A Holistic Approach to Automotive Powder Coating
by
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B.S. Chemical Engineering - University of Maine (1985)

Submitted to the Department of Chemical Engineering in Partial Fulfillment of the Requirements for the Degrees of
Master of Science in Chemical Engineering

Submitted to the Sloan School of Management in Partial Fulfillment of the Requirements for the Degrees of
Master of Science in Management

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Charles M. DeWitt

Submitted to the Department of Chemical Engineering and the Sloan School of Management in Partial Fulfillment of the Requirements for the Degrees of Master of Science in Chemical Engineering and Master of Science in Management

ABSTRACT

The ability to change, innovate and adapt is fundamental to success in technology oriented, manufacturing organizations. Examination of the U.S. Automotive industry's struggle with adopting an environmentally superior painting technology known as powder coating is illustrative of why established firms struggle with technological change. Framing the problem with the ideas of architectural innovation and the dominant design provides insight into the problem. The insight is a prerequisite for understanding a solution. A holistic approach to technology application in established manufacturing firms can enable the firms to innovate their way to success.

A holistic view of automotive powder coating requires integrating business issues with technical understanding. Strategic analysis of the automotive powder coating market shows many forces pushing toward incremental improvement and few forces in favor of step change improvement. A thorough technical analysis which incorporates models for the motion of small particles, electric fields, particle charging and other powder coating phenomena, indicates many areas for technical improvement including tighter control of particle size distributions and lowering of particle resistivity. A holistic leader must understand the technical and business related barriers to change.

Practitioners must also consider manufacturing related issues and site specific applications. Many tools are available to help translate equations, theories and ideas into viable processes and products. As an example, statistically designed experiments in conjunction with non-linear optimization techniques were used to evaluate the performance of an innovative applicator known as a powder bell. Leaders that can understand business, technical, manufacturing, and site specific issues can look past the dominant design and embrace innovations like powder coating.
Acknowledgments

Many thanks to the Low Emission Paint Consortium for providing such a wonderful educational experience. I would like to thank David Lyijnen, Yogen Rahangdale, Ernie McLaughlin and Dirhu Patel for making this possible. Special thanks go out to Ross Good, Peggy Coburn, Tim March, Patrick Schoening, David Decker and Eric Messerly for their help and patience and especially for making the work fun.

I would also like to gratefully acknowledge my thesis overseers, Steve Graves, John Lienhard, and T. A. Hatton for their assistance and support.

Finally, the biggest thanks to my wife Susan and my children Megan, Andrea, and Abigail for their understanding and sacrifice.
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Introduction

"...there is nothing more difficult to take in hand, more perilous to conduct, or more uncertain in its success than to take the lead in the introduction of a new order of things. The reason is that the innovator has for enemies all those who have done well under the old conditions, and lukewarm defenders in those who only may do well in the new. This coolness arises partly from fear of the opponents who have the laws on their side, and partly from the incredulity of men, who do not readily believe in new things until they have had a long experience of them. Thus it happens that whenever those who are hostile have the opportunity to attack they do it like partisans; whilst the others defend lukewarmly, in such wise that the prince is endangered along with them." (Niccolo Machiavelli, The Prince, 1513)

The ability to change, innovate and adapt is fundamental to success in technology oriented, manufacturing organizations, yet as Machiavelli eloquently states, "nothing is more difficult to take in hand". Examination of the U.S. Automotive industry's struggle with adopting an environmentally superior painting technology known as powder coating is illustrative of why established firms struggle with technological change. Framing the problem with the ideas of architectural innovation and the dominant design provides potential "princes" with insight into the problem. The insight is a prerequisite for understanding the solution. A holistic approach to technology application in established manufacturing firms can enable the firms to innovate their way to success.

Background
My thesis is based upon a seven month internship with the Chrysler Corporation, where I was first introduced to automotive powder coating. According to my project description, powder coating technology was under intense development in the automotive industry due to its potential to significantly reduce volatile organic compound (VOC) emissions from painting operations. During my stint, I was one of Chrysler's representatives to the Low Emission Paint Consortium (LEPC). Chrysler, Ford, and General Motors are voting members of the consortium with ABB Paint Finishing systems acting as Design and Construction Partner. The mission of the LEPC is to develop low emission paint technology; its focus is powder painting.

With the innovative establishment of the LEPC, the auto companies took a leadership role in the powder coating industry. While powder coating had been used in some automotive applications, it is still an emerging technology and there are many obstacles to its use in the high quality clear coat application. As a result the LEPC attacked the issue on a number of fronts, forming teams to look at:

- Powder coating materials, especially clear coat
- Facilities and equipment
- The construction of a $20MM "Prove-Out" facility.
The primary goal of the consortium was to improve powder coating of clear coat in terms of process efficiency and clear coat finish quality.

The thrust of my project was to develop a mass flow meter for pneumatically conveyed powder paint. Mass flow of paint is one of the critical variables in the powder paint process. Upon my arrival at Chrysler I naturally wondered, specifically how a mass flow measurement device would improve the powder coating process. This question led to further questions. I soon found that the powder coating process was complex, with many interrelated process and product variables.

In time I became intrigued with the entire powder coating process. As my LEPC colleagues patiently educated me I found that sometimes my basic assumptions regarding powder coating (as an outsider) were different than their basic assumptions. I observed that the differences in the basic assumptions would often cause us to follow very different paths of thought. Fortunately for me the LEPC afforded me the educational opportunity to explore this discontinuity of thought. In this way, quite serendipitously, I stumbled into a rare and valuable opportunity to investigate first hand, the difficulties that a new technology presents to successful, established firms.

What Is Powder Coating?
Powder coating is an environmentally friendly industrial finishing technology. Powder coating systems are slowly being adopted as a replacement for the traditional solvent based painting systems in many applications. In the greater industrial finishing industry, liquid solvent-based paint can poses two environmental concerns:
- As the solvent evaporates it creates VOC emissions
- Paint overspray becomes paint sludge which is considered a hazardous waste.

In automotive paint shops the hazardous waste problem has been eliminated, leaving only the problem with VOC emissions. In both cases environmental concerns surrounding solvent based painting systems have provided an incentive to investigate more friendly technologies.

From the perspective of the solvent based coater, dry powder, with the look and feel of talcum powder, is a substitute for the liquid paint. Raw material suppliers begin the powder production process by mixing the base resin, generally epoxy, polyester, or acrylic, together with a number of additives and then extrude the mixture to form sheets or tubes. The sheets or tubes are then, depending on the manufacturer, sent to various permutations of comminution and separation equipment including crushers, grinders, cyclones, and sieves. The diameter of the powder particles ranges from less than 5 microns to as large as 70 microns.

The powder coating process is very analogous to today's solvent-based coating process. Instead of residing in a tank prior to application as liquid paint does, the powder is fluidized in a hopper. A jet pump delivers the powder via flexible tubing from the hopper to an applicator. The applicator is generally a corona generating device; by passing through the corona, the powder particles pick up a charge. Aerodynamic and electrostatic forces convey the charged particle to the grounded part to be coated.
As one might imagine, a cloud of charged plastic dust in an open room could be a problem. Consequently, parts are coated in an enclosed booth. Air flows are set up in the booth to evacuate the chamber of powder overspray. Oversprayed powder is often sent through a reclaim system and eventually it is either recycled or in some cases disposed of.

After a part has been powder coated, electrostatic forces continue to hold particles to the surface until the job reaches the cure ovens. In the cure ovens, parts are held at approximately 300 deg. F. for 20 to 30 minutes. The curing process at first allows the paint particles to flow creating a smooth surface. As the curing process progresses, cross-linking begins to occur. Polymer cross-linking continues; after 30 minutes or so, depending on the powder, the powder thermosets. The result is a high quality and durable appearance.

Industrial finishers face some environmental pressures but often they adopt powder because of economic or feature advantages. In porcelain enamel applications, powder coating enabled manufacturers to reduce cure oven temperatures from 700 deg F to 300 deg F resulting in significant energy savings. In the lawn furniture market, the ability of powder coating to "wrap" made for a more efficient application when compared to solvent based techniques. In the case of rebar, powder coating made possible higher film builds and better performance. Powder coating is used to finish many products for a variety of reasons: appliances, office furniture, golf clubs and golf carts, baby strollers, metal toys, fire extinguishers and bathroom scales are a sampling.

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Powder paint shop system cutaway, showing powder reclaim system and exhaust under floor.
Problem Statement

Chrysler, Ford, and General Motors are leading the world in automotive uses for powder coating; still, implementation of powder coating presents many challenges. The Big Three have shown a strong interest in using powder coating to solve their environmental problems; to that end they have implemented powder coating in a some primer/surfacer applications and they have formed the LEPC whose focus is to overcome technical hurdles associated with using powder in the more critical clear coat application. But despite a focused effort, only a fraction of North American auto plants make use of production proven powder coating technology for primer/surfacer. Can something be done to accelerate the pace of change?

What are the obstacles to change? One is technical uncertainty. To be confident and to minimize risk, the auto companies must thoroughly understand powder coating; they must understand what makes powder coating tick. Once the technical problems are worked out and understood, the auto makers still face the challenge of applying the physics of the process to the manufacture of painted cars -- without stopping or interfering with production. Business issues must be factored into the analysis to determine how to make money from investments in powder coating. The technical, business, and manufacturing issues all come together in every site specific application where ideas are transformed into reality. To be successful in implementing an innovation like powder coating requires mastery and integration of a number of disparate disciplines.

And efforts need to be orchestrated. Should time be spent developing a mass flow meter or should resources be used in other areas? Functional excellence is necessary to understand the nuances of the technology but breadth is necessary understand how to integrate it. How can a decision maker gain the perspective to see the solution? A leader can play by today's industry rules and try to gain advantage by being better, stronger, and faster, or a leader can take advantage of a new innovation to change the rules. Phrased a slightly different way, the auto companies can view increased environmental regulations as an obstacle to the way things are currently done or they can see it as an opportunity to create competitive advantage.

In this context my thesis addresses some of the questions facing the Big Three including:

- How can use of powder coating be accelerated?
- How can the performance of powder coating be improved in terms of first pass transfer efficiency, film build uniformity, and appearance?
- How can powder coating be made more cost-effective?
- How can the automakers set the direction for the technology?
- Why do some suppliers behave as they do?
- What can the auto companies do to enhance their position?
The State of Powder Coating

A Brief History

Ever wonder why a computer monitor is a dust magnet, or why party balloons stick to the wall after being rubbed against hair, or how powdered plastic is coated onto automobiles? These phenomena are due to electrostatic attraction, a concept that was known to the Greeks as early as 600 BC and quantitatively explained by Coulomb in the years spanning 1785 through 1789.1 After Coulomb's discoveries nearly a century passed before a major industrial application. Electrostatic precipitation, an electrostatic ancestor to powder coating, was first attempted commercially by Sir Oliver Lodge and his associates Walker and Hutchings in 1885, but it wasn't until 1907 that Frederick Cottrell introduced the first successful commercial precipitator.2 Since 1907 electrostatic precipitation has continually developed and today it is a pervasive air pollution control technology.

Electrostatic precipitation harnessed electrostatic forces to charge, transport, and selectively deposit small particles on an industrial scale and as such was a forerunner of industrial powder coating. Of electrostatic precipitation's contributions to powder coating the most important was Dr. Harry J. White's book Industrial Electrostatic Precipitation. The 1963 work embodied the theoretical and practical aspects of electrostatic precipitation and inadvertently served as a theoretical foundation for powder coating.

