70 kV.

The point is that statistical tools can be useful, but they can also be misleading if they are not continuously checked with common sense. When interaction terms appear to be significant in affecting output, then non-linear relationships should be expected (or at least a simple linear model is not adequate). Again, the regression output for transfer efficiency indicated that an interaction term between kV and distance was relatively significant. This may explain for the non-linear relationship seen in the plot above.

Several conclusions were made from the data on the five gun experiments. Applied voltage should be between 70 and 90 kV. A drop in transfer efficiency is seen below an

applied voltage of 70 kV and back ionization is seen when the applied voltage exceeds 90 kV. It was also decided that spacing between guns should be 14 inches. At an applied voltage of 90 kV with 14" spacing between guns and a 12" gun to job distance, the single pass transfer efficiency was in the vicinity of 65% with a film standard deviation of 0.37 mils. At 12" gun spacing, transfer efficiency was slightly better, but film uniformity was considerably worse as the table above shows. These conditions were carried forward into studies with nine guns.

### 2.4.3-3 - Nine Guns

Early tests showed that transfer efficiency and film build uniformity with nine guns is similar to that for five guns. Due to time constraints, it was decided to immediately start looking into the effect of oscillation and see if an improvement could be made in performance characteristics. Sticking with 14" spacing between guns and 90 kV of applied voltage, the gun distance to job was adjusted and the following results were found:

| Test osc # | Distance | Osc. speed (3=high, 1=slow) | Osc. dist. | kV | Ave Film | St. Dev. | Flowrate | TE   |
|------------|----------|-----------------------------|------------|----|----------|----------|----------|------|
| 1          | 12       | 2                           | 8          | 90 | 2.1      | 0.23     | 1233     | 57.9 |
| 2          | 12       | 3                           | 8          | 90 | 2.24     | 0.29     | 1242     | 60.6 |
| 3          | 12       | 1                           | 8          | 90 | 2.22     | 0.35     | 1246     | 61.1 |
| 4          | 10       | 1                           | 8          | 90 | 2.39     | 0.22     | 1258     | 64   |
| 5          | 10       | 3                           | 8          | 90 | 2.67     | 0.4      | 1287     | 69   |
| 6          | 10       | 2                           | 8          | 90 | 2.47     | 0.29     | 1253     | 66.4 |
| 7          | 8        | 2                           | 8          | 90 | 2.8      | 0.43     | 1443     | 64.2 |
| 8          | 8        | 3                           | 8          | 90 | 3.02     | 0.51     | 1442     | 68.5 |
| 9          | 8        | 1                           | 8          | 90 | 3.09     | 0.54     | 1447     | 69.3 |

**Table 2-3**

Statistically analyzing film uniformity and transfer efficiency, we see:

| Estimated Regression Coefficients for St. Dev. (Film build standard deviation) |          |         |         |       |  |
|--|----------|---------|---------|-------|--|
| Term   | Coef     | Stdev   | t-ratio | p     |  |
| Constant   | 0.76556  | 0.51429 | 0.489   | 0.197 |  |
| Distance   | -0.04333 | 0.05076 | -0.854  | 0.432 |  |
| Osc. spe   | 0.05250  | 0.23807 | 0.221   | 0.834 |  |
| Distance*Osc. spe  | -0.00375 | 0.02350 | -0.160  | 0.879 |  |

s = 0.09398 R-sq = 59.0% R-sq(adj) = 34.4%

Analysis of Variance for St. Dev.

| Source         | DF | Seq SS   | Adj SS   | Adj MS   | F    | P     |
|----------------|----|----------|----------|----------|------|-------|
| Regression     | 3  | 0.063592 | 0.063592 | 0.021197 | 2.40 | 0.184 |
| Linear         | 2  | 0.063367 | 0.059996 | 0.029998 | 3.40 | 0.117 |
| Interaction    | 1  | 0.000225 | 0.000225 | 0.000225 | 0.03 | 0.879 |
| Residual Error | 5  | 0.044164 | 0.044164 | 0.008833 |      |       |
| Total          | 8  | 0.107756 |          |          |      |       |

Estimated Regression Coefficients for TE

| Term              | Coef   | Stdev   | t-ratio | p     |
|-------------------|--------|---------|---------|-------|
| Constant          | 82.739 | 16.8861 | 4.900   | 0.004 |
| Distance          | -1.942 | 1.6665  | -1.165  | 0.297 |
| Osc. spe          | 0.242  | 7.8167  | 0.031   | 0.977 |
| Distance*Osc. spe | 0.038  | 0.7715  | 0.049   | 0.963 |

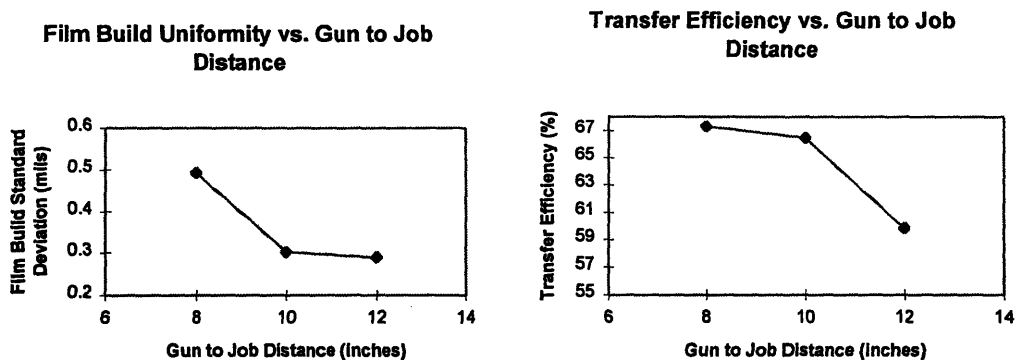
s = 3.086 R-sq = 64.3% R-sq(adj) = 43.0%

Analysis of Variance for TE

| Source         | DF | Seq SS  | Adj SS  | Adj MS  | F    | P     |
|----------------|----|---------|---------|---------|------|-------|
| Regression     | 3  | 85.931  | 85.9308 | 28.6436 | 3.01 | 0.133 |
| Linear         | 2  | 85.908  | 82.1331 | 41.0665 | 4.31 | 0.082 |
| Interaction    | 1  | 0.023   | 0.0225  | 0.0225  | 0.00 | 0.963 |
| Residual Error | 5  | 47.611  | 47.6114 | 9.5223  |      |       |
| Total          | 8  | 133.542 |         |         |      |       |

Table 2-4

Looking at the estimated regression coefficients for St. Dev. (film build standard deviation) and TE (transfer efficiency), these tables indicate that film build uniformity and transfer efficiency seem to be slightly effected by gun to job distance, though the relationship is not strong. Oscillation speed does not seem to have much, if any, effect on film uniformity or transfer efficiency according to the statistical analysis. Plotting this information, a better look at the data can be taken:



**Figures 2-11 and 2-12**

This pair of graphs indicates that a 10" gun to job distance, given oscillation of the guns, is optimal. Transfer efficiency improves dramatically as the guns are moved from 12" to 10", but moving the guns to 8" seems to have little effect on adhesion. Film build uniformity, however, is worsened only slightly as guns are moved from 12" to 10", but becomes much worse as guns are moved closer.

At this point, the guns seem to operate best when gun spacing is 14", gun to job distance is 10", and applied voltage is 70-90 kV. Though oscillation had not been considered in the previous set of experiments, it was decided to look at oscillation in a little more detail.

The following small matrix was run to look at oscillation speed and stroke distance:

| Test # | kV | Gun to Job | Oscillation speed | Oscillation dist. | Ave. Film | St. Dev | TE   |
|--------|----|------------|-------------------|-------------------|-----------|---------|------|
| 1      | 90 | 10         | Slow              | 8                 | 2.82      | 0.43    | 73.9 |
| 2      | 90 | 10         | Fast              | 8                 | 2.86      | 0.37    | 74.7 |
| 3      | 90 | 10         | Slow              | 13                | 2.88      | 0.47    | 74.9 |
| 4      | 90 | 10         | Fast              | 13                | 2.77      | 0.37    | 73   |

**Table 2-5**

Where the slow oscillation speed is equal to 78 oscillations/minute (where the guns moving from the left to the right and back again is considered two oscillations) and the fast oscillation speed is equal to 128 oscillations/minute. An oscillation distance of eight units on the Sames oscillation controller is equal to approximately five inches, while an oscillation of 13 Sames units is equal to approximately eight inches.

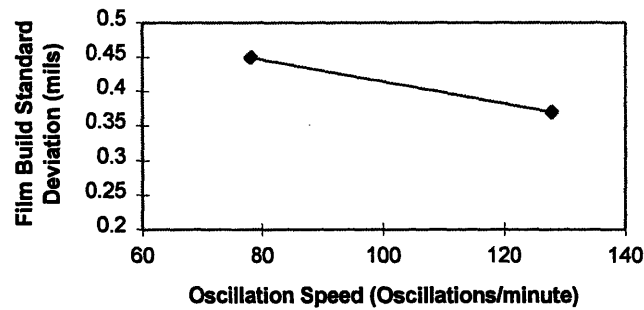
Using MINITAB to analyze these numbers, we get the following results:

| Estimated Regression Coefficients for St. Dev (Film build standard deviation) |           |          |          |          |      |       |
|---|-----------|----------|----------|----------|------|-------|
| Term  | Coef      | Stdev    | t-ratio  | p        |      |       |
| Constant  | 0.532800  | 0.059678 | 8.928    | 0.071    |      |       |
| Speed   | -0.001600 | 0.000400 | -4.000   | 0.156    |      |       |
| Distance  | 0.004000  | 0.004000 | 1.000    | 0.500    |      |       |
| s = 0.02000 R-sq = 94.4% R-sq(adj) = 83.3%                                    |           |          |          |          |      |       |
| Analysis of Variance for St. Dev  |           |          |          |          |      |       |
| Source  | DF        | Seq SS   | Adj SS   | Adj MS   | F    | P     |
| Regression  | 2         | 0.006800 | 0.006800 | 0.003400 | 8.50 | 0.236 |
| Linear  | 2         | 0.006800 | 0.006800 | 0.003400 | 8.50 | 0.236 |
| Residual Error  | 1         | 0.000400 | 0.000400 | 0.000400 |      |       |
| Total   | 3         | 0.007200 |          |          |      |       |
| Estimated Regression Coefficients for TE                                      |           |          |          |          |      |       |
| Term  | Coef      | Stdev    | t-ratio  | p        |      |       |
| Constant  | 75.9930   | 4.02825  | 18.865   | 0.034    |      |       |
| Speed   | -0.0110   | 0.02700  | -0.407   | 0.754    |      |       |
| Distance  | -0.0700   | 0.27000  | -0.259   | 0.839    |      |       |
| s = 1.350 R-sq = 18.9% R-sq(adj) = 0.0%                                       |           |          |          |          |      |       |
| Analysis of Variance for TE   |           |          |          |          |      |       |
| Source  | DF        | Seq SS   | Adj SS   | Adj MS   | F    | P     |
| Regression  | 2         | 0.42500  | 0.42500  | 0.21250  | 0.12 | 0.900 |
| Linear  | 2         | 0.42500  | 0.42500  | 0.21250  | 0.12 | 0.900 |
| Residual Error  | 1         | 1.82250  | 1.82250  | 1.82250  |      |       |
| Total   | 3         | 2.24750  |          |          |      |       |

**Table 2-6**

Again, looking at the estimated regression coefficients, there does appear to be a slight correlation between oscillation speed and film uniformity. The data indicates that oscillation distance does not affect film uniformity and that transfer efficiency is not affected by oscillation speed nor distance. This graph shows the correlation between oscillation speed and film uniformity:

### Film Build Uniformity vs. Oscillation Speed



**Figure 2-13**

The Sames oscillation unit would not go any faster without causing the guns to come loose. It appears that faster oscillation seems to improve uniformity, at least to a certain level. At this point, we decided to run some repetitive tests just to confirm past data. The following matrix was run:

| Re-test # | Distance | Osc. speed (3=fast, 1=slow) | Osc. dist. | kV  | Ave. Film | St. Dev. | Flowrate | TE   |
|-----------|----------|-----------------------------|------------|-----|-----------|----------|----------|------|
| 2         | 10       | 1                           | 8          | 90  | 2.91      | 0.39     | 1364     | 70.8 |
| 3         | 10       | 2                           | 8          | 90  | 2.77      | 0.37     | 1351     | 69.1 |
| 4         | 10       | 2                           | 8          | 90  | 2.79      | 0.44     | 1351     | 71   |
| 5         | 10       | 3                           | 8          | 90  | 2.8       | 0.32     | 1349     | 69.7 |
| 6         | 12       | 2                           | 8          | 90  | 2.5       | 0.31     | 1336     | 63.5 |
| 7         | 12       | 3                           | 8          | 90  | 2.55      | 0.28     | 1302     | 69.4 |
| 8         | 10       | 3                           | 8          | 90  | 2.93      | 0.36     | 1308     | 74.4 |
| 9         | 10       | 3                           | 8          | 100 | 2.9       | 0.32     | 1296     | 74.3 |
| 10        | 10       | 3                           | 8          | 70  | 2.68      | 0.31     | 1297     | 68.5 |
| 11        | 10       | 3                           | 8          | 100 | 2.9       | 0.44     | 1345     | 72.1 |
| 12        | 10       | 3                           | 13         | 90  | 3.04      | 0.39     | 1337     | 75   |
| 13        | 10       | 3                           | 17         | 90  | 2.77      | 0.27     | 1325     | 69.8 |
| 14        | 10       | 3                           | 8          | 90  | 2.98      | 0.38     | 1326     | 75.1 |
| 15        | 10       | 3                           | 3          | 90  | 2.88      | 0.37     | 1342     | 70.6 |