Powder coating's origins can be traced to the late 1940's. "Through the 50s, 60s, and 70s, powder coatings were considered a passing fad or limited to specialized applications." 3,4 During the 1970's the auto companies were among those dabbling in powder coating technology. In 1975, Ford Motor Co. used powder to coat catalytic converters; the powder coating provided superior durability, corrosion resistance, and heat stability.5 In the early 1970's, Ford and General Motors also investigated powder coating for the highest quality body surfaces at pilot facilities in Edison, NJ and Framingham, MA assembly plants. "Each company completed a few thousand color-coat powder jobs before going back to traditional solvent borne liquid paints". Further work on powder was abandoned at that time due to problems with "inconsistent film thickness, difficulties with metallics, and the many tricks inherent in repairing powder paint."6 Nissan also jumped into the powder coating fray in 1976. "After 4 years of technical development, Nissan has constructed a mass-production powder top coating line at its Kyushu Factory where Datsun trucks are produced". But just as Ford and GM found, Nissan also recognized that powder coating required further process development.7

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1 H. J. White, Industrial Electrostatic Precipitation, Addison-Wesley, Reading, MA 1963, p. 3.
2 Ibid., p. 30.
By the early 1980's, powder coating began to be accepted as a viable industrial finishing technology.\textsuperscript{8} GM in particular, pursued the technology and in 1980-81 a production powder primer facility was installed in the new Shreveport, LA truck plant.\textsuperscript{9} Powder coating of auto parts also began to expand in the 1980's and by 1983 parts such as coil springs, engine mounts, suspension rods, hood hinges, decorative components, aluminum wheels and many underbody and underhood areas were being coated with powder.\textsuperscript{10}

In the early 1980's justification for a powder coating system was difficult. Solvent based painting was an established, ubiquitous, cost-effective technology. With high switching costs, the decision to move to powder coating was made infrequently. In some cases investment in powder coating was based on a financial analysis, but more likely in this timeframe powder coating adopters were looking for superior features such as durability. But by the late 1980's US Government would provide industrial finishers with an additional cogent reason for investment in powder coating, environmental regulation.

"Most coating manufacturers agree that the Clean Air Act has had the single greatest impact on the coatings industry, particularly since the Clean Air Act Amendments of 1990 (CAAAA) became law. VOC regulations are requiring increased solvent reductions or substitutions."\textsuperscript{11} In addition to the Clean Air Act, state and local governments are enforcing increasingly stringent laws regarding VOC emissions. "California in particular requires that finishers apply extremely high-solids coatings, or switch to waterborne or powder coatings"\textsuperscript{12}.

VOC emissions are not the only environmental problems facing solvent based painting. While the automotive industry has solved the solid waste problem, for many in the industrial finishing industry solid waste disposal is another critical issue. The solvent based coating process is generally about 50% to 80% efficient. The overspray from the process is officially classified as hazardous waste and therefore is subject to the Resource Conservation and Recovery Act (RCRA) as well as the Comprehensive Environmental Response Compensation and Liability Act (CERCLA a.k.a. Superfund).\textsuperscript{13},\textsuperscript{14} Understanding and managing regulatory compliance is a costly headache and provides considerable impetus toward investing in environmentally friendly coating technologies.

The tougher environmental regulations spawned a resurgent interest in numerous technologies. Some of the technologies are:
- **Waterborne**: These coatings are under intense development for automotive base coat applications, but they have been found to be unacceptable for clear coat applications.

\textsuperscript{12} *Ibid*, p 14.
Waterborne, like solvent-based painting, provides quick color change capability, but does have low level VOC emissions. The current market, estimated at $800 million, is primarily serving the architectural paint users.¹⁵

- Supercritical fluids: In 1991, Union Carbide announced its Unicarb system. The intent of Unicarb was to use supercritical carbon dioxide to replace 70% to 80% of VOCs from industrial painting operations.¹⁶ Some automakers have followed up on the supercritical technology with little success.

- High solids: "Traditional solvent borne coatings typically were 40% resin, pigment, and additives, and 60% solvent. Today that ratio has flipped; some coatings are even 70% solids and only 30% solvent."¹⁷ However, further reduction in solvent is limited due to performance problems.

- UV-cure: While UV-cure is VOC-free with high quality appearance and strong resistance properties, it requires a considerable investment in hardware. In addition the UV-cure coating can pose a safety hazard to workers.¹⁸ UV cure requires line-of-sight between the cure equipment and the surfaces of the part, limiting its usefulness to the coating of flat, simple shapes. For this reason it is an unlikely candidate for use in automotive applications.

- Coil coating: "Coil coating is an environmentally friendly application process in which a coil of metal is unwound, coated, baked, and then rewound for shipment. Although the paint used in the process is solvent-based, the solvents are not emitted into the atmosphere. Instead, the volatile emissions are captured, condensed, and then burned for energy."¹⁹ In applications where corrosion is an issue, coil coating can be a problem because of incomplete coating at the cut edges. Coil coating might have an impact on the industrial finishing market but given today's automotive assembly process it is difficult to see how pre-painted steel from a coil coating could help automotive paint shops reduce VOCs.

- Powder slurry: BASF has recently developed a hybrid technology. Powder is conveyed and applied in slurry form. BASF claims comparable film build and superior appearance to normal powder coating with their powder slurry process.²⁰ Powder coating is but one of the available VOC reducing technologies. Which begs the question: What does powder coating offer that would induce someone to choose powder coating over other painting solutions?

**Powder Coating Today - Pros and Cons**

As industrial finishers, including automotive paint shops, search for ways to meet environmental regulations, powder coating is emerging as the dominant, environmentally friendly technology. In the US automotive industry, "the cost of fitting expensive

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emissions abatement equipment to assembly plants has added at least $5 to the cost of
every new vehicle."21 By turning to powder coating, paint shops not only obviate the
need for abatement equipment but they also capture other economic benefits. While it is
difficult to make broad statements, in general, powder systems provide cost savings in
terms of energy, labor, clean-up, maintenance and sludge disposal.22 23 In fact analysis
by the Powder Coating Institute, taking into account material, labor, maintenance, energy,
sludge disposal and amortized capital costs puts the annual operating costs of a "typical"
powder system at 70% of that of a comparable abated water borne or solvent system.24

Different powders' unique properties also can influence a decision to invest in powder.
Yogen Rahangdale, manager of Paint and Energy Management systems talked about
Chrysler's reasoning for investing in powder coating for the primer paint layer, "This
process has been more beneficial, not only in terms of fewer emissions, but in improved
performance. One of the main purposes for pursuing this technology was to provide an
anti-chip coating, at which the powder system has been successful."25 Superior anti-chip
performance drove Chrysler to at first experiment with and subsequently invest in powder
coating for primer layer of paint. Powder offers advantages over solvent based coatings
because it allows for higher film thicknesses on the target areas to improve chip
resistance.

Powder coating is not a panacea however, as with any developing technology it has its
share of drawbacks. The inability to rapidly change colors is often cited as a major
limitation with powder coating. Color changing limitations coupled with difficulties with
powder coating metallics have led the automotive industry away from powder and toward
water-borne coatings for the base coat. Briefly, other drawbacks include:
- Thicker film builds are necessary to maintain high quality appearance.
- Material handling can be nettlesome with powder agglomeration and build up in
delivery lines and on applicators.
- Powder is sensitive to temperature and humidity - storage can be a problem.
The intent here is to give a flavor for the pluses and minuses of powder coating, a
background for subsequent discussion. Many of these topics will reappear.

The Powder Coating Market
Powder coating is a rapidly growing technology asserting itself in the industrial finishing
market. In 1994 the Powder Coating Institute estimated that "powder comprised 10% of
the total industrial finishing market" and 15% of the market where it competed directly
with liquid finishes."26 At an average of $2.73 per lb., the powder market will be worth

23 E. Miller, User's Guide to Powder Coating, The Association for Finishing Processes of the Society of
Manufacturing Engineers, Detroit MI, 1985, pp. 21-29.
24 Bocchi, p. 3
25 D. Greenfield, "Big Three Join Forces to Develop Powder Applications," Modern Paint and Coatings,
approximately $600 million in 1994. Powder has made particular in-roads into the appliance finishing business; over 40% of all appliances made today sport a powder coating finish. Powder coating has carved out some elbow room in the industrial finishing market, but more importantly powder coating is growing.

Powder coating is experiencing double digit growth, an enviable record considering the 3% growth in the liquid coating market. Powder Coating Institute (PCI) figures, shown in the following graph, demonstrate the exponential growth of powder since 1981.

![Powder Usage Is Growing at Over 15%](image)

Since 1981 powder has grown at over 15% in North America. PCI forecasts a more bullish growth rate of 19% based on the market's performance in the last few years. In either case these growth rates far outstrip the growth of all other industrial finishing technologies. Worldwide, powder is expected to grow 11% in 1995.

The powder coating market is segmented into four rough categories:
- The appliance sector is pegged at about 18% of the overall market. As one would expect it encompasses powder coatings applied to ranges, refrigerators, microwave ovens, dishwasher, water heaters and the like.
- The 15% of the market (roughly 33 million lbs. annually) that is automotive only accounts for the powder coating of parts such as bumpers, aluminum wheels, door handles, and engine blocks. It does not take into account the powder used in primer applications. Considering that a primer application can use a few million lbs. per year, it is expected that the automotive sector will become significantly larger in the next few years.

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28 Bocchi, p. 53.
30 Bocchi, p. 53.
Automotive is a Small Part of the Overall Powder Market

- Lawn and Garden, at 12%, represents items such as the powder painting of lawn mowers and patio furniture.
- General Metal Finishing is a catch all category. Some of the items falling under this rubric are bathroom scales, architectural uses, golf carts, ski poles, and baby strollers.\(^{31,32}\)

The powder coating market is growing rapidly, outstripping the growth of conventional liquid coatings. While the automotive sector is only a small portion of the overall powder market now, expected adoption of powder for automotive primer and clear coat layers will make the automotive sector a powerful one in the coming years. As one analyst put it, "The automotive OEM business is the pot of gold at the end of the rainbow that the powder coating industry has been salivating over for the past 25 years."\(^{33}\)

The Automotive Powder Coating Market
Before launching into a detailed discussion of the automotive powder coating market it is important to understand the automotive painting process. The automotive painting process consist of five steps. The first step is pre-treatment where the surface is cleaned and prepared for painting. In the next step a corrosion resistant coating known as the electro-deposition or E-Coat is applied, usually by immersing the entire vehicle into a coating solution. Subsequent to the E-coat, a primer/anti-chip coating is applied. Traditionally this has been a low cost solvent based painting process, but over the last decade General Motors and Chrysler have installed powder systems to provide part or all of the anti-chip/primer protection in a handful of assembly plants.

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The Different Layers of Automotive Paint

<table>
<thead>
<tr>
<th>Traditionally</th>
<th>Future</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solvent-based</td>
<td>Powder</td>
</tr>
<tr>
<td>Solvent-based</td>
<td>Waterborne</td>
</tr>
<tr>
<td>Solvent-based</td>
<td>Powder</td>
</tr>
<tr>
<td>Water-based</td>
<td>Water-based</td>
</tr>
</tbody>
</table>

The third layer is known as the base coat. Base coat gives the vehicle its color. Often metallic flakes are dispersed within the liquid paint solution. Problems with color changes and metallics have steered the auto companies away from powder for this application. The environmentally friendly substitute for solvent coating for base coats appears to be waterborne. The final coating in the process is the clear coat. The clear coat provides durability, UV protection, and most importantly a high gloss finish. The future for clear coat is powder coating, but today solvent coating is the only acceptable method for applying the critical high gloss finish that customers demand.