**Table 2-7**

The oscillation speeds correspond as follows; speed 1=78 oscillations/minute, speed 2=109 oscillations/minute, and speed 3=128 oscillations/minute. Similarly, oscillation distances correspond as; distance of 3=2 inches, distance of 8=5 inches, distance of 13=8 inches, and distance of 17 = 10 inches. Using MINITAB to statistically analyze the data, the following is found:



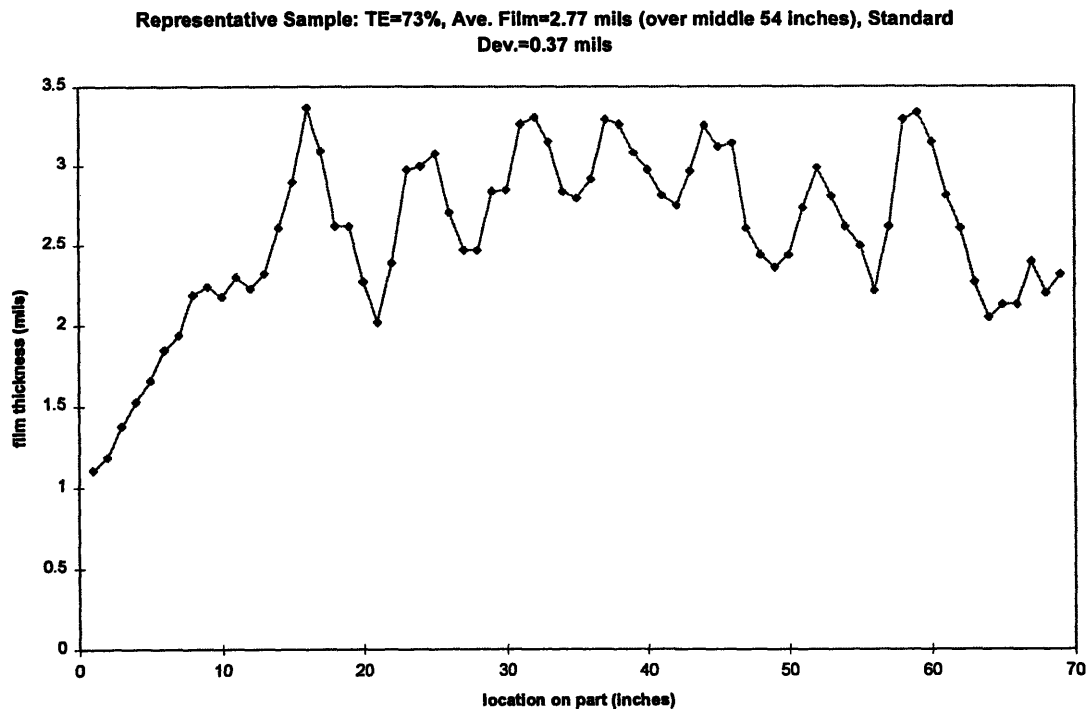
| Estimated Regression Coefficients for St. Dev.   |           |          |          |          |      |       |
|--|-----------|----------|----------|----------|------|-------|
| Term   | Coef      | Stdev    | t-ratio  | p        |      |       |
| Constant   | 0.346194  | 2.25537  | 0.153    | 0.882    |      |       |
| Distance   | -0.002555 | 0.22158  | -0.012   | 0.991    |      |       |
| Osc. spe   | 0.001937  | 0.01888  | 0.103    | 0.921    |      |       |
| Osc. dis   | -0.005428 | 0.00437  | -1.243   | 0.249    |      |       |
| kV   | 0.002333  | 0.00197  | 1.183    | 0.271    |      |       |
| Distance*Osc. spe                                | -0.000293 | 0.00186  | -0.157   | 0.879    |      |       |
| s = 0.04833    R-sq = 49.9%    R-sq(adj) = 18.6% |           |          |          |          |      |       |
| Analysis of Variance for St. Dev.                |           |          |          |          |      |       |
| Source   | DF        | Seq SS   | Adj SS   | Adj MS   | F    | P     |
| Regression                                       | 5         | 0.018634 | 0.018634 | 0.003727 | 1.60 | 0.265 |
| Linear   | 4         | 0.018576 | 0.009431 | 0.002358 | 1.01 | 0.457 |
| Interaction                                      | 1         | 0.000058 | 0.000058 | 0.000058 | 0.02 | 0.879 |
| Residual Error                                   | 8         | 0.018687 | 0.018687 | 0.002336 |      |       |
| Lack-of-Fit                                      | 4         | 0.007170 | 0.007170 | 0.001793 | 0.62 | 0.671 |
| Pure Error                                       | 4         | 0.011517 | 0.011517 | 0.002879 |      |       |
| Total  | 13        | 0.037321 |          |          |      |       |
| Estimated Regression Coefficients for TE         |           |          |          |          |      |       |
| Term   | Coef      | Stdev    | t-ratio  | p        |      |       |
| Constant   | 237.68    | 110.077  | 2.159    | 0.063    |      |       |
| Distance   | -18.52    | 10.815   | -1.713   | 0.125    |      |       |
| Osc. spe   | -1.30     | 0.922    | -1.415   | 0.195    |      |       |
| Osc. dis   | 0.02      | 0.213    | 0.082    | 0.937    |      |       |
| kV   | 0.16      | 0.096    | 1.627    | 0.142    |      |       |
| Distance*Osc. spe                                | 0.13      | 0.091    | 1.481    | 0.177    |      |       |
| s = 2.359    R-sq = 65.3%    R-sq(adj) = 43.7%   |           |          |          |          |      |       |
| Analysis of Variance for TE                      |           |          |          |          |      |       |
| Source   | DF        | Seq SS   | Adj SS   | Adj MS   | F    | P     |
| Regression                                       | 5         | 83.92    | 83.92    | 16.784   | 3.02 | 0.080 |
| Linear   | 4         | 71.71    | 83.82    | 20.956   | 3.77 | 0.052 |
| Interaction                                      | 1         | 12.21    | 12.21    | 12.211   | 2.19 | 0.177 |
| Residual Error                                   | 8         | 44.51    | 44.51    | 5.564    |      |       |
| Lack-of-Fit                                      | 4         | 23.04    | 23.04    | 5.761    | 1.07 | 0.474 |
| Pure Error                                       | 4         | 21.47    | 21.47    | 5.368    |      |       |
| Total  | 13        | 128.44   |          |          |      |       |

**Table 2-8**

These results do not correspond well with some of the things seen before. For example, this analysis claims that oscillation speed has no effect on film uniformity, but that

oscillation distance does. It does, however, indicate that increased oscillation speed hurts transfer efficiency. The experimental conditions are not particularly robust (not orthogonal in design), though, and the correlations do not appear to be strong, so it was chosen to disregard this output. This data was meant to confirm some of our earlier findings and it does appear to give us similar results.

It appears that the ideal operating conditions for the guns shown are 14" spacing between guns, 10" distance to job, 90 kV, an oscillation speed near 128/minute, and an oscillation distance of approximately five inches (though this is not so important). The flow rate should be in the neighborhood of 150 grams/minute on each gun with atomizing and shaping air in the recommended ranges and the medium sized (15/16" diameter) deflectors should be used. Given a relative humidity of about 60% and a temperature of 65-70°F, we can expect a film build of 2.8-3.0 mils with a standard deviation of 0.3-0.4 mils and a transfer efficiency of 69-74%. The following graph depicts a cross-sectional look of a representative hood:



**Figure 2-14**

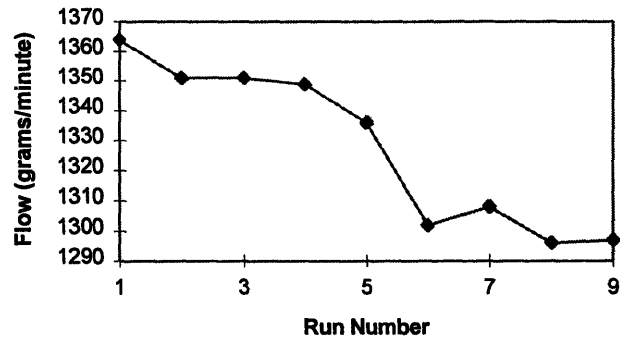
#### **2.4.4 Recommendations**

Film build uniformity seems to be related to both gun spacing and gun to job distance and the interaction between the two. Transfer efficiency increases as the gun to job distance is decreased, but film build uniformity gets much worse. It should be possible to move the guns closer to the job without sacrificing film build uniformity if appropriate shaping air and deflectors were available. The marginal increases in transfer efficiency that are obtained by moving the guns closer are decreasing. Similarly, applied voltage should be increased to the point at which transfer efficiency does not increase with increasing voltage. Back ionization is a concern if voltage is increased too high and it is simply unnecessary. Powder flowrates should be adjusted to the point where the desired film build is being obtained. Shaping and atomizing air should be adjusted so that film build deviation is minimized while transfer efficiency is not hurt.

Applicator performance seems to be dependent on the system being evaluated, and extensive experiments should be run on each system being tested. There is no reason to expect that data will be reproducible from one set of applicators to another. Furthermore, as chapters three and four will show, there are other environmental and operating parameters that can significantly affect application performance.

It is not shown in the data presented in this chapter, but there appears to be a relation between powder level in the hopper and powder flowrates in the gun. One hopper showed the following relation on consecutive runs:

### Powder Flow on Consecutive Runs



**Figure 2-15**

It appears as if there is a head pressure - flowrate relation, similar to what one would expect with a liquid. This would indicate the need to maintain tight control over the powder level in feed hoppers. This should be considered in future studies and the evidence should be confirmed or refuted.

## **Chapter Three - Particle Size Effects**

DeWitt and his work with the Low Emission Paint Consortium (LEPC)<sup>14</sup> laid some groundwork in exploring the technology associated with the electrostatic powder coating of automobiles. In particular, he implied the importance of particle size and material electrical resistivity on application performance. This chapter takes a deeper look into the issues regarding particle size and the applicability of this to the LEPC.

The importance of particle size and electrical resistivity cannot be explored without concurrently examining other issues in the phenomenon of electrostatic powder coating. The particle charging mechanisms, including generation of a corona and the electric field itself, must be considered simultaneously. The high degree of interaction between different application parameters makes it difficult to consider one issue at a time. Some of the material that follows is fairly well understood, but it is critical to understanding the effect that powder coating can have on automobile painting processes.

Section 3.1 looks at the theory behind the powder particle charging mechanism. Section 3.2 considers how the electric field and particle size together affect particle trajectories and the charge to mass ratio which influences the powder before reaching the substrate surface. Finally, section 3.3 evaluates the effect of particle size on the charged powder once it has deposited on the substrate surface. Throughout the chapter, the applicability of this material to the LEPC will be considered and existing data will be applied.

### **3.1 - Charging Mechanism**

Charge can only be separated, not created; so that in any charging mechanism both positive and negative charges will co-exist. One sign of charge must be disposed of in some manner so that only the charge of opposite sign remains for the purpose of particle charging. Corona and tribo charging are the two most common particle charging

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<sup>14</sup> DeWitt

mechanisms being used today. These methods will be briefly discussed here. Induction charging is discussed by Hughes<sup>15</sup> where the particle is contacted with a low voltage electrode such that no free ions are generated. The elimination of free ions could have a tremendous effect on application performance. The problem with induction charging is that it requires a material with low electrical resistivity. As discussed in later sections, electrical resistivity is a critical material characteristic that is difficult to optimize, especially when low resistivity is desired. For this reason, induction charging has not been given serious consideration by applicator manufacturers.