The automotive industry has been slow to embrace powder as a solution to their environmental problems. General Motors began their long-term relationship with powder in 1981 with the Shreveport, LA plant; Chrysler began their powder experience in the 1988-1989 time period; Ford has yet to use powder on Class A surfaces in a significant way. Even with over a decade of experience, the table shows that the expansion of powder use has been limited.


<table>
<thead>
<tr>
<th>Assembly Plant</th>
<th>Vehicle</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chrysler Belvidere</td>
<td>Dodge/Plymouth Neon</td>
<td>Anti-chip/sills, entire hood</td>
</tr>
<tr>
<td>Chrysler Jefferson North</td>
<td>Jeep Grand Cherokee</td>
<td>Anti-chip: sills</td>
</tr>
<tr>
<td>Chrysler Sterling Heights</td>
<td>Dodge Stratus, Chrysler Cirrus</td>
<td>Full-body anti-chip</td>
</tr>
<tr>
<td>Chrysler St. Louis (1995)</td>
<td>Dodge Caravan, Plymouth Voyager</td>
<td>Full-body anti-chip</td>
</tr>
<tr>
<td>Chrysler Windsor (1995)</td>
<td>Dodge Caravan, Plymouth Voyager</td>
<td>Full-body anti-chip</td>
</tr>
<tr>
<td>GM Baltimore</td>
<td>Astro Safari van</td>
<td>Anti-chip sills, leading edge primer/surfacer</td>
</tr>
<tr>
<td>GM Janesvi.²ᵃ</td>
<td>Chevrolet Suburban, Blazer</td>
<td></td>
</tr>
<tr>
<td>GM Linden</td>
<td>Sport Utility, S/T Trucks</td>
<td></td>
</tr>
<tr>
<td>GM Moraine</td>
<td>Sport Utility, S/T Trucks</td>
<td></td>
</tr>
<tr>
<td>GM Shreveport</td>
<td>Chevrolet S-10, GMC</td>
<td></td>
</tr>
<tr>
<td>Harley Davidson York</td>
<td>Motorcycles</td>
<td>Clear topcoat; black basecoat on frames</td>
</tr>
<tr>
<td>Saturn</td>
<td>Saturn</td>
<td>Blackout: door header</td>
</tr>
</tbody>
</table>

The LEPC companies are leading the automotive industry with powder coating installations. But even so, The Big Three operate over 60 paint shops in North America, and only a small fraction are using powder coating. Why? What has prevented the auto industry from more rapidly converting from solvent based systems to low emission systems like powder?

The Low Emission Paint Consortium (LEPC)
The auto companies recognized a need to better understand and implement low emission coating technology. In a unique and forward-thinking move, in 1993 Chrysler, General Motors, and Ford decided to form the Low Emission Paint Consortium (LEPC) under the auspices of USCAR.

"The mission of the LEPC is 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 emission 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. Emission reduction via material change or higher efficiency equipment is our priority when cost effective, rather than 'end-of-pipe', add-on abatement systems. There are several possibilities currently in various stages of development that may fall into the category of 'low emissions paint'. However, the LEPC members have all committed now to a low emission paint system 'vision' for the future that includes a powder primer surfacer (PS) followed by a waterborne base coat (BC) or color coat and then a powder clear coat (CC). Although some implementation of powder PS has already occurred, considerable effort is still being expended to improve both the process efficiency and the smoothness of the surface. Because it is a top coat, powder CC presents a much greater challenge to implement as the appearance and durability of our products comes into question. Powder experience thus far has taught us that film thickness uniformity, material usage and smoothness (for a high glamour appearance) are still challenges to be solved."  

The focal point for much of the LEPC activity is the proposed $20 MM Prove-Out facility scheduled for completion in the 1995-1996 timeframe. The Prove-Out facility is essentially a pilot/testing facility capable of simulating production "speeds and feeds". Through the Prove-Out facility the LEPC hopes to especially understand how to make powder viable for clear coat application.

A key player in the consortium is ABB Paint Finishing, a unit of Asea, Brown and Bovari (ABB). ABB Paint Finishing is acting as the Design and Construction Partner for the Prove-Out facility. This role puts ABB Paint Finishing in a very interesting and perhaps enviable position which will be further explored in the strategic analysis section of the thesis.

Another unique aspect of the LEPC and the Prove-Out facility is the use of the bailment process. Bailment is a legal term for lending. The LEPC has entertained numerous bailment proposals from a wide array of equipment suppliers. In bailment meetings suppliers presented their qualifications and then offered an equipment and service package to the LEPC. Essentially equipment suppliers were offering to give/loan a

considerable value in equipment and services for incorporation into the Prove-Out facility. Of course the unstated but implicit expectation was that use of their equipment in the prove out stage would give the supplier an inside track on the potentially huge and lucrative automotive powder coating market. Interestingly, material suppliers seemed to express only a passing interest in LEPC activities. Possible reasons for this will again resurface in the strategic analysis of the thesis.

Summary and Transition
Environmental regulatory pressure in the U.S. has forced industrial finishers such as automotive paint shops to search for environmentally friendly coating technologies to replace traditional solvent based systems. The emerging dominant technology appears to be powder coating with growth rates between 15% and 20%, far in excess of the liquid industry growth rate of 3%. The automotive industry has been using powder for primer applications since 1981, yet powder is currently used in only a fraction of automotive paint shops.

The Detroit auto makers recognized a need to better understand and develop low emission painting technologies, specifically powder coating. To this end Chrysler, GM and Ford took on a leadership role and formed the Low Emission Paint Consortium whose primary mission is to "test and evaluate powder paint, painting equipment, and facilities with emphasis on powder clear coat." While the Big Three lead the world in automotive powder coating, widespread implementation is still an uphill climb.

What are the factors that complicate the decision to adopt powder coating? NPV calculations, quality concerns, risk associated with a powder coating, or some other factors. If powder coating truly is a superior technology --an innovation -- then what can established firms do to accelerate the implementation of the innovation?

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The Framework

"Innovations shift competitive advantage when rivals either fail to perceive a new way of competing or are unwilling or unable to respond."..."A firm's ability to sustain its success is most likely a result of constant innovation to adapt to changing circumstances" (Michael Porter, Competitive Advantage of Nations, pp. 45-47, 65)

Innovation is widely acclaimed as a key to success. Why then do firms struggle with change? In searching for answers to this question I have found a number of ways of looking at the problem, points of view that build upon each other and weave together a graspsable picture. Conventions and perceptions of reality are strong forces in favor of the status quo. To supplant an 'old' reality with a 'new' reality -- to bring innovation to a firm -- a change agent must be aware of the powerful forces at work. A framework is needed.

The Paradigm Wars
Around 300 BC Euclid established the foundation for geometry. Based on Euclidean geometry, for over two thousand years it was "true" that a triangle had 180 degrees. In 1851 Riemann shared with the world a complete geometry in which triangles had more than 180 degrees. This became the new truth. In a similar manner, in 1666 Newton put forth an amazingly complete model of the physical world which was accepted as reality until Einstein created a better description, a better reality. The point is, what is commonly accepted as fact in any time period is only the most popular perception of reality.

David Adamson, in his entrepreneurial guidebook Walking the High-Tech High Wire37, has coined the struggle surrounding the ascendancy of a 'new' reality as a paradigm war. Adamson made clear a number of elements of a paradigm war:
• a paradigm has a rational component based on logical extensions of previous work and an arbitrary component predicated on historical and personal events.
• the inability of an established paradigm to explain phenomenon creates a need for a new paradigm.
• new paradigms meet with strong resistance as Machiavelli observed and Galileo experienced.
• new paradigms will only become established if they can overwhelm the skeptical forces acting against them.

Adamson's purpose in describing the paradigm wars was to emphasize to potential entrepreneurs and innovators that in many cases, they were trying to change reality. Changing reality is hard.

A Cultural Perspective
The reality of an organization is the organization's culture. Edgar Schein, in his book Organizational Change and Leadership, explains the foundations of culture or the basic assumptions.

"When a solution to a problem works repeatedly, it comes to be taken for granted. What was once a hypothesis, supported only by a hunch or a value, comes gradually to be treated as a reality. We come to believe that nature really works this way... Basic assumptions... become so taken for granted that one finds little variation within a cultural unit. In fact, if a basic assumption is strongly held in a group, members will find behavior based on any other premise inconceivable."

Basic assumptions are core beliefs and they are so ingrained that they are not even subject to debate. If the environment is changing such that the basic assumptions are no longer successful in solving the firm's problems, the firm will either adapt and change their assumptions or decay. A change agent must recognize that in the face of a changing environment, culture can be an obstacle to success.

Some innovations change an industry's environment in such a way that established firms must change their culture. The introduction of transistors dramatically changed the vacuum tube market, the introduction of personal computers and word processors made typewriters obsolete, and the obvious success of the Toyota Production System forever changed the auto industry. Leaders in the established firms must understand the dynamics of culture change if they are to have any chance of successfully leading the organization to a new era.

Schein describes the dynamics of cultural change with the three steps of unfreezing, cognitive restructuring, and refreezing. In the unfreezing step an organization must internalize the existence of a problem. The firm must recognize that the basic assumptions are no longer useful for solving their problems. For insiders to the company this recognition is extraordinarily difficult. Objective data such as poor profitability, loss in market share, inability to attract and keep highly skilled employees indicate a company's failure to deal with external conditions, but rarely do insiders make the link between these problems and the organization's basic assumptions. The information creates cognitive dissonance. As Schein explains, "It is easier to distort new data by denial, projection, rationalization, or various other defense mechanisms than to change the basic assumptions." (p. 27) Often outsiders or truly visionary leaders are the only people capable of seeing the problems and recognizing their relationship to the organization's culture.

Once a problem has been brought into the open, change can begin. Unfortunately for many firms, the cultural inertia is so strong that only incremental changes can successfully hurdle the many barriers to change. An evolution as opposed to a revolution occurs. In a highly competitive environment, faced with a radical innovation, firms that evolve will go the way of the dinosaur. Extinction is a pervasive theme in business as some industrial dinosaurs have demonstrated:
- RCA failed as a small radio manufacturer.
- The Knickerbocker Ice Company was run out of the ice harvesting business.
- Underwood's manual typewriters were replaced by electric typewriters.

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Evolution is not always a losing strategy. In a less competitive environment or in an atmosphere of incremental innovation, evolution may enable a firm to continue to exist, even flourish. Whether evolutionary or revolutionary, cognitive restructuring -- the process of finding basic assumptions that will solve the company's problems -- is a necessary step for a firm struggling with change.

If the cognitive restructuring creates new assumptions that solve the organization's problems, then the new assumptions must become part of the culture. Schein calls this process refreezing. A skunk works or a rogue division in a company may have discovered a set of assumptions that work in the new environment, but for the company to thrive, their learning must be disseminated and ingrained in the rest of the corporation. Refreezing is a difficult process. For the staid, established divisions, the arguments are:

"that was just a flash-in-the-pan, that division was lucky"
"sure, give me those resources and I could do the same thing"
"we're not the problem, the problem is Division Y"
"that kind of thinking won't work here, this is a more complex process"

In the end it is often the case that, "the identity that the organization has built up and that has been the source of its success must be preserved, even if that means ultimate failure to adapt successfully to a changing environment." (Schein, p. 300)

Innovation and culture are tightly coupled. Innovation can restructure a group's external environment obviating the usefulness of certain core assumptions. In fact the basic assumptions that were so necessary to bring the firm to a position of dominance in the industry often are destructive in an environment reshaped by innovation. A change agent must recognize that the firm's culture will act as a stabilizing force and that it will resist change. While the resistance may be irrational and lead to the firm's demise, it is real in the minds of members of the group. The long time constants associated with the dynamics of change are the rule, not the exception. Established firms struggle with innovation because adapting requires the firms to change deeply held cultural beliefs; a firm that can shorten time constants of change will have a tremendous competitive advantage.

The Dynamics of Innovation
Where Schein describes how change is linked to culture, James Utterback in his book, *Mastering the Dynamics of Innovation*\(^{39}\) relates how innovation affects an industry. The life of an innovation progresses through two distinct phases. The infancy and childhood of an innovation are marked by significant creativity, change and uncertainty. As the innovation matures and becomes defined, it enters a second phase where the focus is upon efficiency, volume and cost. The innovation continues to mature until it is surpassed by a new innovation. The impact of the innovation on a firm depends a great deal upon whether the firm is entrepreneurial and riding the crest of a new wave or if the firm is established and washing up on the shore.

With the introduction of a radical innovation, be it an enabling process technology or a radical product design, an industry enters a very fluid phase. A radical innovation gleams like gold, and in a fashion similar to the Gold Rush of 1849, it attracts a number of prospectors. The market participants are all looking for the mother lode and they create a flurry of product designs with the goal of establishing THE PRODUCT. The many firms put forth a dizzying number of product designs, characterized by short life spans and diversity, as the marketplace decides what it wants. Eventually the market reaches a consensus and a dominant design emerges.

This common phenomenon has many examples. In the auto industry, "between 1902 and 1909, 47 firms entered the market... by 1921 there were 88 auto firms in the U.S. ... by 1931 consolidation had occurred, with General Motors controlling about a third of industry sales." 40 In the early days of automobiles, these vast number of competitors built cars with gasoline, electric, or steam engines, with steering wheels or tillers, and with wooden or metal bodies, but once the all-steel closed body was introduced by Dodge in 1925, it became the dominant design and the industry experienced the classic 'shake-out'. 41 42 Other examples prove that the dominant design is not necessarily the technologically superior product. The IBM PC and the Lotus 1-2-3 spreadsheet are two illustrations of 'just good' products becoming the dominant design. The phenomenon continues to appear; currently encryption software and Internet browsers are in their innovation infancy with companies vying to establish the dominant design. 43

Powder coating in its present state and the IBM-PC are 'just good' designs. How does a 'just good' design become an industry standard? Utterback explains four mechanisms other than the technology itself that foment a dominant design. 44

- Collateral assets are a firm's advantages such as market channels, brand name, and customer switching costs that allow a firm to enforce its product as the dominant design. In 1981 IBM leveraged its brand name and distribution channels to establish the IBM PC as the dominant design.
- Industrial regulation can play a significant role by legislating standards favoring one product design over another. High definition television is an example of this kind of intervention.
- Strategic maneuvering at the firm level, when properly executed, can enable a firm to establish its product as the dominant design. Utterback cites JVC's success in establishing VHS over Betamax in the video cassette recorder business as an example of strategic maneuvering.
- A firm with closer customer communication can exert its product as the dominant design. Rapid prototyping, short product development cycle times and a customer

44 Utterback, pp. 26-29.
focus are the tools some firms like Motorola use to provide customers with technologically superior and eventually dominant product designs. Clearly the ability to set the dominant design such that it plays to a firm's competitive advantages can be very profitable as IBM PCs, JVC's VHS recorders, and Motorola pagers all demonstrate. But once the dominant design has been set the dimensions of competition change.

In the product design phase (infancy and childhood) creativity, flexibility and speed are the most important assets of a firm, but once the dominant design is established (adulthood), efficiency and low cost production become prized assets. Utterback calls this -- the transition from product innovation to process innovation phase. As manufacturers incrementally optimize their production processes to take advantage of the dominant design, they constrict their flexibility. Utterback relates the essence of the transformation to process innovation:

"The linkages between product and process are now extremely close. Any small change in either product or process is likely to be difficult and expensive and require a corresponding change in the other. Even what may seem like a small change -- such as shifting production from manual to electric typewriters -- is viewed as revolutionary by manufacturing, which by now has fully automated operations geared to highly efficient, low-unit-cost production of highly specified products." (p. 96)

Firms also adapt their organizations to match the transition from product to process innovation. Darwinian forces drive free-spirited, entrepreneurial organizations toward a cost-effective, functional orientation. In time the industry matures and a once entrepreneurial firm becomes an established firm.

Utterback provides a nice summary of the dynamics of innovation in the following table.

<table>
<thead>
<tr>
<th>Product</th>
<th>From high variety, to dominant design, to incremental innovation on standardized products</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process</td>
<td>Manufacturing progresses from heavy reliance on skilled labor and general-purpose equipment to specialized equipment tended by low-skilled labor</td>
</tr>
<tr>
<td>Organizational</td>
<td>From entrepreneurial organic firm to hierarchical mechanistic firm with defined tasks and procedures and few rewards for radical innovation</td>
</tr>
<tr>
<td>Market</td>
<td>From fragmented and unstable with diverse products and rapid feedback to commodity-like with largely undifferentiated products</td>
</tr>
<tr>
<td>Competition</td>
<td>From many small firms with unique products to an oligopoly of firms with similar products</td>
</tr>
</tbody>
</table>

From the inception of an innovation, through the fluid product design phase, to the establishment of a dominant design, and on into the efficiency-minded process design

45 Utterback, p. 91.
phase -- the innovation, industry and firm continually evolve. In time, a new major
ingovation will come along and the established firm will either incorporate the innovation
or fade away. We have looked at paradigm wars, cultural implications and innovation
dynamics; one more piece of the puzzle is necessary before we fully address the question
of why established firm struggle with change.

Architectural Innovation - Understanding the Linkages
Thus far innovation has been bandied about as a generic term with only a gross
distinction between radical and incremental innovation, but this characterization of
innovation seems lacking. Adding a dimension to the view of innovation is helpful in
understanding why firms respond as they do to change. Rebecca Henderson has looked
closely at industries in which once dominant companies fall by the wayside as others,
capitalizing on incremental innovations, seize the dominant market position. She
distinguishes certain kinds of innovation as architectural and describes why this particular
type of innovation is difficult for established firms to handle. Her insights and
framework are particularly relevant to the auto industries' response to powder coating.

Architectural innovation is defined as "innovation that changes the way in which the
components of a product are linked together, while leaving the core design concepts (and
thus the basic knowledge underlying the components) untouched." Traditionally
innovation is thought of as an overturning of core concepts, an introduction of new
technology or ways of thinking that revolutionize a product. The idea of architectural
innovation brings the importance of linkages to light. Edison recognized importance of
linkages and systems thinking when he created not just a light bulb but a lighting system
requiring the simultaneous development of lamps, wiring, sockets, generators and other
equipment. Similarly Eastman laid the groundwork for Kodak to dominate the
photographic industry for over 80 years, not with a single revolutionary product, but with
a photographic system. These two creative giants, innately understood the fundamental
importance of understanding an entire system, of understanding linkages.

The two-dimensional depiction of innovation then becomes:

<table>
<thead>
<tr>
<th>Core Concepts</th>
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<tr>
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<tr>
<td>Reinforced</td>
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<tr>
<td>Incremental Innovation</td>
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<tr>
<td>Modular Innovation</td>
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<tr>
<td>Overturned</td>
</tr>
<tr>
<td>Architectural Innovation</td>
</tr>
<tr>
<td>Radical Innovation</td>
</tr>
</tbody>
</table>

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46 R. Henderson and K. Clark, Architectural Innovation: The Reconfiguration of Existing Product
14.
47 Utterback, p. 182.
48 Henderson and Clark, p. 12.
In this context incremental innovations are those described by Utterback in the process design phase. They are small changes bounded by the dominant design. Radical innovations are those that both overturn core concepts and create an entirely new systems. Utterback cites many examples such as the revolutionary change from electric typewriters to personal computers and the elimination of the ice harvesting business by ice making machines. In addition to incremental and radical, Henderson describes two further kinds of innovation. One type is modular innovation; the replacement of an analog telephone with a digital phone would be an example. Modular innovation brings a revolutionary technology to an existing process, but it is a "drop-in" and does not upset the system. Architectural innovation, on the other hand, is seemingly innocuous but potentially deadly to existing firms. It uses existing or incrementally improved technology and puts it together in a different way creating a new system.

Henderson describes many examples.

"Xerox, the pioneer of plain-paper copiers, was confronted in the mid-1970s with competitors offering copiers that were much smaller and more reliable than the traditional product. The new products required little new scientific or engineering knowledge, but despite the fact that Xerox had invented the core technologies and had enormous experience in the industry, it took the company almost eight years of missteps and false starts to introduce a competitive product into the market. In that time Xerox lost half of its market share and suffered serious financial problems" (p. 10)

Other examples include Sony's crippling of RCA in the radio receiver market, four generations of change in the photolithographic industry, and the automotive industries' response to high-strength-low-alloy steel for auto bodies. In each case relatively minor product innovations wreaked havoc upon the linkages within the system.

Why are architectural innovations insidious for established firms?: Because the dominant design drives an organization to think in terms of the dominant design. In the vernacular, if the only tool you have is a hammer, then every problem becomes a nail. The dominant design carries with it certain basic assumptions; it is the prevailing paradigm in the industry. When a company buys into a dominant design, in the name of efficiency, it sets up structures predicated on the dominant design. As organizational structures, information filters, and strategies succeed in solving an organization's problems, they become the basic assumptions that are the foundations of an organization's culture, inseparably linked. The organization views the world through "dominant design colored glasses".

In a similar manner after the dominant design is established, functionalization becomes increasingly important. Companies rely on heuristics to screen out unimportant information and link various functions. Henderson crystallizes this point:

"At Boeing the design of a new aircraft is a problem of enormous complexity, and in consequence the detailed design of new components is left to hundreds of engineers who coordinate their work through well established technical protocols and sophisticated design tools. They also work in the shadow of a number of powerful heuristics. In the words of one observer, "they would kill their grandmothers to save weight." (Rinearson, 1983). This is an example of a heuristic that serves to link the multitude of detailed engineering decisions that must be made to a single overriding customer objective - the desire to save operating costs. As long as the technical and
industry environment remains reasonably stable, it is a heuristic that acts as a very efficient information processing device.\textsuperscript{49} Of course, what happens when information technology becomes cost-effective for Boeing -- ending the need for some of the crude heuristics, or when airlines begin to demand increasingly varied and customized aircraft ending the usefulness of grand-matricide? How do established companies like Boeing deal with architectural innovation problems?

Architectural innovation is a neat framework; it integrates Adamson's paradigm wars, with Schein's cultural analysis and Utterback's dynamics of innovation. As an innovation reaches the end of its childhood, a dominant design emerges. This dominant design has won the paradigm war that was waged during the product innovation phase and it becomes the 'new' reality. Implicit in the dominant design is a system. The organization builds an architecture to solve problems posed by the dominant design. It is inexorably tied to an organization's culture. Not surprisingly then, Henderson's analysis of established firm's problems with architectural innovation are nearly identical to Schein's analysis of the dynamics of culture change.