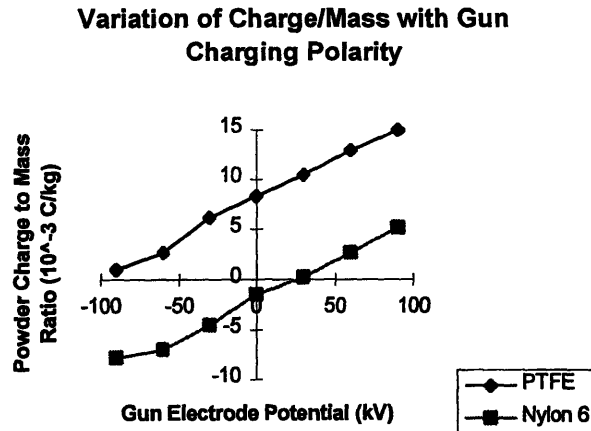
### **3.1.1 - Tribo Charging**

When two different materials contact each other, electrical charge will be redistributed at the point of contact. After contact, one material will have excess electrons while the other material will be deficient in electrons. The unpredictable nature of tribo charging is the biggest reason that tribo charging application guns have not gained much popularity. Tribo charging performance is dependent on numerous parameters, including duration of contact, temperature, conductivity, permittivity, density, humidity, surface pretreatment, number of contact points, etc. Most importantly, tribo charging performance is dependent on the two materials in contact. This is demonstrated in figure 3-1 shown below where an epoxy/polyester powder is used in two different guns, one made of teflon (PTFE) and the other made of nylon:<sup>16</sup>

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<sup>15</sup> Hughes

<sup>16</sup> Ibid.



**Figure 3-1**

Figure 3-1 shows how important it is to understand the relationship between gun and powder materials. It is actually possible to offset applied voltage with tribo charged effects. For example, it would be foolish to apply an electrode voltage of -90 kV to an epoxy/polyester powder in a teflon gun as shown in the above graph. The corona and tribo charges would nearly cancel each other out.

This information is applicable to the LEPC because differently formulated materials are being considered for clear coat application. The possibility of distinct materials performing differently under certain operating conditions (and applied voltage, in particular) must be considered. This will be made more clear in Chapter Four. Most LEPC studies have focused on the use of acrylic materials, but as blend and other formulations are considered, additional experiments will need to be run with respect to applied charge.

### 3.1.2 - Corona Charging

Corona charging was discussed considerably in the last chapter. Charging polarity is usually negative, but gun manufacturers have been slow in identifying the importance of the correct choice of polarity for different materials.<sup>17</sup> It is

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<sup>17</sup> Ibid.

believed that the electrical breakdown levels are higher for negatively charged particles which would result in less back ionization. Many experts in the electrostatic coating industry feel that corona charging leaves much to be desired in that only a small fraction of ions generated adhere to powder particles. It is unclear how many of these free ions eventually arrive on the coated substrate, but it is clear that this ionic capture can lead to the electrical breakdown of the powder layer resulting in back-ionization. Some manufacturers are trying to overcome this problem by retracting the electrode tip into the gun barrel so that no free ions emanate from the gun nozzle. Several applicator manufacturers have discussed the possibility of such a gun being made available to the LEPC. If it is true that free ions contribute greatly to powder layer electrical breakdown, such a product could result in higher transfer efficiencies by allowing for higher applied voltages to be used. The great advantage of corona charged guns, however, is that they offer a dependable source of current.

### 3.2 - Electric Field

#### 3.2.1 - Equations

The motion of a particle depends on the electrostatic and aerodynamic forces acting upon it. The solution of the electrostatic forces requires solving for the electric field strength ( $E$ ) and the ionic space charge density ( $\rho$ ) in the interelectrode space between the applicator and the substrate. Since the electric field strength ( $E$ ) depends on the ionic space charge density ( $\rho$ ) and the ionic space charge density ( $\rho$ ) depends on the electric field strength ( $E$ ), an iterative technique is used to solve the problem. The following equations govern the solution:<sup>18</sup>

$$\nabla \vec{E} = \frac{\partial \vec{E}}{\partial r} + \frac{\partial \vec{E}}{\partial z} = \frac{\rho}{\epsilon_0} \quad \text{Poisson's Equation (1)}$$

$$\frac{\partial \rho}{\partial t} = \nabla \vec{J} = 0 \quad \text{Conservation of Charge (2)}$$

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<sup>18</sup> Ali, F.S., Base, T.E., Inculet, I.I., "Mathematical Modeling of Powder Paint Trajectories in Electrostatic Painting," IEEE Applications Meeting, 1994



$$\vec{J} = b\rho\vec{E} - D\nabla\rho$$

Current Density Equation (3)

$$\vec{E} = -\nabla\phi$$

Electric Field Equation (4)

where,

$\vec{E}$  = electric field (V / m)

$\rho$  = charge density (C / m<sup>3</sup>)

$\epsilon_0$  = permittivity of free space,  $8.86 \times 10^{-12}$  (F / m<sup>3</sup>)

t = time (s)

$\vec{J}$  = current density (A / m<sup>2</sup>)

b = mobility (m<sup>2</sup> / V · s)

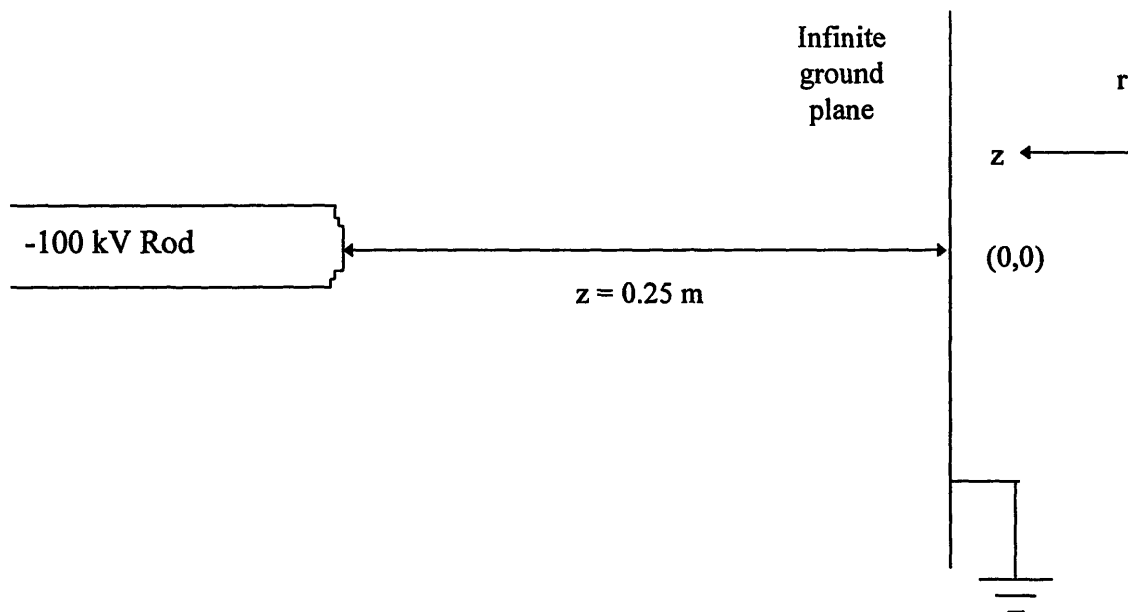
D = displacement flux density (C / m<sup>2</sup>)

$\phi$  = electrical potential (V)

### 3.2.2 - Electric Field Calculation

Ali, Inculet, and Base solved for the electric field using an iterative numerical technique employing the combined method of the Charge Simulation (CSM) and the Method of Characteristics. This scheme assumed the charge density distribution to be known throughout the volume of the discharge, then the CSM was used to calculate the resulting electric field. Assuming the field to be known, the MOC was used to determine the resulting charge distribution. These two methods were applied iteratively until the equations converged on a consistent field solution.

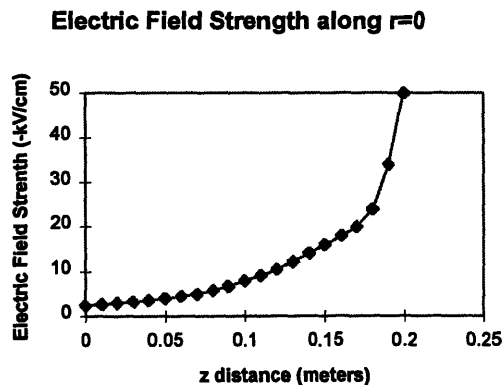
Several boundary conditions were imposed on this model, including a potential at the corona conductor of -100 kV, a grounded plane potential of 0 kV, and a corona onset value of 150 kV/cm for a 0.5 mm diameter wire. Furthermore, a rod to plane spacing of 25 cm was used. The mobility of ions were assumed constant and the diffusion of the ions were neglected. The following diagram shows the rod-plane geometry:



**Figure 3-2**

The z-axis is defined as originating at the substrate panel (0 m) and extending to the tip of the electrode (approximately 0.25 m). The r-axis refers to radial coordinates where the origin is directly below the electrode tip and increases as one progresses away from the radial tip.

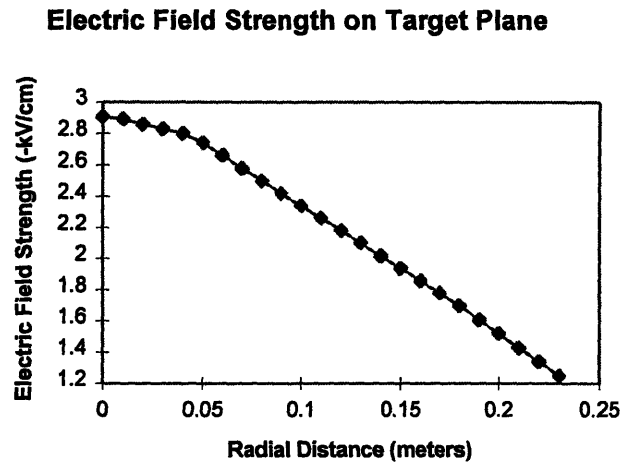
Calculating the electric field strength between the grounded plane ( $z=0$ ) and the tip of the corona wire at  $r=0$ , we see:



**Figure 3-3**

In figure 3-3, the x-axis represents the distance between the electrode tip and the grounded panel substrate. The plane itself is at  $x = 0$  m where the electric field strength is very weak. At the electrode tip, where  $x = 0.25$  m, the electric field strength is much higher.

Looking at the electric field strength along the target surface:



**Figure 3-4**

From figure 3-4, one can see that electric field strength is dependent upon position. The electric field strength gets weaker at distances further from the corona tip in both the radial and axial directions. This will have implications upon both particle charging and transport. Aerodynamic fluid forces must be considered as well when modeling the particle charging.

### 3.2.3 - Trajectory Model

Ali, Base, and Incullet modeled the trajectory of a particle based upon Newton's law with consideration to the effects of drag and electrostatic forces. This can be applied easily by making a few simplifying assumptions:

$$\sum \vec{F} = m\vec{a} = \vec{F}_d + \vec{F}_e$$

where,

$$\vec{F}_d = 3 \rho_f \nu \pi d (\vec{u}_f - \vec{u}_p) = \text{drag force}$$

$$\vec{F}_e = q \vec{E} = \text{electrostatic force}$$

$$\rho_f = \text{fluid density (kg / m}^3\text{)}$$

$$\nu = \text{kinematic coefficient of viscosity (m}^2\text{ / s)}$$

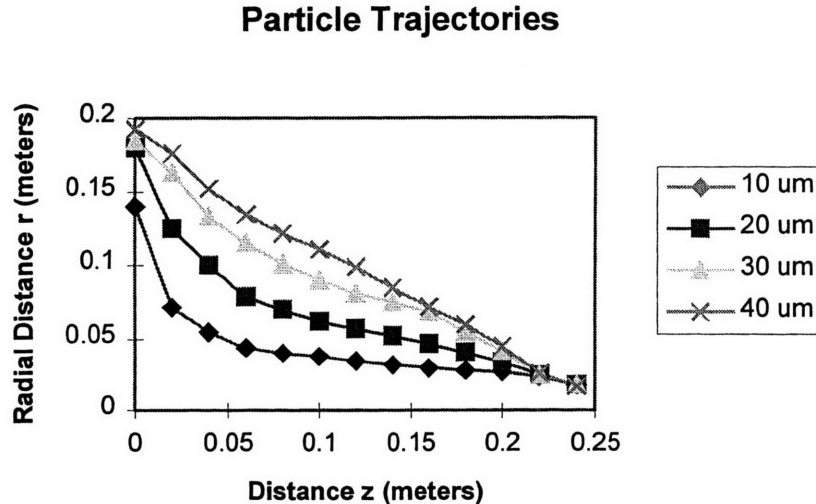
$$d = \text{particle diameter (m)}$$

$$\vec{u}_f = \text{fluid velocity (m / s)}$$

$$\vec{u}_p = \text{particle velocity (m / s)}$$

$$q = \text{charge (C)}$$

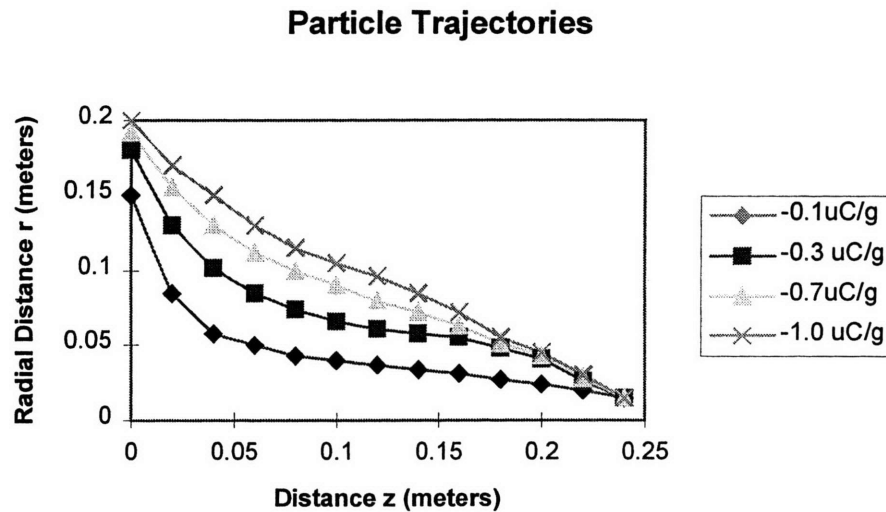
The actual path of the particles are dependent on the shape of the applicator's nozzle and the deflector dimensions. Several simplifying assumptions can make particle path modeling much easier. For example, figure 3-5 shows the effect of particle size (for particles of 10, 20, 30 and 40 microns in diameter) assuming an applied operating voltage of -100 kV and a constant charge/mass ( $q/m$ ) ratio of  $-0.7 \mu\text{C/g}$ :



**Figure 3-5**

Figure 3-5 shows that smaller particles tend to fall closer to the radial center than larger particles. As a matter of fact, particles with a diameter of 10 microns will fall approximately five centimeters closer to the radial center than will particles with a diameter of 20 microns.

Using the above equations and assuming an applied operating voltage of -100 kV and a constant particle diameter of 30  $\mu\text{m}$ , it is possible to calculate the charge/mass ratio at various points within the electric field. The following graph shows the effect:



**Figure 3-6**

The implications of these last two graphs are not clear at first glance. On one hand, particles with the highest charge to mass ratio will tend to deposit further from the radial center than particles with lower charge to mass ratios (assuming the same size particles). At the same time, the particle trajectory model shows that smaller particles deposit closer to the radial center than do large particles (assuming the same charge/mass ratio). As the next section will show, however, smaller particles tend to have higher charge to mass ratios than large particles.

Experiments performed by the LEPC have shown that back ionization tends to occur near the radial center of a spray pattern. This could indicate two things. First, it may be that the smallest particles with the highest charge to mass ratio are depositing closer to the radial center than are large particles. It may also be that free ions which do not attach themselves to powder particles are causing back ionization to occur near the radial center.

There does seem to be substantive reasons to believe that particle size affects the location of deposition on the substrate panel. It should be possible to distribute the particle sizes of the powder being used to take advantage of the particle trajectory and charging effects. At the very least, this information should provide evidence for using consistent and well understood application parameters, as well as a controlled range of particle sizes.

### 3.2.4 - Charge/Mass Ratio

It would stand to reason that particles which charge efficiently would tend to selectively adhere to the panel substrate over particles which do not charge efficiently. In other words, particles with a high charge to mass ratio should tend to adhere more easily than would particles with a low charge to mass ratio. The saturation charge on a particle is known as the Pauthenier limit and is expressed as follows:

$$q_s = E_o r^2 \pi [3\epsilon / (\epsilon + 2)]$$

where  $q_s$  = the saturation charge on a particle  
 $E_o$  = the electric field intensity  
 $r$  = the particle radius  
 $\epsilon$  = the dielectric constant of the particle

Thus, as particles get larger they can theoretically hold more charge. Charging efficiency must be considered from a different standpoint, however. The charge to mass ratio is easily derived from the Pauthenier limit by dividing the saturation charge with the particle mass:

$$q / m = [3E_o (3\epsilon / (\epsilon + 2))] / 4dr$$

where  $q / m$  = charge to mass ratio  
 $d$  = particle density

This equation shows that the charge to mass ratio is inversely proportional to the particle radius. In other words, as the particle becomes larger the charge to mass ratio becomes smaller. This would indicate that smaller particles should adhere selectively over large particles. Later in this chapter, the effects of particle size on deposited powder will be considered.

### 3.2.5 - Field Lines

Before looking at the effect of particle size on deposited powder, it is important to consider how particle size will affect the field lines that the powder particles follow as they traverse from the gun to the panel. An electrostatic field develops between the gun and the grounded substrate panel as soon as the gun is activated. The field lines extend from the electrode tip to the part surface where they end at right angles to the part surface. The field is thus shaped by the part. The field lines also concentrate at sharp angles on the part surface which explains why deposition is greater at edges than at other part surfaces. This also results in a phenomena known as the Faraday cage effect, which simply explains the inability to get powder to deposit inside sharp corners (such as the corners of pickup truck beds).

### **3.3 - Charging Effects on Substrate Panel**

The forces acting on a particle during transport from the spray gun to the panel were discussed earlier in this chapter and in chapter 2. Once the particle deposits on the surface of the substrate panel, there are additional forces that take action. These forces include 1) the force due to the image charge of the particle, 2) the force due to the image charge of the underlying powder layer, 3) the repulsive force between the charged particle and the underlying charged powder layer, and 4) the van der Waals attractive forces between the particle and the adjacent particles deposited on the surface. In a series of experiments performed by Banerjee and Mazumder,<sup>19</sup> a powder film was deposited on a

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<sup>19</sup> Banerjee, S., Mazumder, M.K., "Microstructural Surface Properties of Powder Film in Electrostatic Coating Process," IEEE Applications Meeting, 1994

conducting disc-shaped substrate of radius R and the high voltage was turned off. The following forces are acting on the deposited particles:

$$F_{im} = \frac{\pi\rho^2 d^6}{9\epsilon_o (t+d)^2} (q/m)^2 = \text{the attractive image forces}$$

$$F_{re} = \frac{Qr^3 \rho t}{3\epsilon_o R^3} (q/m) = \text{the net repulsive forces}$$

$$F_{van} = \frac{Ad}{12x_o^2} = \text{the van der Waals attractive forces}$$

where

$\rho$  = particle density

$d$  = particle diameter

$t$  = film thickness

$q/m$  = charge to mass ratio

$\epsilon_o$  = dielectric constant of free space = 8.854 pF / m

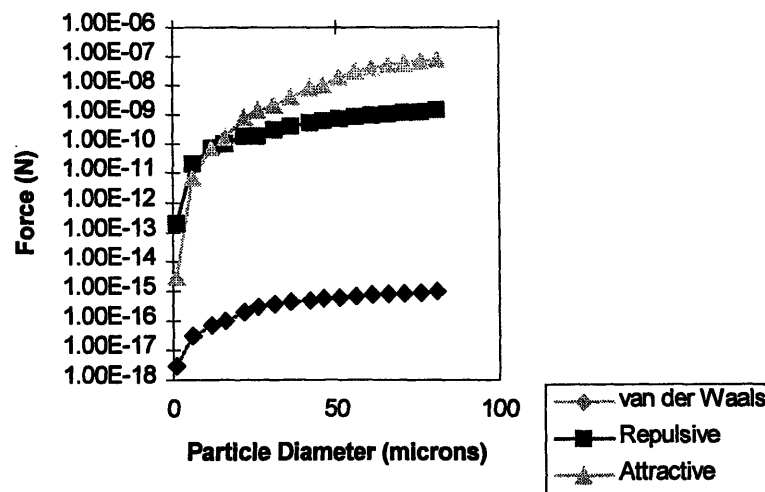
$Q$  = total charge of powder film

$A$  = Hamaker constant

$x_o$  = minimum separation between particle surface and surface of substrate

The comparative effects of these forces can be seen in the following graph:

**Adhesive Forces Acting on Particles of Different Diameters on an Electrostatically Deposited Film of thickness 50 microns**



**Figure 3-7**



Noting that the y-axis is scaled logarithmically, it is clear that the van der Waals attractive forces between adjacent particles is insignificant relative to the other forces acting on the particles. The repulsive forces seem to dominate the attractive forces for small particles (with diameters approximately less than 10 microns in diameter). As the particle size gets larger, however, the attractive forces - which are mostly due to image attractions - tend to take over. This conflicts with the theory which predicts that smaller particles with a higher charge to mass ratio will selectively adhere over larger particles. This is the same theory that was derived earlier in this chapter regarding a particle in motion flight. As a matter of fact, the attractive forces acting on a particle with a diameter of 50 microns are nearly two orders of magnitude greater than the repulsive forces.

This graph matches well with actual tests performed in the General Motor's powder laboratory. A powder supplier sent two shipments of powder which were formulated exactly the same. One shipment had an average particle diameter of 23 microns while the other shipment had an average particle diameter of 32 microns. Running the same test under the constant operating parameters several times gave the following averaged results:

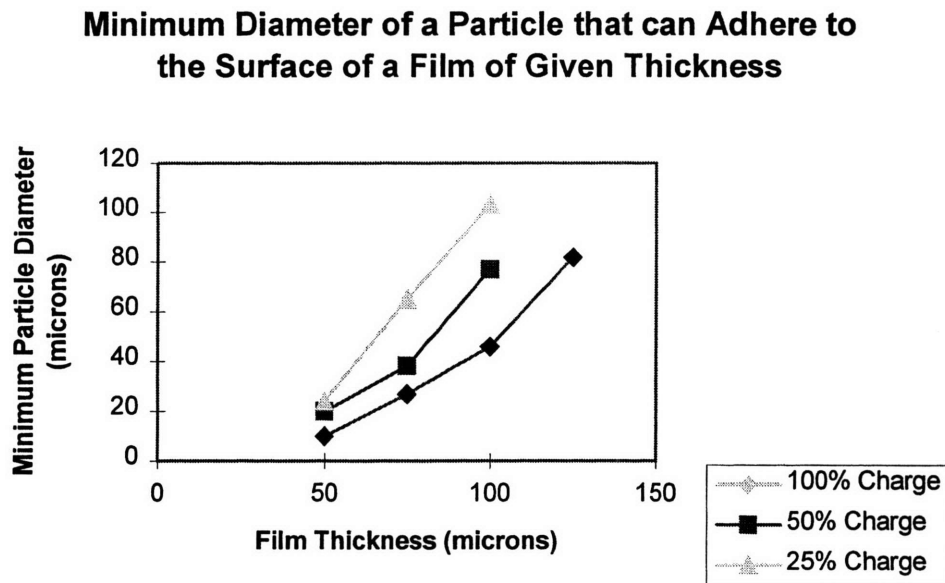
| <b>Powder Size (<math>\mu\text{m}</math>)</b> | <b>Transfer Efficiency</b> | <b>Average Film Thickness (mils)</b> | <b>Film Build Standard Deviation (mils)</b> |
|---|----------------------------|--------------------------------------|---|
| <b>23</b>                                     | 61%                        | 2.4                                  | 0.33  |
| <b>32</b>                                     | 64%                        | 2.5                                  | 0.49  |

**Table 3-1**

The transfer efficiency for the larger particles was as much as 6% higher than for the smaller particles. On the other hand, film uniformity was much better for the smaller particles than for the larger particles. Both of these differences were seen as statistically significant.

The above equations and graph, along with the concept of back-ionization, leads to the idea of self-limiting thickness. Cross, Singh, and Ahmed<sup>20</sup> described back-ionization as occurring when the air trapped in the powder layer is so highly stressed that it breaks down into positive and negative ions. Positive ions are attracted to the negative spray gun and negative ions flow to the workpiece. These oppositely flowing ions add to the total workpiece current. The positive ions leaving the workpiece form a stream of “back” ions oppositely charged to the powder which tend to discharge it.

The following graph shows the phenomena of self-limiting thickness:



**Figure 3-8**

Larger particles allow for thicker film builds. The charge to mass ratio for the smaller particles is so high that the repulsive forces dominate. Furthermore, as the % saturation charge increases, the powder film approaches the electrical breakdown voltage at which back-ionization occurs.

<sup>20</sup> Cross, J.A., Singh, Sampuran, Ahmed Abu Bakar, “Deposition Efficiency of Powders in the Electrostatic Powder Coating Process,” *Journal of Oil Colour Chemistry Association*, Vol. 63, 1980

This phenomena leads to the unfortunate “catch-22” that plagues powder paint users. Large particles allow for higher transfer efficiencies and thicker film builds, which results in better durability characteristics. Unfortunately, the smaller particles have much better film build uniformity and overall appearance. This would indicate that the manufacturer must decide what the particular customer desires. For example, the customer who is cost conscious may prefer a paint job that was sprayed using large particles because costs would be minimal due to high transfer efficiencies. The payoff, however, would be that the appearance would not be as good as for the customer who is willing to pay a little more for a paint job sprayed using smaller particles. This is a marketing issue that does not seem to be taken into consideration when evaluating a new painting technology.