The initial step of unfreezing described by Schein requires a recognition of a problem. Henderson echoes this sentiment, explaining that in order to solve problems created by architectural innovation a firm must first devote "significant time (and resources) to identify a particular innovation as architectural."\textsuperscript{50} Henderson also cites problems with cognitive dissonance, "organizations facing threats may continue to rely on their old architectural knowledge and hence misunderstand the nature of a threat. They shoehorn the bad news, or the unexpected new information, back into the patterns with which they are familiar."\textsuperscript{51} The similarities continue.

After unfreezing Schein describes cognitive recognition (finding new solutions) and refreezing (incorporating solutions into the culture). Henderson's analog: "Once an organization has recognized the nature of an architectural innovation, it faces a second major source of problems: the need to build and to apply new architectural knowledge effectively."\textsuperscript{52} Both Schein and Henderson agree that the process is difficult and time consuming.

**Summary and Transition**
Established organizations struggle with innovation. Change agents, Machiavelli's "princes", need frameworks to make sense of the problems that innovation creates for an established firm. The ideas of paradigm wars, cultural dynamics, cognitive dissonance, and dynamics of innovation are well captured by Henderson and Clark's framework of architectural innovation.

\textsuperscript{51} Henderson and Clark, p. 17
\textsuperscript{52} Henderson and Clark, p. 17.
So how does this apply to automotive powder coating? In the next section we will use Henderson's and Clark's framework to discuss a potential solution to problems with architectural innovation using the automotive painting industry as an example.

Two relevant observations both conclude this section and set the tone for later sections:

"Established organizations may invest heavily in new innovation, interpreting it as an incremental extension of the existing technology or underestimating its impact on their embedded architectural knowledge. But new entrants to the industry may exploit its potential much more effectively, since they are not handicapped by a legacy of embedded and partially irrelevant architectural knowledge."(Henderson and Clark, p.17)

"Since architectural innovation has the potential to offer firms the opportunity to gain significant advantage over well-entrenched, dominant firms, we might expect less entrenched competitor firms to search actively for opportunities to introduce changes in product architecture in an industry"(Henderson and Clark, p. 18)

Does the firm's architecture hinder it from properly adopting an innovation and conversely can an organization use the architecture of other firms against them? In the next section, the framework of architectural innovation will be pivotal in forming a solution to the problems facing the automotive powder coating industry.
A Holistic Approach to Automotive Powder Coating

"A critical pattern in the dynamics of technological innovation - and one that should give every business strategist a great deal of discomfort - is the disturbing regularity with which industrial leaders follow their core technologies into obsolescence and obscurity." "It takes a rare kind of leadership to shift resources away from areas where one currently enjoys success to an area that is new and unproven" (Utterback, pp. 162, 163)

Established firms struggle with change because they are successful and established. They have embraced the dominant design. They have cast away creativity and in its place they have erected efficient information channels, functional organizations, simplifying yet hobbling heuristics. When an innovation comes along that requires them to change their system, their architecture, they find they cannot. Utterback describes a number of studies that have looked at this problem and he summed up their findings this way:

"None of these studies, unfortunately, successfully addresses the key problem: how established firms can renew their core technologies when they become obsolete, thereby avoiding retrenchment and failure." (p. 197)

I offer a solution to the problem. A holistic approach can enable firms to renew their core technologies and competencies. I hope to show, by way of an extensive example, how this can be done.

Successful implementation of an innovation requires the integration of four basic facets:
- physics and technology
- manufacturing
- business issues
- site specific application.

In addition these must be integrated under an umbrella of open-mindedness, a learning atmosphere, and a risk-taking bent. In an established firm the four basic principles have been compartmentalized and functionalized with a high degree of specialization. The onslaught of efficiency mongers over the years has tended to close minds, hampered the ability to learn and minimized any risk-taking.

In the case of powder coating, functionalization of the four basic principles has occurred. Understanding the physics and technology of the process means understanding ideas such as the phenomenon of particle changing, the motion of small particles, and the effects of particle resistivity. The LEPC cites the functions responsible for this knowledge:

"Developments (in powder clear coat technology) are anticipated to come from suppliers, from current production efforts, from within our own research and development groups, and from other R&D centers, such as universities and private and public institutes." 53

The people who understand the fundamentals of manufacturing are similarly compartmentalized. Tools like Design for Manufacturing (DFM), Statistical Process Control (SPC), Design of Experiments (DOE), and preventive maintenance are usually only practiced by design engineers, statisticians, manufacturing engineers, and

maintenance engineers. Business ideas such as strategic planning, marketing, resource allocation, and competitive advantage are generally the sole province of upper management, marketing managers, financial analysts, and product managers. Finally site specific application, understanding how to translate ideas to reality, is the responsibility of the process engineers, production supervision, and suppliers' on-site personnel. The degree of specialization is staggering. Even with the formation of the LEPC, managing the integration of the specialists as the automotive industry slowly adopts powder coating is formidable.

As Henderson and Clark point out, when a firm faces an innovation like powder coating, how can they ensure that it isn't interpreted as an incremental extension of the existing technology? How can so many specialists, steeped in solvent based coating, come together and think outside the box created by the dominant design? How can they break the powerful heuristics that have served them so well? By themselves it is likely that they can't.

An outsider, or team of outsiders however is not bound by the same reality. An outside perspective combined with knowledge of the four facets is a powerful combination that can break through the influence of the dominant design. Without the constricting influence of the dominant design it is possible to chart a course forward that can create competitive advantage from an innovation like powder coating. In the coming sections I describe a holistic approach to automotive powder coating. Without an ingrained knowledge of the dominant designs of either solvent based coating or powder coating -- conceived in the image of solvent based coating -- it is possible to take a fresh look at automotive powder coating. Based on analysis of the four facets, with a particular focus on business and technology issues, I offer the LEPC a potential path forward.
A Holistic Approach to Powder Coating

Learning Atmosphere

Open Mind

Fundamental Understanding of Physics/Technology
- particle charging
- particle resistivity
- particle dynamics
- process control
- fluidization

Take Risks

- Ph.Ds
- Tech Center
- Suppliers Researchers

Fundamental Understanding of Manufacturing
- robust design
- bullet proof
- production worthy
- maintainable
- SPC, DOE, PM

Understanding of Site Specific Process
- communication
- problem solving
- teamwork and relationships
- mgmt. by anecdote
- day to day leadership
- process eng.
- maintenance eng.
- production
- production supervision
- the gurus

Fundamental Understanding of Business Issues
- project justification
- competitive advantage
- marketing implications
- industry evolution
- strategic analysis

- Financial analysts
- Product Managers
- Marketing managers
- Upper managers
Understanding the Business of Powder Coating

The business aspects of automotive powder coating have a profound effect upon the dynamics of innovation. The preponderance of business forces are driving the industry toward incremental innovation; however, a few are pushing toward more radical, step change improvements. Understanding these forces may allow the LEPC to harness them and drive toward step change improvements, improvements that could provide significant environmental advantages and still give the auto companies a high quality, cost-effective finish.

What do I mean by incremental change? The Detroit auto makers have led the world in automotive powder coating applications but despite their leadership, the entire industry has been slow to convert paint shops from solvent to powder. Installation of additional powder coating in primer/surfercer applications would almost certainly help the auto companies accelerate their learning of the technology, and help all auto companies to achieve LEPC-like objectives. In addition, most industry observers agree that environmental regulations will continue to constrain the auto companies' options and in some East Coast and West Coast instances force them to adopt powder coating. Can the idea of architectural innovation help explain the slow expansion of powder coating use in the auto industry in general and the more rapid but incremental growth in the use of powder by the Big Three?

Different players in the industry are facing different competitive situations which when framed in terms of architectural innovation, show them to behave in understandable and even predictable ways. The auto makers are the most in control of their destiny with regard to automotive powder coating, but material suppliers and equipment suppliers are influential and can significantly alter the path of progress. The factors affecting these three groups will be explored. The focus of the business analysis will be primarily strategic. Strategic analysis in conjunction with the framework of architectural innovation, provides strong insight and clearly shows how the LEPC can drive toward step change improvements.

Forces Acting on the Auto Companies

Michael Porter outlines the competitive strategy of emerging industries in his book *Competitive Strategy*. Porter's work dove-tails nicely with many of Utterback's observations regarding the response of established industries to innovations. I have integrated both authors views with my own to look at the competitive forces dictating incremental and architectural change.

If it were possible to objectively look at powder coating, in all likelihood, in the absence of 80 years of solvent based history, powder coating would have manifested itself in a radically different way. But many forces drive, what might otherwise be radical innovations, toward the incremental and modular side of the spectrum; uncertainty and existing architectural knowledge are in cahoots:

- The established architecture is overly constrained.
• Improving the current process can yield low risk gains.
• Switching from solvent-based systems to some other system implies high costs and the switch carries a great deal of technological uncertainty and product risk.
• Discounted cash flow tends to under-value uncertain cash flows.

Even a good crystal ball can't predict the strategic implications of fully adopting a radical innovation.

The forces of incrementalism are clear, staring a decision maker in the face. The forces in favor of step change improvement are considerably more tenuous, especially in the uncompetitive environment facing automotive paint shops. Paint shops are captive buyers of upstream operations and the only suppliers to downstream operations. With no direct competition, regulation is one of the only driving forces for change and as Porter says, "When buyers are compelled by regulatory fiat to purchase a new product...buyers usually will purchase the lowest cost (and lowest risk) alternative that meets the technical requirements". 54

The Clean Air Act drove industrial paint finishers to look for new environmentally friendly technologies. Powder coating appears to be emerging as the dominant design but it is a schizophrenic dominant design. Instead of being developed solely based on its technology, it has risen to ascendancy at least partially because it has been force fit into the solvent based coating paradigm; it has been conceived in the image of liquid coating. Because of this force fit, the innovation of powder coating has a duality -- part radical (due to its intrinsic nature) and part incremental extension of existing technology.

The result is not accidental but an attempt to minimize risk and uncertainty. Porter cites technological uncertainty, strategic uncertainty and high initial costs but steep cost reductions as common structural characteristics of an emerging industry. The Clean Air Act created a great deal of uncertainty. Interpretation of the CAA and the Maximum Available Control Technology (MACT) provision by various agencies and administrations created moving regulatory targets. How would paint shops comply? How much would this cost? Would my operation pick the wrong technology?

By substituting powder for liquid, paint engineers could maintain their architectural knowledge and treat powder coating as a modular innovation. By treating it as a modular innovation they could reduce technological uncertainty and focus only on a relatively simple modular change, not a much more complex systemic change. They could reduce strategic uncertainty since they were complying with regulations and still operating paint shops in essentially the same way, with the same strategy. Finally, in adopting the solvent-based coating 'reality', paint shops minimized high initial costs and the opportunity for cost reductions. While powder retrofits were expensive, they were not as expensive as a major departure from existing architecture would have been; the basic architecture remained the same. The risk averse (not a value judgment) auto plants once again proved one of the fundamental premises of finance -- low risk brings a low return.

For the industrial paint finishing industry, the existing architectural knowledge was a strong stabilizing force in favor of incremental change. Over the decades the solvent-based architecture became deeply embedded in the auto industry. As paint engineers strove to improve process efficiency, the web of constraints grew. When subjected to a new, external constraint, it clearly made sense to try to find a solution that maintained the integrity of the current architecture. In Utterback's words:

"The lesson for technology managers and business strategists is straightforward: understand the constraints of systems, user learning, habits, and collateral assets already imposed by the existing dominant design if there is one. And as you develop innovative products, consider how these products will fit with current constraints." (p. 51)

The web of constraints strongly favored modular innovation over architectural innovation.