## **Chapter Four - Electrical Resistivity**

DeWitt<sup>21</sup> expressed a concern with powder material electrical resistivity, bringing it to the attention of the LEPC in 1995. It has been speculated that the electrical resistivities of the powder materials being considered for automotive applications are too high, but very little work has been done to quantify these effects. While additional work needs to be done by the LEPC in this area, this chapter is meant to look further at this concern and some of the problems that could be associated with it.

Section 4.1 reviews the concept of particle charging and how it changes with time. Section 4.2 introduces the concept of electrical resistivity while considering charge dissipation and how this affect powder deposition. Section 4.3 takes these concepts and applies it the concept of self-limiting film thickness. Finally, section 4.4 considers several options that are available to the LEPC regarding resistivity.

### **4.1 - Particle Charging and Resistivity**

Particles become charged when they collide with ions and the charge is adsorbed onto the particle surface by the image force of induced dipoles. As ions continue to collide with the particle, charge will increase until the electrostatic field established by the retained charge becomes sufficiently high to repel additional ions from flowing to the particle. This is the saturation charge level described by Pauthenier in Chapter Two.

Remembering that most of the particle charging takes place near the electrode tip of the applicator and assuming that the particles are spherical, that they are not affected by the presence of another particle, and that the electric field is constant, Moreau-Hanot and Pauthenier,<sup>22</sup> the charge as a function of time can be described as:

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<sup>21</sup> DeWitt

<sup>22</sup> Pauthenier, M. M., Moreau-Hanot, M. "Journal of Physical Radium," 3, 590, 1932

$$q(t) = q_s \left\{ \frac{1}{1 + (\tau / t)} \right\}$$

where  $q(t)$  is the charge acquired in time  $t$ ,  $q_s$  is the saturation charge and  $\tau$  the time constant defined by:

$$\tau = 4\epsilon_o / (\rho_i \mu)$$

where  $\epsilon_o$  is the permittivity of free space,  $\rho_i$  is the ionic charge density, and  $\mu$  the ionic mobility.  $\tau$  is typically in the neighborhood of  $10^{-3}$  to  $10^{-4}$  seconds. Given that the time of flight for a 10 inch spray distance is about 0.2 seconds, there is usually enough time for charge saturation to occur. The saturation charge was discussed in chapter 2 by the Pauthenier equation which states that charge is proportional to particle size squared.

$$q_s = 12\pi \left( \frac{k}{k+2} \right) \epsilon_o d^2 E_o$$

where  $k$  is the dielectric constant of the particle,  $d$  is the particle radius and  $E_o$  is the charging field.

The point of this is that charge is more a function of size than it is of material properties. The dielectric constant is typically about 4 and changes little with differently formulated materials. A 50% change in the dielectric constant value only changes the saturation charge by about 20%. As discussed in Chapters Two and Three, there are more than enough ions near the electrode tip of an applicator to adequately charge the powder particles being sprayed. Reaching the saturation charge of a particle is not as much of a concern as is the rate at which that charge is lost once the particle leaves the electric field. This leads to a discussion of electrical resistivity.

## 4.2 - Resistivity and Deposition

Resistivity controls the rate of charge dissipation from a powder particle which, in turn, affects the deposition characteristics of the powder particles. Resistivity plays an insignificant role in charge accumulation.<sup>23</sup> The relaxation time for charge dissipation from an ideal charged body is given by:

$$\tau = \epsilon \sigma$$

where  $\tau$  is the relaxation time,  $\epsilon$  is the permittivity, and  $\sigma$  is the resistivity. For an acrylic powder with a resistivity of  $10^{10}$   $\Omega$ -cm., the relaxation time will be about 0.004 seconds. This is far less than the 0.2 seconds it takes for the powder to travel from the gun's electrode tip to the substrate panel. Thus, the powder will act like a perfect conductor and not deposit electrostatically. Wu<sup>24</sup> classified powders into three resistivity types: low (conductive), medium (semiconductive), and high (insulating). The three categories can be described as follows:

1) *Low resistivity (conductive)* powders (less than  $10^{10}$   $\Omega$ -cm). have relaxation times less than 0.01 seconds. Such powders will lose their charge either during transport to the panel or immediately thereafter. The charged powders that do reach the surface will become oppositely charged by induction near the substrate surface and be immediately repelled by a repulsive force. This force is proportional to the particle diameter squared and will cause particles greater than 5 microns in diameter to instantly fall off the substrate. According to Corbett,<sup>25</sup> conductive powders can be deposited if the applied charge is low enough so that this repulsive affect is avoided. Such depositions are difficult to control, however.

2) *Medium resistivity (semiconductive)* powders ( $10^{10}$  to  $10^{13}$   $\Omega$ -cm.) have relaxation times in the neighborhood of 10 seconds. The voltage on the powder stays low because such powders leak charge off gradually. The coating will grow

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<sup>23</sup> Wu

<sup>24</sup> Ibid.

<sup>25</sup> Corbett, R.P., "Science and Technology of Surface Coatings," *Academic*, New York, 1974

steadily without experiencing self-limiting thickness, but adhesion may still be poor.

3) *High resistivity (insulating) powders* (above  $10^{13}$   $\Omega$ -cm.) with relaxation times ranging from several minutes to several hours. Typical powders give uniform and efficient deposition, except as the self-limiting thickness is approached.

Insulating powders are necessary for industrial coating operations, but there may be an optimal level of resistivity, as discussed in the rest of this chapter.

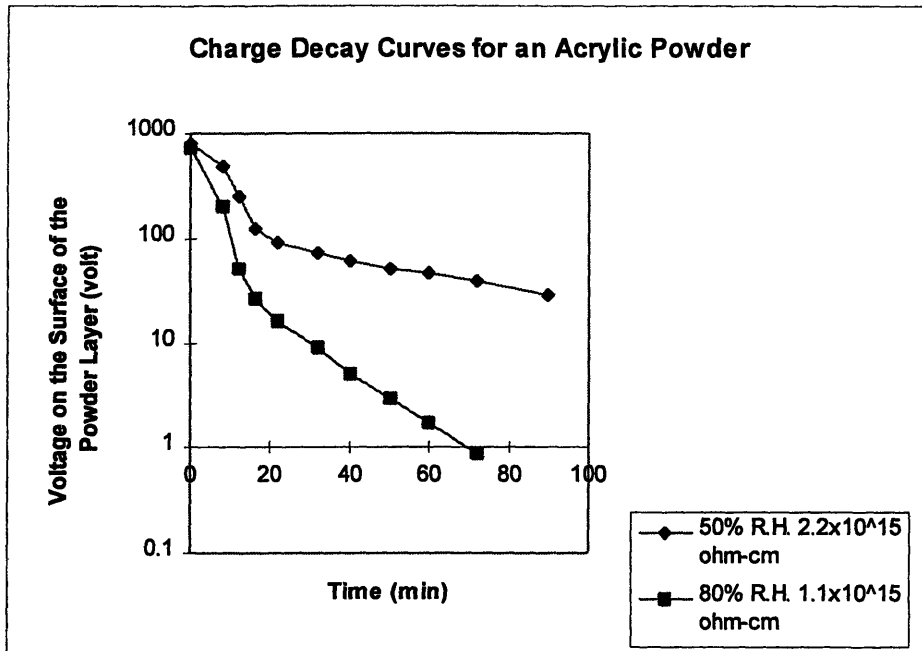
Wu's findings contradict some of the work done by DeWitt and the LEPC. Given the fact that only a small percentage of ions deposit on the powder particles, Wu believes that obtaining enough charge to be sufficient for deposition is not a problem for most materials. Wu feels, however, that powder charge decay due to low electrical resistivity can cause a deposition problem. This would indicate that electrical resistivity is not as important of an issue as once thought.

Wu described the charge decay from a powder layer as being composed of two superimposed relaxation processes. He described the rate of voltage decay on the surface of a powder layer as:

$$V(t) = V_1 \exp(-t/\tau_1) + V_2 \exp(-t/\tau_2)$$

Where  $V(t)$  is the voltage on the powder layer at time  $t$ ,  $\tau_1$  (fast mode) and  $\tau_2$  (slow mode) are the relaxation times for the initial and secondary responses, respectively, and  $V_1$  and  $V_2$  are constants. The fast mode predominates in the initial period, while the slow mode controls the later period. According to Wu, the initial relaxation time,  $\tau_1$ , depends on the humidity and powder resistivity. It decreases with lower resistivity and higher humidity. Figure 4-1 was derived for an acrylic material at 50 and 80% relative humidity:





**Figure 4-1**

Golovoy and Colvin<sup>26</sup> agreed with the concept of voltage decay being composed of two relaxation processes. They formulated a relationship between  $\tau$  and both temperature and relative humidity. The effect of humidity on the rate of charge decay can be described as;

$$\tau = \tau_0 \exp(-b * RH)$$

where RH is the relative humidity and b is a parameter which depends on the chemical composition of the polymer. The effect of temperature is described as;

$$\tau = \tau_0 \exp(E / kT)$$

where E is the activation energy of the charge decay, k is the Boltzman constant, and T is the absolute temperature. For most polymers, the activation energy is in the range of 0.4-2.7 eV.

<sup>26</sup> Golovoy, A., Colvin, A.D., "Charge-Decay from Electrostatically Charged Powders," Society of Manufacturing Engineers' 3rd Powder Coating Conference, Cincinnati, OH., September 1974

Obviously, the voltage on the surface of the powder layer is dependent of the charge retained by a deposited particle. Golovoy described the average charge as a function of surface resistivity and time. This equation is shown here:

$$q(t) = q_s \exp\left(\frac{-t}{\sigma \epsilon_0 \epsilon}\right)$$

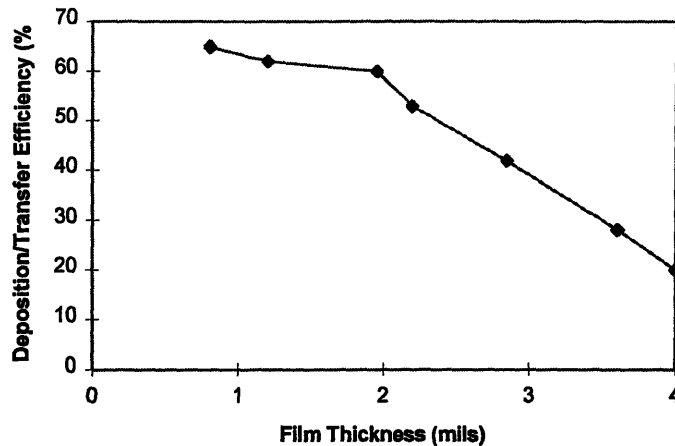
where,  $\epsilon$  is the dielectric constant of the particle and  $\sigma$  is the surface resistivity. As mentioned earlier, particle size also plays a role in particle charging as well.

### **4.3 - Film Thickness and Deposition**

Golovoy discussed the importance of film thickness on deposition efficiency in an article written at Ford Motor Company. The deposition efficiency and film thickness are ultimately limited by the voltage that has built up on the surface of the powder film. As discussed earlier, the film thickness is limited because the voltage drop across the powder layer causes electrical breakdown to occur which prevents other powder from depositing. Electrical resistivity will affect the charge on each particle and the voltage drop across the powder layer which in turn affect the film thickness and the potential for back ionization.

This is demonstrated in figure 4-2, based on work by Golovoy using an applied charging voltage with various targeted film thicknesses:

**Deposition Efficiency vs. Film Thickness at  
60 kV Applied Voltage**

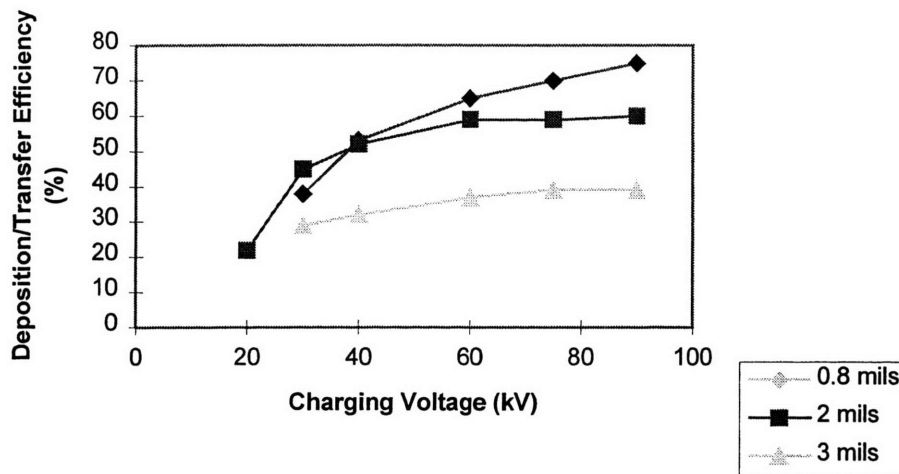


**Figure 4-2**

This is somewhat more extreme than data produced by the LEPC, but it makes a valuable point. At the thicker film builds, the resistivity of the powder is simply too high to leak off enough charge for additional powder to be applied. In other words, transfer efficiency decreases as the target film build is increased. Unfortunately, LEPC studies were not performed to test this concept, but studies indicate that transfer efficiency can be increased by 5-7% by cutting target film build by 0.5 mils.