Another potential solution to an additional external constraint that preserves architectural knowledge is to simply make the existing process better. According to Utterback, established firms will actively fight a threatening innovation by redoubling their focus on improvement of the existing process. Graphically he has shown this:

The paint industry did pursue this avenue with their work on high solids paints. Paint suppliers have taken the percent of solid material in solvent based paints from 15% to 70%, significantly reducing solvent content in the paint and solvent emissions. Further solids increase however, are unlikely due to paint performance problems. In time, just as the Utterback graph shows, the new powder coating technology, being inherently superior, will supplant the old solvent-based system. Extension of the current technology is another phenomenon that delays "cashing-in" on the new technology.

The dominant design evolves partially as a function of a firm's investment, investment which many times hinges on a Net Present Value (NPV) financial analysis. NPV analysis is another force pushing toward less risky, incremental improvement. NPV analysis favors projects with certain outcomes and easily predicted cash flows. Projects with uncertain cash flows or significant strategic value are often undervalued. Sir Alastair Pilkington captures the essence of this idea when he discussed his investment in the radical, and eventually dominant innovation of float glass technology:
"If you went to an accountant and said, 'I've got a great idea to create a massive negative cash flow for certain, and it may -- if it's a great success -- break even in its cash flows in 12 years,' you wouldn't find many accountants who'd say 'that's exactly what I want.'" (Utterback, p. 119)

What NPV analysis fails to account for is the value of the option to make follow on investments. Option pricing techniques, such as those described in Brealey and Myers "Principles of Corporate Finance", can be used to better assess strategic options. In the case of powder coating, investment may yield a competitive advantage or give the auto companies regulatory compliance options which could have great value. But the powerful option pricing techniques are rarely used and therefore can only be reactively applied in an academic setting.

So NPV analysis, which heavily favors the surety of the dominant design, is used to resist change. When faced with a retrofit decision and a choice among:

- upgrading a current solvent based system with the necessary pollution abatement devices or
- investing in a modular type of powder coating system or
- investing in a radically new powder coating system,

uncertainty will cause NPV analysis to paint an increasingly bleak financial picture as one deviates from the status quo. When queried about Ford's lack of powder coating installations, an executive commented, "Our financial analysis shows that an investment in powder has a significantly worse payback than just upgrading existing (solvent-based) facilities." The nature of financial analysis penalizes projects with uncertain cash flows and difficult to quantify strategic value. Financial analysis creates a bias for incremental improvement.

_Fear of failure is a strong force driving incremental innovation._ The incentives facing managers are asymmetric. If the innovation is architectural and creates significant value for the firm, the manager will only receive a small fraction of the benefit. If the architectural innovation fails, the manager will often bear the full responsibility for the failure.

_The leader that faces a decision to invest in powder coating in an automotive paint shop faces an uncertain and top-heavy risk/reward ratio._ Paint is necessary, but not generally viewed as an axis of competition for the automakers. Porter phrases the situation facing decision makers this way:

"Buyers who face a relatively high cost of product failure will usually be slower in adopting a new product than ones whose risk is lower. Buyers whose use for the new product involves plugging it into an integrated system often face very high failure costs, as do buyers who pay particularly high penalties from interrupted service of the product for some reason." (p. 227)

A leader that decides to go with an architectural innovation in paint shop had better understand how to eliminate uncertainty and ensure that the new investment does not hinder production. Lower paint shop installation and operating costs and improved paint

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56 Oster, p. 281.
quality don't cancel out significant production problems that limit the number of cars going out the door.

Occasionally, a leader does step up to the forces of incrementalism. Bucking "conventional wisdom", the leader pushes on with step change improvements. Many times step change improvements can only happen by changing the system, thinking outside the box imposed by the dominant design. What enables these rare leaders to drive architectural change? A weak force driving toward step change improvement is the fear of the other guy. Many in the LEPC recognize BMW's active work in the area of powder coating for clear coat application, but while BMW's work causes discomfort, it is not a driving force for change.

To bring off an architectural or radical innovation in an established firm is extraordinarily difficult and requires a holistic approach. The catalyst for change must first understand that there is an existing architecture bounding the thinking of the industry and organization. Then the change agent must somehow look past that architecture. Along the way the leader must find a way to minimize the technological and strategic uncertainty inherent in a new, as yet undefined, design. And through all of this, the leader must not only convince herself, she must convince a quorum of the specialists of the superior nature of the innovation. A holistic approach is required. A leader with vision sees the technology, sees the business opportunities, and understands how to implement the technology in manufacturing. Only by understanding the WHOLE business can the leader see past the dominant design and understand how to minimize technological and strategic uncertainty; only then can a leader help an established firm embrace a new innovation.

Uncertainty, the hallmark of an emerging industry, cripples an organization's ability to objectively evaluate the nature of the expected benefit of a new technology. A desire for certainty drives incremental advances and modular replacement over step change improvements and architectural re-design. Auto industry paint shops, seeking to preserve their architectural knowledge, have sought the least cost, most certain solution to their regulatory problems. But the paint shops are not acting alone. Their suppliers are willing accomplices.

**Material Suppliers to the Automotive Powder Coating Market**

Michael Porter has made famous an industrial analysis technique known as Five Forces analysis. Porter suggests that an industry is bounded, with five internal and external forces acting on it. Pictorially this is:
Porter's Five Forces

Five forces analysis is helpful in determining the nature of competition in a given industry. Applying the analysis to the North American Automotive Powder Coating Material Supplier market is enlightening.

- **Industry Competitors:** In the North American Automotive Powder Coating Material Supplier market there are only three suppliers: DuPont Automotive, PPG Industries Inc. and BASF Corp. DuPont is essentially GM's sole powder paint supplier, PPG is Chrysler's dominant powder supplier and BASF is Chrysler's secondary powder supplier. The three appear to have cultivated a comfortable arrangement and do not appear to be aggressively competing on the basis of price, marketing, service, research and development or any other dimension. The question is: Why?

- **Substitutes:** An investment in powder coating equipment precludes material substitutes in the short term. If the cost of powder were to suddenly dramatically rise, an automotive powder coating installation would still be forced to use powder. In the long term however, if prices remained high the paint shop could choose to take out the powder equipment and replace it with solvent-based equipment in an effort to introduce substitutes. The lack of substitutes in the short-term gives material suppliers market power.

- **Suppliers:** Suppliers to PPG, DuPont, and BASF for the production of powder are close to perfect competitors. Acrylic, Polyester and many of the additives like TiO2 that are raw materials are essentially commodities. In addition equipment for material blending, grinding and separation -- things like sieves, cyclones, and extruders -- are established technologies. PPG, DuPont and BASF have many options with regard to suppliers and as a result, suppliers exert little in the way of competitive pressure upon the industry.

- **Potential Entrants/Barriers to Entry:** One of the most potent competitive advantages of the material suppliers is the extreme barriers to market entry that other potential competitors such as EvTech and Seibert face. The trusting relationship built up between the suppliers and the auto companies is based on years of personal interaction and is difficult to replicate. Also a number of people in the auto paint
community have cited technological risk associated with potential entrants as a serious concern. Fear of failure is real:
"General Motors Corp. and Ford Motor Co. are paying dearly for paint-system changes attempted in the '80s that didn't work out well. Peeling paint on 1985-91 F-Series pickups and other models could cost Ford as much as $1.5 billion over two years, the Wall Street Journal reports. GM has had similar peeling problems..."57

With no threat of other entrants to the industry, the industry is extremely stable and existing competitors can reach implicit agreements regarding the nature of competition.

• **Buyers:** In this market three sellers are selling to two or potentially three buyers. In economic terms this translates to a monopoly (DuPont, PPG, and BASF acting as one) meeting a monopsony (GM, Chrysler, and Ford acting as one). "Monopsony power and monopoly power will tend to counteract each other... both the buyer and the seller are in a bargaining situation."58 Whether the buyers or the sellers gain a competitive advantage is largely determined by negotiation.

On the whole the North American Automotive Powder Material Supplier market is extremely uncompetitive. A lack of rivalry, no substitutes, competitive suppliers, and high entry barriers give DuPont, PPG and BASF significantly monopoly power. Fortunately, the auto companies represent a monopsony. In this situation the nature of competition is dictated by negotiation. With this in mind, certain market attributes become comprehensible.

Pricing anomalies, when viewed from a five forces perspective, seem less odd. *Remember that the average market price for powder in the much more competitive general powder coating market, in 1994 was $2.73 per pound.* A few years ago automotive acrylics were considered high value-added and were priced accordingly at around $6.00 per pound. The perceived lower value-added automotive polyester powder was priced from $4.50 to $5.00 per pound. However, recently as the use of polyester powder began to expand at the expense of acrylic powder, acrylic powder prices magically came down to the within pennies of the polyester prices. Prices seem to be whimsically set.

Logically, unless automotive powders contain some exotic and expensive additive or unless the price of automotive powder includes gratis on-site technical support, automotive powder prices should be similar to those in the greater powder coating market. A recent LEPC information gathering trip to Europe supported the idea that GM and Chrysler were paying above market prices for their powder. LEPC members learned that prices for automotive powder in Europe were nearly half that paid in the United States. Although prices between Europe and the U.S. cannot be directly compared, a difference in price does exist. Further, since prices are set through negotiation these dramatic arbitrage occurrences are not surprising. *What the analysis points out is an opportunity for the auto companies to drive prices toward the lower market prices through negotiation.*

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The insufficiency of competition also explains the unwillingness of material suppliers to enthusiastically participate in LEPC development activities. There is little incentive to incite competition on the basis of research and development and upset the stability of the current lucrative competitive position. As one LEPC member put it, "They (the material suppliers) have been dragging their feet, but all we really need to do is light a fire under them and they'll come around." -- a succinct characterization of competition in the material supplier market.

Material suppliers exist in a profitable, uncompetitive, and static world. Because of a desire for stability, they do not wish to drive for step change improvements. Through their inaction they enforce the dominant design and impede change. They face monopoly buying power so they are not all-powerful; outcomes are not as dependent upon economic forces as they are upon bargaining. The LEPC appears to be tiring of constant bargaining with material suppliers. Recently the LEPC has encouraged competition among seven suppliers in the drive to develop powder for clear coat applications. In the end the LEPC must recognize that if they expect material suppliers to work to the next dominant design, the LEPC must either introduce competition by lowering entry barriers, or negotiate every step of the way.

**Five Forces Analysis of Equipment Suppliers**
Utterback describes a common role of suppliers after the establishment of a dominant design:

"Another hallmark of stability is the emergence of a set of captive suppliers of equipment and components. Although such suppliers can be an initial source of innovation and growth, they may ultimately become a conservative force, further stabilizing the competition and change within the product market segment and creating yet another barrier to entry." (p. 89)

A five forces analysis of equipment suppliers demonstrates the wisdom of Utterback's observation. Unlike the material supplier market, the equipment supplier market is not as clearly delineated and is in a state of change. Industry evolution is therefore important.