The same concept is pertinent if the applied voltage is increased as shown in the diagram below. Comparing deposition efficiency with applied voltage with targeted film builds of 0.8, 2, and 3 mils shows that the application is less efficient as film build is increased. It also indicates that increasing applied voltage will increase transfer efficiency. This effect agrees with LEPC data for the most part (though LEPC data showed higher numbers at thicker film builds), except that LEPC data showed that transfer efficiency seems to drop off at extremely high application voltages (most likely due to the onset of back ionization). This effect was shown in chapter Two. Golovoy's data is shown here:

### Deposition Efficiency vs. Charging Voltage at Film Thicknesses of 0.8, 2, and 3 mils



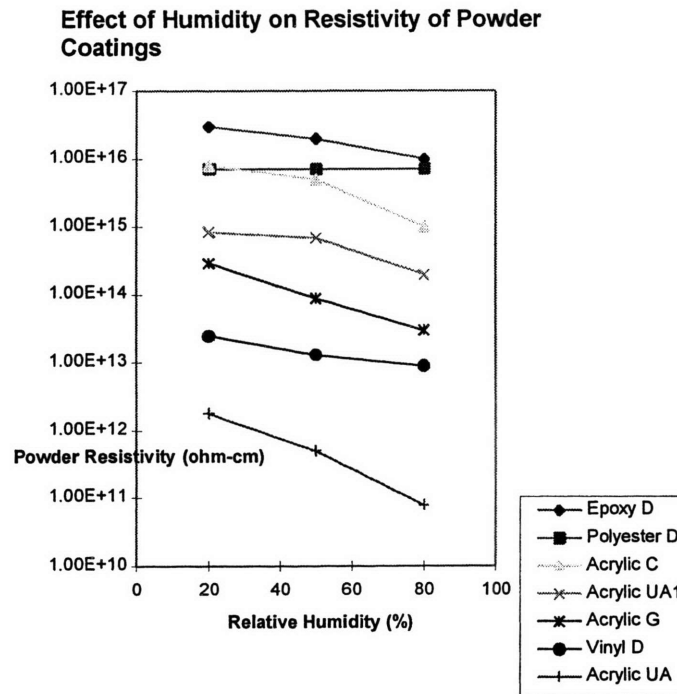
**Figure 4-3**

The importance of resistivity was shown in an experiment by Golovoy where two acrylic powders were sprayed, one with a resistivity of  $1.3 \times 10^{18} \Omega\text{-cm}$  and the other with a resistivity of  $2 \times 10^{16} \Omega\text{-cm}$ . The material with the higher resistivity had a transfer efficiency of 40%, while the less resistive material had a transfer efficiency of 65%, both at a film thickness of 2 mils. This occurred because of the approach of a self-limiting thickness under those conditions.

#### 4.4 - Options

It should be realized that electrical resistivity is just one parameter that affects transfer efficiency and that resistivity is closely related to film thickness, charging voltage, particle diameter, etc. If the resistivity of a material can be changed with all other things remaining equal, then application performance can be affected. Carefully designed experiments should be run to understand the application conditions with respect to the effect of electrical resistivity that are optimal for the material being used.

It is believed that the resistivity of a material can be affected by a number of things. The effect of humidity has been considered and presented in several papers, including those by Wu, Golovoy and Colvin, and Corbett. Corbett<sup>27</sup> showed the effect of humidity on a number of materials. This is demonstrated here:



**Figure 4-4**

Increasing humidity can decrease resistivity by as much as two orders of magnitude. Some experts, however, claim that this decrease in resistivity does not justify the potential problems that could develop with powder handling and storage as far as clumping and sticking of powder are concerned. Either way, it appears to be something that should be evaluated by the LEPC.

Another option to reduce electrical resistivity is the addition of antistats in the powder coating formulation. Labana, Chang, Theodore, Rubin, Jadwin, and Golovoy<sup>28</sup> have

<sup>27</sup> Corbett, R.P., "The Electrostatic Deposition of Conducting and Semiconducting Powders," *Electrostatic Deposition*, 1974

<sup>28</sup> Golovoy, A., German Patent 2,261,327 (1973); Jadwin, T.A. and Rubin, B.J., German Patent 2,327,371 (1973), Labana, S.S. and Theodore, A.N., U.S. Patent 3,758,632 (1973), Labana, S.S., Chang, Y.F., and Theodore, A.N., U.S. Patent 3,758,635 (1973)

patented surfactants used in polymerization that can lower resistivity two to five orders of magnitude. Wu showed, however, that these changes in resistivity only come when critical amounts of antistats are used. In other words, it is difficult to change the resistivity slightly by adding only small amounts of antistats. Instead, the resistivity will not change at all until the critical level is reached, at which point the resistivity will change drastically.

Another option is to adjust voltage at different points during application. Golovoy found that coating a panel to three mils using three passes and by increasing application voltage each time (from 60 to 75 to 90 kV) allowed him to increase transfer efficiency to 65% from 40% when the applied voltage was 90 kV for a single pass. This makes sense because it does not allow as large of a voltage drop to build up at the lower levels of the powder. This prevents the powder from reaching the self-limiting thickness as quickly which causes transfer efficiency to drop dramatically.

The most important thing to take from this chapter is how dynamic and complex the whole process is with respect to electrical resistivity. Properly run experimental designs need to be run to achieve small improvements in transfer efficiency. It is vital to understand how transfer efficiency, film build, charging voltage, and other important variables all come together.

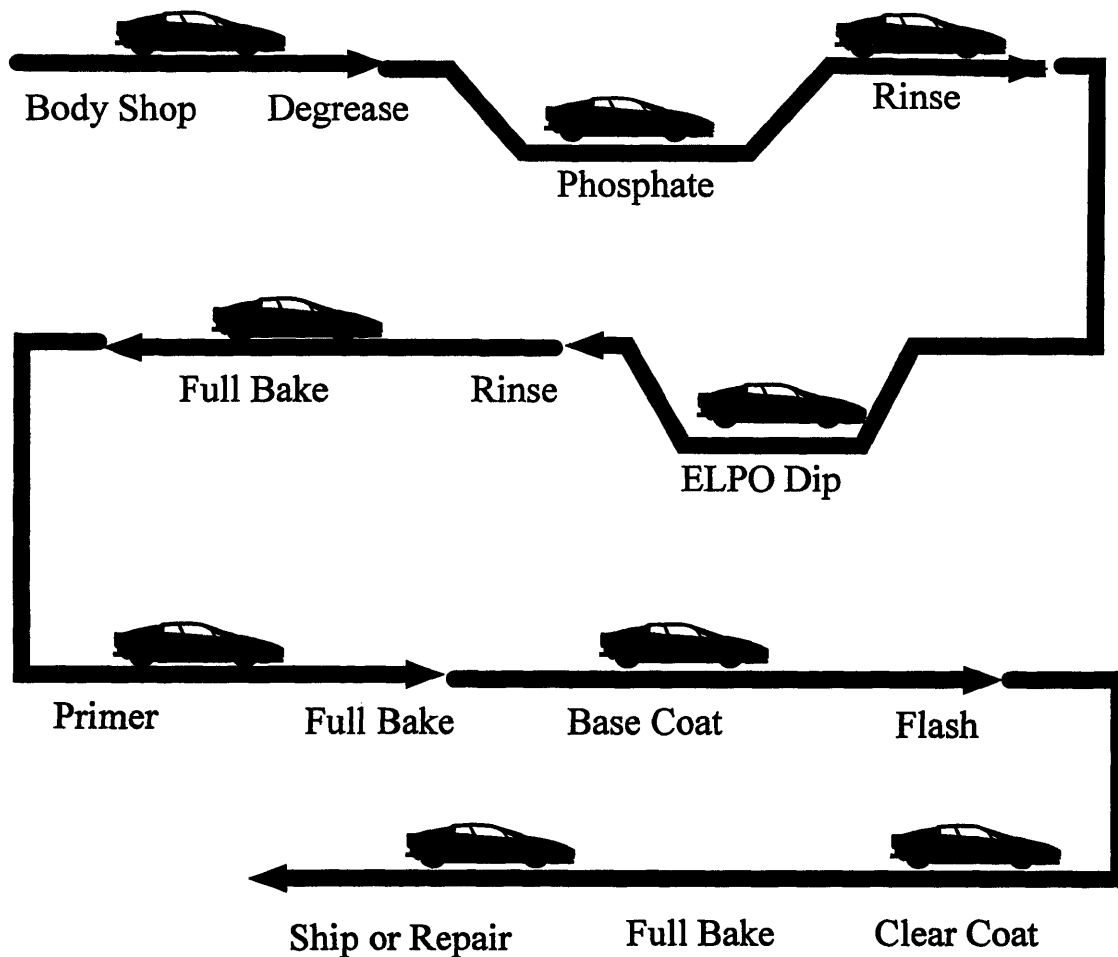
## **Chapter Five - Powder Cost Issues**

While the Low Emission Paint Consortium (LEPC) was formed for environmental reasons, implementation of powder paint systems will eventually require an economic evaluation before being put into use. Powder paint systems will require different equipment and facilities. Operational cost differences can be expected as well. While it is difficult to predict exactly what cost differences will result from the implementation of powder paint technology in automotive coating systems, this chapter will look at some of those costs and how they can be evaluated. The first part of the chapter will look at equipment and facility issues, while the second part will consider operational cost differences.

In this chapter, section 5.1 looks at the equipment and facility cost differences between liquid and powder paint systems. Section 5.2 focuses on the operational cost differences between liquid and powder paint. Section 5.3 performs a sensitivity analysis on some of the operational cost factors such as transfer efficiency, material costs, and film thicknesses. Finally, section 5.4 concludes this chapter and makes recommendations for additional work.

### **5.1 - Equipment and Facilities**

A drawing of the key steps in a standard coating system is shown here in figure 5-1:



**Figure 5-1**

Various aspects of these process steps will change if and when powder technology is fully implemented, though the overall framework will remain the same.

The car bodies run on a conveyor system throughout the entire paint shop. At some points, they are hung from a conveyor system while they ride on a belt at other points. The different process steps are explained here briefly.

*Body Shop* - The car bodies (shell only) are assembled outside the paint shop. All plastic or fiberglass parts, such as bumpers, are painted in another facility.



*Degrease* - Any oils or contaminants on the car body from the welding processes are removed using a wash spray. This will be the same with or without powder technology being used in automotive coating.

*Phosphate* - Further cleans the car from oils and prepares the metal for coating. Powder coating technology for automotive applications will not change this step. This is followed by a rinsing step before going onto the next step.

*ELPO Dip* - An electro-deposition dip process is used for rust inhibition of the metal substrate surface. After this step, a rinse is performed before going to an oven where the ELPO coat is baked onto the surface. The coated car body runs on the conveyor system through a long oven. Several types of ovens are used depending on the coating material being used, but some similarities are common to all ovens. Most importantly, the ovens are the primary source of VOC venting that is emitted by the paint materials being applied. These vents are recovered and sent to an incineration unit where natural gas is added to incinerate the VOC's from the paint. The incinerators have scrubbing and monitoring systems that control the final emissions. The ELPO step will not change if and when powder technology replaces liquid technology.

*Primer* - Several assembly plants at both General Motors and Chrysler are using powder primer to replace the liquid primers that have been available for years. A liquid primer system has several issues that must be addressed which do not exist in powder primer systems. Liquid primer that does not adhere to the car body goes to a liquid recovery system underneath the car. The sludge that results must be treated and disposed of. The air in the spray booth must be continuously replenished to prevent excessive fumes from building up. The displaced air carries solvents that are sent to an incineration system where gas is added to allow combustion to take place. The powder system does not have an incineration or sludge recovery system. Instead, the powder system has an extensive air conditioning system that ensures the air going to the spray booth is consistent with respect to humidity and temperature. The powder that does not adhere to the car body

falls through grates in the floor and is transferred to a powder recovery system from which the powder can be either recovered or disposed.

*Base Coat* - The base coat systems are very similar to the liquid primer systems only most, if not all, plants have switched to water-based from solvent-based systems. The application differences between the two systems are not significantly changed. The car is sent through a flash zone after the base coat application so that the surface of the liquid becomes tacky, though the paint is still wet underneath the surface. The clear coat is then applied over the still damp base coat. The car body is then sent to an oven where the liquid in both the base and clear coat evaporate.

*Clear Coat* - The facilities for the liquid and powder clear coat systems are the same as for the respective liquid and powder primer coat systems. There are some concerns with powder clear coat regarding a phenomenon known as “solvent pop.” When powder clear coat is applied over a base coat that is still damp, the powder clear coat will begin cross-linking before the water in the base coat is able to evaporate. Pin-hole sized bubbles will appear as the water in the base coat finds its way out. This phenomenon is not seen with solvent-based clear coat. As a result of this, it is suspected that a larger flash zone will be needed between the base coat application and the powder clear coat spray booth.