- **Industry Competitors:** The industry is really composed of two types of players, small equipment suppliers and system integrators who often also supply their own small equipment. The numerous small equipment suppliers provide a wide variety of system components as the industry seeks to refine aspects of the dominant design. The system integrators, companies like Nordson Corporation, Gema, Binks Industrial Powder Systems, Sames Electrostatic Inc., Durr, Eisenmann and ABB Paint Finishing, have been consolidating for the past few years. The focus of the strategic analysis will be on system integrators since these are the companies that the LEPC most frequently deals with. Rivalry among the system integrators is significant but not intense. Competition is increasing. While there is some competition on price, other dimensions enter into the competitive mix. Service, research and development, and the ability to offer turn-key fully integrated systems are some notable areas of competition.
- **Substitutes:** The alternative to system integrators is to perform the integration in-house. The LEPC has no desire to do this and for that reason it hired ABB Paint
Finishing to perform the project management function for the $20MM Prove-Out facility. With a Design and Construction Partner, the LEPC can then induce competition not only among system integrators but among individual equipment suppliers as well. In the future, the automotive paint industry will likely become increasingly dependent upon system integrators.

- **Suppliers:** The trend in the system integration industry is to vertically integrate or to deal with very competitive component suppliers. Both techniques tend to create little competitive tension in the system integration market.

- **Potential Entrants/Barriers to Entry:** In the past Nordson in particular had the inside track on the North American Automotive Powder Coating Equipment market. The first-mover advantage and their reasonably good relationship with GM and Chrysler created a moderate barrier to entry. But in recent years, Nordson complacency has opened the door to other competitors. The end result is an increasing level of competition in the system integration market.

- **Buyers:** The auto companies represent the first class of buyers. They are willing to pay higher margins for higher value added system solutions. They also are something of a monopsony. The rest of the industrial finishing market represent a second class of buyers. While these buyers pay lower margins, the industrial finishing market is significantly larger than the automotive paint finishing market; so in some measure the monopsony power is offset.

Currently the system integration market is in a state of consolidation and flux. A dominant system design appears to be in place, driving consolidation, efficiency-minded incremental innovation, and increased competition. Companies like Nordson created the dominant design and are strong forces in favor of the status quo. They have a significant installed base and an established product line. They have no desire to cannibalize their current products. Nordson does a great deal of business with the general paint finishing market and therefore is less affected by monopsony power of the LEPC. They have no incentive to increase industry competition along any dimension including, price, service, or research and development.

Companies like Gema and Sames have upped the competition ante with introductions of supposedly superior modular innovations. At Powder Coating '94 Gema touted their new mass flow control system and Sames hyped their new powder bell. In this way they have increased industry competition along the research and development axis. Despite patents, it is unlikely that these modular innovations will result in long term competitive advantages. Nordson and others have already announced powder bells and many suppliers, external to the powder coating industry, provide similar powder flow control systems.

In general, system integrators are bolstering the current dominant design for powder coating. Like their material supplier brethren and the auto industry itself, they are strong forces driving away from step change improvement and toward incremental improvement.
Smelling an Opportunity

But, some feel that the current dominant design is lacking. These groups, including ABB Paint Finishing and a small start-up known as eNexus, are probing the architecture of the dominant design to look not only at modular innovations but also to look for a better way to put together the powder coating process.

Whether they realize it or not, ABB Paint Finishing has strategically positioned themselves to dominate the powder coating system integration market. As the Design and Construction Partner for the LEPC, ABB Paint Finishing has had the opportunity to see a majority of the competitors' top of the line offerings. Of course ABB's access makes many of the competitors uneasy. To put competitors at ease, ABB Paint Finishing often explains that they are not in the equipment business; they have no desire to make filters, or applicators, or fluidizing hoppers. ABB continues to say they are only interested in system integration. If I were in Nordson's shoes I would not start celebrating based on ABB's disclaimer. The five forces analysis shows that the industry is trending toward vertical integration and system integration. ABB can buy all the OEM equipment it wants at competitive prices. The auto companies value answers, systems, and solutions to their problems. In the end they don't care if Nordson guns or Sames Bells are the applicators of choice as long as the system cost-effectively produces superior firs, pass transfer efficiency, film build uniformity, and appearance. The LEPC and the industrial powder coating market will pay premium prices to the system integrator with the best design.

Not only does ABB Paint Finishing have bird's-eye view of the best in today's technology, they recognize, in some measure anyway, that the dominant design is flawed. Subsequent sections on the technology of powder coating will show that the current dominant design has inherent technical limitations; the system integrator that exploits these limitations will come out on top. I have had extensive discussion with ABB researchers in Vaxjo and Heidleberg, and in my estimation they are curious, asking many of right questions. In addition, the business people in ABB Paint Finishing appear to be listening to their researchers. They have the attitude, facilities and R&D firepower to develop and commercialize a new dominant design.

ABB Paint Finishing, as Design and Construction Partner of the "Prove-Out" facility, is also in the position to erect a significant barrier to entry. Strong business and personal relationships between the LEPC and ABB if appropriately handled will be mutually beneficial at the expense of other system integrators. From the LEPC's perspective, they would certainly be willing to pay premium prices to a known, trusted, capable, and likely superior system integrator like ABB. The LEPC wants answers not sales pitches. From ABB's perspective, if they take care of and continue to feed the relationship they will virtually ensure that they are the system integrator of choice in what could be significant follow-on business. Currently ABB Paint Finishing facilities are the site of a majority of LEPC meetings. ABB has provided office space to LEPC team members. ABB has taken the lead in coordinating LEPC ancillary activities such as a recent two week fact-finding trip to Europe. Close personal and business relationships could be a significant barrier to entry.
While it may be the case, it is hard to believe that ABB Paint Finishing has proceeded in this way as the result of a random walk. They have leveraged and cultivated many competitive strengths. They are in a position to create significant market power, which is after all the purpose of most businesses. Is this bad? I guess if you're Nordson it is, but for the industry as a whole ABB's active pursuit of a new dominant design will likely result in a net gain. For their efforts, ABB will be compensated.

The entrepreneurial eNexus may also figure prominently in the new dominant design. According to Utterback, organic firms like eNexus are the likely leaders in bringing a radical innovation into general acceptance. eNexus is leveraging its fresh technical approach and solid financial support to create and establish a dominant design. eNexus' flexibility and creativity are its strong suits. They are not mentally bound by any kind of dominant design. In this way they are superior to ABB Paint Finishing; despite ABB's assets, they still think in terms of the dominant design. As an example, where ABB may be thinking how to optimize the reclaim system, eNexus may not even acknowledge that a reclaim system is necessary.

But eNexus' ability to think creatively and come up with radically new designs is also its weakness. eNexus is fighting the paradigm wars. They may come up with the superior technology and lose out to an inferior dominant design due to collateral assets, strategic maneuvering on the part of other system integrators, or a lack of close customer communication. In any event, the LEPC should closely watch eNexus developments.

Summary, Conclusions and Transition
Strategic analysis shows how the forces of incremental improvement match up with the forces of step change improvement.

**An External Constraint Upsets the Balance and Forces Change**
*Will it be an incremental or a step change improvement?*

<table>
<thead>
<tr>
<th>INCREMENTAL</th>
<th>STEP CHANGE</th>
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<tbody>
<tr>
<td>Technological Uncertainty</td>
<td>Fear of the other guy</td>
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<tr>
<td>Strong</td>
<td>Weak</td>
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<tr>
<td>Strategic Uncertainty</td>
<td>ABB Paint Finishing</td>
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<tr>
<td>Strong</td>
<td>Medium</td>
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<tr>
<td>High initial costs but steep cost reductions</td>
<td>eNexus</td>
</tr>
<tr>
<td>Strong</td>
<td>Medium</td>
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<tr>
<td>Existing web of constraints</td>
<td>A leader</td>
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<tr>
<td>Strong</td>
<td>Wildcard?</td>
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<tr>
<td>Desire to improve current technology</td>
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<tr>
<td>Medium</td>
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<td>Misuse of financial analysis</td>
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<td>Strong</td>
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<td>Fear of failure</td>
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<td>Strong</td>
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<td>High cost of product failure</td>
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<td>Strong</td>
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<tr>
<td>Uncompetitive material supplier market</td>
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<td>Strong</td>
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<tr>
<td>Slightly competitive system integrators</td>
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<tr>
<td>Strong</td>
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The forces of incrementalism are powerfully aligned against a step change improvement. The outcome is not forgone however; a leader with conviction can carry off a step change improvement. A leader must gain broad and deep knowledge of the business and the innovation to minimize uncertainty. A leader must recognize that she is working within an architecture and that she is striving to establish a new architecture.

The business strategy is but one fundamental part of the architecture. It frames the opportunities for creating competitive advantage and channels technology options. A leader cannot specialize in business strategy and expect to achieve successful step change improvements. A leader must understand the technology, how it is applied and more importantly how it could be applied in the constantly evolving context of the business.
Understanding the Technology of Powder Coating

"Commercial coating systems are notoriously inefficient, with deposition efficiencies of around 60% being about the best that can be achieved..." (John Hughes, Senior Lecturer in Applied Electrostatics, University of Southampton, 1992.)

Knowledge is Power (Francis Bacon, 1597)

The LEPC needs to understand the technology of powder coating to achieve their objectives of improved first pass transfer efficiency, film build uniformity, and appearance. Unfortunately their efforts are hampered by the thought-constricting influence of the dominant design. For a majority of the industry, the closest technological analog to powder coating is thought to be solvent based coating. The solvent based paradigm, combined with the uncompetitive material and equipment supplier markets have choked off much technological innovation that does not fit in the current architecture. For instance, applicator suppliers have little incentive to work with material suppliers to produce a chemically and electrically optimized powder and applicator. While such a teaming could produce step change improvements, in today's environment it will not be done for two reasons:

- It would increase competition in the equipment and material supplier markets
- To yield the largest benefit it would require a significant deviation from the solvent based paradigm.

A different analog is required.

A few in the industry, including me, have found electrostatic precipitation to be a much more useful analog. Electrostatic precipitation has been around for about a century. In that time a lot of good work has been done describing the charging and motion of small particles. I have used the framework of electrostatic precipitation as a springboard and developed a fairly comprehensive, albeit first order explanation of the phenomenon of powder coating.

Transfer Efficiency

Transfer efficiency (TE) is the ratio of the amount of powder that sticks on the part to the amount of powder sprayed at the part. The term transfer efficiency can mean many different things to many different people. Sometimes it reflects the influence of overall performance which factors in a recycling system, powder blown out during purge cycles and the like; for my purposes, I am focusing on first pass transfer efficiency.

Perhaps the biggest difference between electrostatic precipitation and automotive powder painting lies with the analysis of collection efficiency a.k.a. transfer efficiency. Unfortunately, due to geometry consideration, the derivations for collection efficiency equations for an electrostatic precipitator are not as useful when applied to powder coating. Therefore the expressions for TE as a function of other coating parameters are of my own design which may account for their lack of sophistication.
Simplistic Derivation for Transfer Efficiency

Assume a constant Electric Field
Assume uniform particle size distribution
Assume small particle (lt. 30µm)

K-car?

gun to job distance is 10 inches

gun pumping powder at 100 gr./min

A particle will attach to the job if it reaches the job before the job moves on.