#### Equipment and Facilities Summary

In summary, there are a number of facility issues that will create a cost differential when installing a powder coating system versus a liquid system. Conversations with experienced project managers at both Chrysler and General Motors revealed that installing a powder system at a greenfield site will cost \$4-5 million less than would installing a liquid system. Retrofitting a liquid system to use powder is estimated to be about half the cost of installing a brand new powder system at a greenfield site. This cost, however, is very dependent on the particular paint shop where the installation is taking place. The cost to retrofit a liquid paint shop can be significantly higher if space is

not available for items like a powder storage room or the longer ovens needed for powder curing.

A liquid paint system has several capital items that do not exist in a powder system. These items include facilities for treating and disposing liquid paint sludge, and a liquid recirculation system. The liquid paint that does not adhere to the car is collected in a separation system where the solids are removed as sludge and the solvents are returned to the paint mix room where the paint condition is continuously monitored. Air treatment, such as heating or dehumidifying incoming air, requires more equipment in a liquid system than in a powder system. Because of the presence of flammable solvents, all air must be vented to an incinerator. Also, because the fire danger in a liquid system is greater than in a powder system, a more elaborate fire extinguishing system is required.

A powder system, on the other hand, has some unique capital items as well. Powder that does not stick to the car is recovered in a reclaim system that allows the powder to be either returned to the spray hoppers or disposed of. As mentioned above, the flash zone before powder clear coat will likely need to be longer, as will the curing ovens after the primer and clear coat applications. While the air condition used in a powder system is very important, most of the air that passes through the spray booth can be returned and reused in the same booth. The powder storage room must be kept cool and dry so that the powder does not clump together causing problems in the fluidizing beds.

## **5.2 - Operational Cost Differences**

The operational cost differences between powder coating and liquid coating will be an important issue when powder technology implementation is being considered. Many of the changes that take place when powder technology is introduced will not significantly affect the operational costs of running a paint shop. The information presented in this section come from numerous conversations with corporate paint experts in both Chrysler and General Motors. This data includes assumptions on both their part and mine. In

some cases, the cost differences are assumed to be negligible, though the process may be changing dramatically. For example, the amount of electricity required to run an electrostatic paint applicator was assumed to be the same as the requirements for a liquid applicator.

This section will discuss the issues considered when comparing the operational cost differences between powder and liquid paint application. This section will also attempt to quantify those differences using collected data. Finally, a sensitivity analysis will be conducted so that the importance of various operational costs can be better understood.

#### 5.2.1 - Issues Considered

Each step of the auto coating process was considered and discussed with personnel familiar with both the powder and liquid application. Much of the analysis is based on speculation with respect to powder clear coat which is only available in small quantities from selected paint suppliers. General Motors and Chrysler each have several powder primer facilities that could be used for data. Most of the cost differences are in the primer and clear coat areas, though e-coat and base coat will be slightly affected by the use of powder versus liquid.

*ELPO Coat* - The use of a powder primer requires slightly less e-coat, but it is not enough to warrant a comparison based on discussions with personnel familiar with material usage's in both liquid and powder primer facilities.

*Primer Coat* - Material cost differences between powder and liquid are significant and are dependent on both transfer efficiency and film build. These differences will be discussed later in this chapter. The application cost differences were not considered to be significant, though the application methods are completely different. Manpower cost differences for application and repairs were also considered, but were not expected to be significant. The application and inspection of the final paint job are essentially the same

from the operator's standpoint. Sludge and water treatment costs for liquid systems are a significant expense that do not exist in powder systems. Incineration costs are similar. Oven heating costs will be slightly different, but vary from one process to the next. Though curing temperatures are slightly higher for powder applications, the complexity of liquid system ovens likely offset any additional cost.

*Base Coat* - It is not expected that there will be any differences in the amount of material or the application process itself with regard to the color base coat. It is likely, however, that a longer flash zone will be needed prior to the clear coat application due to the tendency for "pin holing" as discussed earlier. The operating cost differences between the liquid and powder flash zone were not expected to be significant enough to warrant any calculations.

*Clear Coat* - The operational cost differences for the clear coat application will be very similar to the differences for the primer coat. The material cost difference between powder and liquid will be different, as will the sludge/water treatment and the incineration costs. Otherwise, the operational expenses will be more or less the same.

### 5.2.2 - Difference Calculations

This section will look at the material cost differences between liquid and powder for both primer and clear coat, sludge treatment, and incineration. After summarizing the cost differences, a sensitivity analysis will be performed on some of the variables that could significantly affect the overall cost differences.

#### *5.2.2-1 - Primer Cost Differences*

The amount of powder primer needed for a car body can be easily calculated knowing the exterior area of the automobile, the average film build being applied, the density of the powder, and the transfer efficiency for the application.

Using data from one of Chrysler's assembly plants with an annual production of approximately 180,000 cars/year, cost calculations for powder primer can be performed. The exterior area of the automobile is 16,363 in<sup>2</sup> with a target film build of 3.5 mils and a sill area (the area along the base of the car doors and behind the wheels) of 1,700 in<sup>2</sup> with a target film build of 8 mils. The primer powder being applied has a density of 1.15 gm/cm<sup>3</sup> and a price of \$4.40/lb. Assuming a transfer efficiency of 95% (which assumes powder is recovered and reused), these numbers can be utilized to determine that this car has approximately 3.10 lbs or \$13.55 worth of powder paint. Assuming an annual production rate of 180,000 cars/year, the total cost of powder primer is approximately \$2.44 million/year.

Applying liquid primer to the same car body requires different application parameters. The film build required for similar performance parameters is 1.2 mils and the assumed transfer efficiency is only 60% since the liquid cannot be recycled. Given that the solids percentage is about 46.5%, the average car body requires 0.3934 gallons/unit. At a price of \$30/gallon, the cost per unit is \$11.83. Assuming a production rate of 180,000 cars/year, the total cost for liquid primer is \$2.13 million/year.

#### *5.2.2-2 - Clear Coat Cost Differences*

Assuming the same car dimensions (16,363 in<sup>2</sup> exterior area plus 1,700 in<sup>2</sup> for the sills) and a film build of 3 mils for powder clear coat, calculations similar to primer can be reached. Given a powder density of 1.12 g/cm<sup>3</sup> and an assumed transfer efficiency of 95% (which assumes powder reclaim and reuse), 2.53 lbs of clear coat is needed for each car. While this price is not available at this time, it is expected that this cost will be about \$12.50/lb which will lead to a cost per car of \$31.63. Assuming a production rate of approximately 180,000 cars/year, the total amount of money spent on powder clear coat will be about \$5.69 million/year.

Applying liquid clear coat to the same car requires only 2.2 mils to achieve the same performance parameters. The transfer efficiency for clear coat at Chrysler facilities is assumed to be roughly 80% and the percentage of solids in the liquid clear coat is 46.5%. The typical car requires approximately 0.533 gallons at \$30.50/gallon. This results in a unit cost of \$16.23/car or about \$2.92 million/year based on an annual production goal of 180,000 cars.

### *5.2.2 - 3 Sludge Treatment/Disposal*

Most data for sludge treatment and disposal are on a per unit basis, though some aspects of the sludge system process are performed on a routine basis and have less to do with production rates than with planned plant shutdowns. After going through data from several Chrysler Assembly plants for primer and clear coat, the following data seem to be representative:

| <u>Item</u>                         | <u>Cost/Unit</u> |
|-------------------------------------|------------------|
| Chemical Treatment                  | \$0.70           |
| Sludge Transportation               | \$0.099          |
| Sludge Disposal                     | \$0.209          |
| Sludge System Cleaning (2 annually) | \$1.64           |
| Maintenance                         | \$0.509          |
| Operation                           | \$0.339          |
| Booth Water Dump                    | \$0.013          |
| Miscellaneous (filters, etc.)       | \$0.027          |
| <hr/> <hr/>                         | <hr/> <hr/>      |
| Total Cost per Unit                 | \$3.536          |

Again, items such as sludge system cleaning and booth water dumps are performed on a regular, timely basis, rather than on a volume basis, but this will be neglected for the purpose of this analysis. Based on an annual production volume of 180,000 cars, the total cost associated with the operation of the paint sludge system for both primer and clear coat is \$636,000.

#### *5.2.2-4 - Incineration*

Data in this section comes from conversations with experts at Chrysler who are familiar with the operational costs for incineration systems. Air that is vented from curing ovens and air that passes through the liquid spray booths contain organic solvents that are damaging to the atmosphere. These organic materials can be contained by passing the vent streams through an adsorption unit or by sending them to a thermal oxidizer for incineration. Incineration is the method most frequently used. Since the concentration of organic materials in the vent streams is usually low, natural gas must be used to ensure near complete combustion.

The operational costs associated with an incineration system include the services of an on-line technician (assume 2 shifts at \$40,000 per shift per year), and the part time services of maintenance personnel (assume \$45,000 per year for labor and materials). The total labor costs of an incineration system, then, is \$125,000 per year.

Based on an estimate of 425,000 CFM of air through the booths, the vent stream requires about 74 million BTU/hr for combustion. With 1000 BTU/ft<sup>3</sup> and \$6.47/1000 ft<sup>3</sup>, the fuel cost for operating the incinerator is approximately \$480/hour. Assuming an annual production volume of 180,000 cars/year at approximately 50 cars/hour, the incinerator will operate for 3600 hours/year. The resulting annual fuel cost is approximately \$1.73 million. Together with labor costs, the operational cost for the incineration system is about \$1.85 million/year.

#### *5.2.2-5 - Summary of Operational Cost Differences*

Given the assumptions described above the operational cost of the powder system will exceed the operational cost of the liquid system by about \$600,000 per year. The



operational cost differences between a liquid and powder paint shop can be described as a function of those assumptions using the following equation:

$$\begin{aligned}
 &\text{Operational Cost Difference (Liquid minus Powder)} = \\
 &-\$125,000 + 480 * \frac{\text{Annual Production Volume}}{\text{Hourly Production Rate}} \quad \leftarrow \text{Incineration Cost} \\
 &- \$3,536 * \text{Annual Production Volume} \quad \leftarrow \text{Sludge Treatment Cost} \\
 &\text{Powder Primer Cost} \rightarrow - \$3,536 * \text{Annual Production Volume} \\
 &+ \$\text{Annual Production Volume} * \frac{(58.9 * \text{Primer Film} + 6.1 * \text{Primer Si II Film})(\text{powder density}) \left( \frac{\text{Powder Primer Cost}}{\text{lb}} \right)}{\% \text{ Transfer Efficiency}} \\
 &\text{Powder Clear Cost} \rightarrow - \$\text{Annual Production Volume} * \frac{19.7 * \left( \frac{\text{Liquid Primer Cost}}{\text{gal}} \right) (\text{Film Thickness})}{\% \text{ Transfer Efficiency}} \quad \leftarrow \text{Liquid Primer Cost} \\
 &+ \$\text{Annual Production Volume} * \frac{71.5 * (\text{Clear Film}) * (\text{Powder Density}) * \left( \frac{\text{Powder Clear Cost}}{\text{lb}} \right)}{\% \text{ Transfer Efficiency}} \\
 &\text{Liquid Clear Cost} \rightarrow - \$\text{Annual Production Volume} * 19.3 * \frac{(\text{Film Thickness}) * \left( \frac{\text{Liquid Clear Cost}}{\text{gal}} \right)}{\% \text{ Transfer Efficiency}}
 \end{aligned}$$

Using this equation to model the operational cost differences between liquid and powder paint systems, it is easy to perform a sensitivity analysis around certain variables. For example, the effect of powder clear coat transfer efficiency on the overall cost difference can be analyzed by differentiating this equation with respect to powder clear coat transfer efficiency. The decision to reclaim and reuse powder clear coat should be fully understood from a cost standpoint. The next section will look into these issues more deeply.

### 5.3 - Sensitivity Analysis

The above equation can be manipulated in a variety of ways to evaluate how sensitive the overall operational cost difference is with respect to certain variables. For example, there may be questions regarding how transfer efficiency affects the big cost picture. Transfer efficiencies of 90% are possible if material is recovered and reused, but the chances of contamination increase considerably. Transfer efficiencies in the 60-70% range are more realistic which causes material costs, and thus overall operational costs, to go up. Putting the above equation onto a spreadsheet, matrices can be easily derived that allow cost differences to be quickly determined for different operating outcomes. Table 2-1 shows such a matrix:

**Annual Operational Cost Differences: Powder minus Liquid  
(in \$millions)**

|                      |     |                          |      |      |      |      |      |
|----------------------|-----|--------------------------|------|------|------|------|------|
|                      | 100 | 5.58                     | 3.78 | 2.49 | 1.52 | 0.77 | 0.17 |
| Powder Primer TE (%) | 90  | 5.84                     | 4.03 | 2.75 | 1.78 | 1.03 | 0.43 |
|                      | 80  | 6.16                     | 4.35 | 3.07 | 2.10 | 1.35 | 0.75 |
|                      | 70  | 6.57                     | 4.77 | 3.48 | 2.51 | 1.76 | 1.16 |
|                      | 60  | 7.12                     | 5.31 | 4.03 | 3.06 | 2.31 | 1.71 |
|                      | 50  | 7.89                     | 6.08 | 4.8  | 3.83 | 3.08 | 2.48 |
|                      |     | 50                       | 60   | 70   | 80   | 90   | 100  |
|                      |     | Powder Clear Coat TE (%) |      |      |      |      |      |

**Table 2-1**

Knowing the powder primer and the powder clear coat transfer efficiencies, the additional operating cost of running a powder system can be determined. As can be seen, the annual operating cost of running a powder system becomes significantly more expensive than running a liquid system as the transfer efficiency of the powder application drops.

Additionally, the cost savings (or losses) associated with a change in transfer efficiency can be calculated from this chart. For example, if the powder clear coat transfer efficiency is 60% and the powder primer transfer efficiency is increased from 60% to 70%, an annual cost savings of \$540,000 can be expected. On the other hand, if the powder primer transfer efficiency is 60% and the powder clear coat transfer efficiency is increased from 60% to 70%, an annual cost savings of \$1.28 million would be expected. Obviously, the primary difference is due to the higher expected cost of powder clear coat.

Using the same equation on the same spreadsheet, other variables can be manipulated to analyze the effect of other variables. For example, the effect of powder primer film thickness and powder primer transfer efficiency can be observed in table 2-2:

**Powder Primer Film Thickness vs. Transfer Efficiency**

|                                     |                      |      |      |      |      |      |       |
|-------------------------------------|----------------------|------|------|------|------|------|-------|
| Powder Primer Film Thickness (mils) | 4.0                  | 3.30 | 2.44 | 1.83 | 1.37 | 1.01 | 0.72  |
|                                     | 3.5                  | 2.76 | 2.00 | 1.45 | 1.03 | 0.71 | 0.46  |
|                                     | 3.0                  | 2.23 | 1.55 | 1.07 | 0.70 | 0.42 | 0.19  |
|                                     | 2.5                  | 1.70 | 1.11 | 0.69 | 0.37 | 0.12 | -0.07 |
|                                     |                      | 50   | 60   | 70   | 80   | 90   | 100   |
|                                     | Powder Primer TE (%) |      |      |      |      |      |       |

**Table 2-2**

As can be seen, the cost of operating a powder system can be reduced significantly if the required film thickness can be decreased. Certain materials may allow for slightly thinner film builds without sacrificing performance characteristics. Decreasing the film build variation also allows for a reduction in material usage. The minimum paint thickness on

a substrate ultimately controls the ability of a panel to resist abrasion and corrosion. Minimizing the film build variation allows for a lower film thickness target and less material. A similar table can be developed for clear coat where the material performance characteristics are not completely understood yet.

### Powder Clear Coat Film Thickness vs. Transfer Efficiency

|                                  |                   |      |      |      |       |       |       |
|----------------------------------|-------------------|------|------|------|-------|-------|-------|
| Clear Coat Film Thickness (mils) | 3.5               | 7.50 | 5.40 | 3.90 | 2.77  | 1.90  | 1.20  |
|                                  | 3.0               | 5.70 | 3.90 | 2.61 | 1.65  | 0.90  | 0.30  |
|                                  | 2.5               | 3.90 | 2.40 | 1.32 | 0.52  | -0.11 | -0.61 |
|                                  | 2.0               | 2.10 | 0.90 | 0.04 | -0.61 | -1.11 | -1.51 |
|                                  |                   | 50   | 60   | 70   | 80    | 90    | 100   |
|                                  | Clear Coat TE (%) |      |      |      |       |       |       |

**Table 2-3**

Table 2-3 shows the significance of clear coat film thickness on the overall operating cost of a powder system compared with a liquid system. For example, at a transfer efficiency of 60%, reducing the target film thickness from 3.0 to 2.5 mils will save \$1.5 million annually. The cost savings that result from film thickness reductions are larger for clear coat than for primer because the expected cost of powder clear coat is more expensive than powder primer. A table can be created that considers the effect of powder clear coat cost and compares it with transfer efficiency.

## Powder Clear Coat Cost vs. Transfer Efficiency

|                                |                          |      |      |       |       |       |       |
|--------------------------------|--------------------------|------|------|-------|-------|-------|-------|
| Powder Clear Coat Cost (\$/lb) | 15.00                    | 7.86 | 5.70 | 4.16  | 3.00  | 2.10  | 1.38  |
|                                | 12.50                    | 5.70 | 3.90 | 2.61  | 1.65  | 0.90  | 0.30  |
|                                | 10.00                    | 3.54 | 2.10 | 1.07  | 0.30  | -0.31 | -0.79 |
|                                | 7.50                     | 1.38 | 0.30 | -0.48 | -1.06 | -1.51 | -1.87 |
|                                |                          | 50   | 60   | 70    | 80    | 90    | 100   |
|                                | Powder Clear Coat TE (%) |      |      |       |       |       |       |

**Table 2-4**

This table shows the significance of powder clear coat material prices on the overall operating costs. For example, if the powder clear coat cost was \$10/lb, powder technology can become more attractive than liquid systems if the powder application transfer efficiency is high enough. A break-even point, defined as the point at which the operational costs between powder and liquid are even, occurs at a transfer efficiency of 84.5%. At a powder clear coat cost of \$7.50/lb, the break-even point occurs at a transfer efficiency of 63.5%. In other words, with all other variables at the points defined above, powder systems become cheaper to operate as transfer efficiencies exceeds 63.5%.

## 5.4 - Conclusions

This chapter looked at the cost differences for liquid paint and powder paint systems. The primary focus was on the cost of painting facilities and the operational costs for the two systems. While powder primer is being used in a number of Big Three assembly plants, there are not any plants using powder clear coat. Thus, the clear coat data for both facility and operating costs are somewhat speculative.

It appears that the cost of building a powder paint facility is cheaper primarily due to the incineration, air handling and sludge treatment systems that a liquid paint facility requires. The powder handling and recovery systems are significant expenses, however, they do not require the capital investment that a liquid system needs. It is expected that the Wixom Prove-out facility will provide much more accurate data once experiments can be run. At this time, however, it appears that a powder facility will cost in the range of \$4-5 million more than a liquid facility for a greenfield site.

The operational cost differences between liquid and powder systems tell a different story, however. Despite over \$2.5 million/year being spent on sludge treatment and incineration for a liquid system, the material costs associated with powder will more than offset these expenses. The sensitivity analysis performed on the operational data showed the dependence of cost on transfer efficiency, film thickness, and material costs. In particular, the expected material costs for powder clear coat will be particularly significant with respect to other operating costs.

## **Chapter Six - Conclusions**

This paper looked at several topics of interest with regards to the electrostatic application of powder paint in the automotive industry. The technical concerns reviewed include a detailed look at the actual application process itself, the effect of particle size on application properties, and the importance of electrical resistivity on adhesion. From a business standpoint, this paper considered cost issues associated with building and operating a powder paint facility as compared with a liquid paint system.

### **6.1 - Applicators**

Theory shows that most charging occurs near the electrode tip and that the tip condition has a significant effect on the generation of corona. The theory also showed that most ions created by the electrode tip do not attach to the powder particles that flow past. The free ions that do not attach to the powder particles, however, do not create interaction problems for the particles in transport or on the panel substrate.

This chapter also looked at the effect of various environmental and operational factors on the application process. Temperature and pressure do not significantly influence the application performance, but it does appear that humidity alters the electrical resistivity of the powder material, though it is not clear how exactly.

Numerous operational variables were considered including gun to job distance, spacing between guns, applied voltage, powder flow rates, oscillation of guns, shaping air, and atomizing air. It was found that gun to job distance and the spacing between guns (and the interaction between these two) have a critical effect on transfer efficiency, film build, and film build uniformity. It was also shown that increased applied voltage up to a certain level will increase transfer efficiency, but that transfer efficiency may drop off at very high levels of applied voltage due to back ionization and the phenomena of self-limiting thickness. Shaping and atomizing air can be used to improve film uniformity,

but it can also hurt transfer efficiency. Under optimal conditions with a target film build of 2.5 - 3.0 mils, a transfer efficiency of 65-70% with a film build uniformity of 0.3 - 0.5 mils can be expected.

## **6.2 - Particle Size Effects**

Calculations show that the electric field drops off in the radial direction and along the axis as a particle moves away from the electrode tip, and that most particle charging occurs very close to the electrode tip. This chapter looked at the effect of particle size on the trajectory path. From this model, it was also possible to determine the charge on particles by position throughout the electric field. It was found that the electric field gradient along with the particle size variation results in a distribution of particle sizes across a panel. The particle size differences create a charge distribution across a panel as well. This can result in different self-limiting thicknesses and back ionization occurring at different points across a panel. For this reason, it seems that a fairly tight distribution of particle sizes is important, though LEPC studies have not been performed to confirm this. Actually, it may be possible to skew the particle size distribution slightly to take advantage of particle size on particle trajectories and charging.

This chapter also discussed the forces acting on a particle that have already adhered to a panel. A model was developed that showed the tendency for larger particles to have stronger adhesive forces. This was confirmed in LEPC experiments that compared the transfer efficiency for two samples of the same material with different particle sizes. This chapter pointed out the unfortunate “catch-22” that plagues powder paint shops. Larger particles tend to have higher transfer efficiencies, but their appearance is not as good as smaller particles which appear very smooth after curing.

## **6.3 - Electrical Resistivity**



This chapter looked at the effect of electrical resistivity on particle charge decay. A material's electrical resistivity can be classified as low (less than  $10^{10}$   $\Omega$ -cm), medium ( $10^{10}$  to  $10^{13}$   $\Omega$ -cm) or high (above  $10^{13}$   $\Omega$ -cm). Low resistivity powders will lose their charge during transport to the panel or shortly thereafter. The particles that do reach the surface will become oppositely charged by induction and repel any incoming particles. Medium resistivity powders lose their charge in approximately ten seconds. This is long enough for the particles to adhere so that self-limiting thickness is not experienced, but adhesion will be poor as the particles lose their charge. High resistivity powders will retain their charge for at least several minutes allowing for efficient deposition, but self-limiting thickness will limit the amount of material that can be applied. The electrical buildup across the powder layer will prevent the realization of extremely high transfer efficiencies.

This chapter showed the importance of a material's electrical resistivity when considered along with targeted film thickness, particle size, humidity, and applied voltage. Each of these variables will uniquely affect the application performance. Optimal conditions need to be found for each material and designed experiments need to be run around target conditions.

#### **6.4 - Cost Comparisons**

The cost of building a powder paint facility on a greenfield site is cheaper than the cost of a similar liquid system by \$4-5 million, though the greater operational cost for a powder system will likely more than erase that difference. The powder facility is cheaper due to the need for incineration, air handling, and sludge treatment systems in a liquid system. The Wixom prove-out facility should provide considerably more data and information on powder facility costs.

Given current expectations for powder clear coat, which is still being developed commercially, the operational cost associated with a complete powder system is expected to be more expensive than for the liquid system, despite over \$2.5 million/year (per plant) being spent on sludge treatment and incineration. The thicker film builds, higher material costs, and transfer efficiencies associated with a powder system require more money being spent on materials. In particular, the expected material costs for powder clear coat are very expensive relative to the cost of liquid clear coat. The matrices shown in this chapter demonstrate the sensitivity associated with some of these variables.

### **6.5 - Recommendations**

Extensive experimental designs need to be run in a laboratory environment with the actual applicators and actual materials that are to be used in the plant. The difference between applicator systems is significant and slight adjustments in the operating parameters can give weighty gains in terms of transfer efficiency and film build uniformity. Similarly, not all materials are the same and they may actually vary from lot to lot based on particle size and distribution. Furthermore, the application performance is also affected by the target film build, not to mention environmental factors, such as humidity, that add additional noise. The numerous operational variables that can affect the application performance should be manipulated in a controlled experiment to determine the most “robust” operating conditions for a particular set of spray guns/bells and the material being used.

The discussion on operational costs shows that the LEPC should push for reduced powder clear coat costs. Reducing these costs by 20-40% will make powder technology operational costs comparable to liquid. It appears that first pass transfer efficiency will never exceed 70%, but reclaim and reuse may allow efficiencies in the neighborhood of 90%. The result of such transfer efficiencies with powder would result in annual cost savings of \$1-2 million per plant compared with liquid systems. There are reasonable concerns with contamination and powder deterioration in reclaim systems, but the cost

savings may justify solving these problems. Finally, minimizing the film build for powder coatings will also result in recognizable cost savings. Improving the performance properties of the materials is one way to minimize the powder required, but improving film build uniformity will also help. The performance properties of a material are controlled by the minimum film thickness. By minimizing the film build standard deviation (maximizing uniformity), a lower film build can be targeted.



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