Duration that job is under the gun:
\[
\frac{\text{length of job (l)}}{\text{speed of job (v)}} = \text{time that job is under gun} = t_j
\]

Time for particle to reach job:
\[
\frac{\text{gun to part distance (d)}}{\text{migration velocity (w)}} = \text{time it takes for particle to reach job} = t_p
\]

When the gun fires, it establishes the electric field. Assuming that the gun fires, just as the job passes under the gun tip, then transfer efficiency for any particle size can be written:

\[
\text{efficiency} = TE = \frac{t_j - t_p}{t_j} = 1 - \frac{d \cdot v}{w \cdot l}
\]

From an electrostatic precipitation perspective, the above derivation is analogous to the Uniform Field, Uniform Laminar Flow model.\(^{59,60}\) As a first order approximation the TE equation makes sense and it explains a great deal. To increase TE, the term \(d \cdot v / w \cdot l\) must become small. Within the limits of the assumptions this can be done as follows:

- Decrease the gun to job distance (d)
- Decrease line speed (v)
- Increase the length of the job (l)
- Increase the migration velocity (w)

One caveat to the equation is that TE is always greater than or equal to zero. The implication is that \(t_p\) must be less than \(t_j\).

\(^{60}\) White, p. 161.
Obviously improving TE is not as easy as simply decreasing gun to part distance, or increasing migration velocity. The factors are not independent, and at the limits, the assumptions become unrealistic; but we now have some concrete avenues of investigation:
• Determine what affects migration velocity
• Determine what happens when gun to part distance is changed.

Along the way we will encounter many complications associated with varying electric fields, varying particle size, booth air and others, but by starting with simple models we can expand our understanding to at least qualitatively assess the effects of the complications. With a new level of understanding we can begin to sculpt a "perfect electrostatic coating world" an idealization that will guide change.

The Motion of Small Particles
The transfer efficiency equation points out the importance of understanding migration velocity or in other words, the forces affecting the motion of small particles. With some reasonable assumptions and analysis it is possible to gain some insight to the relative importance of the factors of:
1. Tube exit velocity or initial particle velocity
2. The Electric Field
3. The particle charge
4. Gravity
5. Downdraft velocity
6. Sidedraft velocity
7. Particle size

I do not intend for the models to be predictive in an absolute sense. The models, with firm theoretical foundations, capture the essence of small particle motion. Enhancements are left for the eager beavers and Ph.Ds.

The Motion of Pneumatically Conveyed Particles
What is the initial velocity of the particles as they exit the applicator and begin their trek toward the job? That is largely dependent upon the exit air velocity. In practice the measured air flow rate in a powder delivery hose ranges from 1 to 3 cubic feet per minute (CFM), a function of the amount of transport and atomizing air used, the frictional characteristics of the delivery system, the efficiency of the jet pump, and the amount of fluidizing air in the hopper. With typical tube diameters ranging from 3/8ths inch to 1/2 inch, the following matrix shows the typical exit air velocities associated with automotive powder coating. Velocity is essentially volumetric flow divided by tubing cross sectional area.
"Typical" Exit Velocities (meters/sec)

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<thead>
<tr>
<th></th>
<th>3/8ths inch</th>
<th>1/2 inch</th>
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<tbody>
<tr>
<td>1 CFM</td>
<td>6.63</td>
<td>3.73</td>
</tr>
<tr>
<td>3 CFM</td>
<td>19.90</td>
<td>11.19</td>
</tr>
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</table>

Perhaps in a misleading way, the matrix displays quite a range of velocities. In reality each hopper/hose/applicator flow system can operate in only a part of the above shown range. For instance, a long and snakelike approach hose would create significant frictional losses and dead spots, making it impossible to obtain a 3.73 m/s flow rate without surging. To eliminate surging, operations would increase the flow air which would increase the velocity.

**Theory at Work - tip #1:** Powder and equipment suppliers suggest short, straight runs of hose. One reason is to allow operations to minimize air velocity without surging. Generally when tuning in a system it is desirable to use convey air only, at first, and achieve the desired mass flow of powder. To eliminate surging, flow air is increased. Convey air must be increased to then maintain the mass flow of powder, this may create surging again so the process is iterated until mass flow is maintained without surging. If the process is carried out carefully, operations will achieve the minimum velocity necessary to convey a given amount of powder without surging. Shorter, straighter hose runs minimize dead spots and frictional losses and allow operations to run with lower overall velocities. Lower velocities are better in terms of system wear, impact fusion, and particle charging.

**Reynolds Number for Pneumatically Conveyed Powder**

In a Chemical Engineering thesis, sooner or later, the Reynolds Number is going to appear. The Reynolds Number is a dimensionless number that represents the ratio of inertial forces to viscous forces acting on a pneumatically conveyed powder particle. In the case of a spherical powder particle it is calculated as follows:

\[
N_{Re} = \frac{D_p \ u \ \rho}{\mu}
\]

- \(D_p\) = diameter of the particle
- \(u\) = relative velocity between particle and main body
- \(\rho\) = fluid density
- \(\mu\) = fluid viscosity
- \(N_{Re}\) = Reynolds Number (dimensionless)

The problem with the above calculation is that the relative velocity (air velocity - particle terminal velocity) is what's important, not just the air velocity. The terminal velocity of the particle is a function of the Drag coefficient. The Drag coefficient of the particle however, is dependent upon the Reynolds Number in the following way:
Therefore, after writing a force balance, finding the relative velocity looks to be an iterative process. But thanks to a shortcut provided in Perry's Handbook it is possible to directly calculate the particle velocity.

"For solid to gas weight rate ratios less than 5 in horizontal pipes (a typical powder coating weight ratio is 2), such as those usually employed in conventional pneumatic conveying systems, ... the following relation was determined experimentally"\(^{62}\)

\[ V_s = V_G \left( 1 - C_1 D_s^{0.3} \rho_s^{0.5} \right) \]

Where:
- \( V_s \) = particle velocity in (m/s)
- \( V_G \) = superficial gas velocity, in our case essentially exit gas velocity (m/s)
- \( C_1 \) = dimensional constant of 0.0639 in SI units
- \( D_s \) = diameter of the particle (m); typical of \( 30 \times 10^{-6} \)
- \( \rho_s \) = density of the solid particle (kg/m\(^3\)); typical of \( 1.3 \times 10^3 \)


Theory at Work - tip #2: For the typical values given and over the range of particle sizes and particle densities in powder coating, a good rule of thumb is that the particle velocity will be 90% of the air velocity. This assumes well developed flow which is a good assumption with about 10 inches of reasonably straight tubing prior to the end of the tubing.

Reynolds Numbers in powder painting then range from 0.7 to 10, bridging the area between Stoke's Law and the Intermediate Law. While the shortcut obviated the need to explicitly calculate the Reynolds Number it is nonetheless useful to know the flow regime of the operations. In the near future we will see that the assumption of Stoke's Law flow will lead to a useful simplification. For now a more complete discussion is left to the McCabe and Smith's chapter Flow Past Immersed Bodies\textsuperscript{63} which more fully explains the shortcomings of the assumption of spherical particles, and the implications of Intermediate Law and Stoke's Law flow. For our illustrative purposes it suffices to know that the initial velocity of powder particles exiting from a tube can range from about 4 m/s to 15 m/s.

The Dry Derivations of Equations of Particle Motion
The forces at work on a particle as it travels from the applicator to the job are:

1. Gravitational force \( F_g = mg \)
2. Electrical force \( F_e = qE \)
3. Viscous force \( F_\eta = 6\pi \eta w \)
4. Inertial force \( F_i = m \, dw/dt \)

where
\[
E = \text{ electric field} \\
q = \text{ charge on the particle} \\
\eta = \text{ viscosity of the medium} \\
a = \text{ particle radius} \\
w = \text{ relative velocity of the particle} \\
m = \text{ mass of the particle} \\
g = \text{ acceleration of gravity}
\]

The gravitational, electrical, and inertial forces are basic relations that are prominent in first year Physics books. The viscous force however is a little more involved. As seen in the previous section, for 30\( \mu \)m powder painting particles in air, when the relative velocity between the fluid and the particle is small, the Reynolds Number falls in the Stoke's Law region. If Stoke's Law can be assumed, a reasonable assumption when particles are close to their terminal velocity as they are for most of their flight, then the drag force is simply written.\textsuperscript{64}

\textsuperscript{63} McCabe and Smith, pp. 138-171.
\textsuperscript{64} McCabe and Smith, pp. 151-154.
**Stoke's Law**  
\[ C_D = \frac{24}{N_{RE}} \]

**Drag Force**  
\[ F_D = \frac{C_D w^2 \rho A_p}{2 g_c} \]

**Projected Area**  
\[ A_p = \pi a^2 \]

**Putting them together**  
\[ F_D = 6 \pi a \eta w \]

Rather than reinvent the wheel, in the subsequent analysis I have taken liberally from Oglesby and Nichols. Their book *Electrostatic Precipitation* puts together a cohesive story regarding particle kinetics.\(^{65}\)

A free body diagram gives a pictorial representation.

**Free Body Diagram of Forces Acting on a Negatively Charged Particle**

![Free Body Diagram](image)

According to Oglesby and Nichols the forces in the y-direction are generally small compared with the forces in the x-direction and for now we will neglect the forces in the y-direction. We will revisit them later when looking at downdraft velocity.

Summing the forces in the x-direction gives:

\[ F_e - F_\eta - F_i = 0 \]

Substitution and rearrangement lead to

---

\[
\frac{dw}{dt} + \frac{6\pi \eta w}{m} = \frac{qE}{m}
\]

a first order linear differential equation whose solution is:

\[
w = \frac{qE}{6\pi \eta} - C \exp\left(-\frac{6\pi \eta t}{m}\right)
\]

The velocity description could be useful if estimates of mass (m), particle charge (q) and the electric field (E) can be found.

Mass of the particle can be estimated if the particles are assumed to be spheres of uniform density. The relationship is then given by:

\[
m = \frac{4}{3} \pi a^3 \rho
\]

where \(\rho\) is the density and is assumed to be \(1.3 \times 10^3\) kg/m³.

For particle charging, since most powder particles are greater than 1 µm in diameter, it is appropriate to assume that field charging is the dominant charging mechanism. As a first order approximation we will assume that the particle has reached its saturation charge. In reality the charging mechanism is very involved. It will be explored more fully in later sections. For now, while not entirely accurate, the approximation of saturation charge is appropriate for the illustrative purposes of the calculation to come. The equation is:

\[
q = 12 \frac{\kappa}{\kappa + 2} \pi \varepsilon_o a^2 E_o
\]

where

- \(\kappa\) = dielectric constant of material - for plastics usually between 2 and 3
- \(\varepsilon_0\) = permittivity of free space \((8.85 \times 10^{-12}\) farads/meter\)
- \(a\) = particle radius in meters
- \(E_o\) = Electric field in the corona, usually about 2 to 6 \(\times 10^5\) volts/meter in electrostatic applications (Oglesby and Nichols and Fundamentals of Air Pollution Engineering)⁶⁶

To compute velocity as a function of time all that is needed is the viscosity of air which is \(1.8 \times 10^{-5}\) kg/(meter-sec.) and the initial condition. From the preceding section we know that at time = 0, the initial velocity in powder painting applications can range from 4 m/s to 15 m/s. To obtain the distance as function of time is a matter of integrating the velocity equation derived above.

\[ w = \frac{dx}{dt} = \frac{qE}{6\pi \eta} - C \exp\left( -\frac{6\pi \eta t}{m} \right) \]

at \( t = 0, \frac{dx}{dt} = w_0 \) (the particle exit velocity), and \( x = 0 \).

\[ C = \frac{qE}{6\pi \eta} - w_0 \]

integrating gives:

\[ x = \frac{qE}{6\pi \eta} t - \frac{m}{6\pi \eta} C \exp\left( -\frac{6\pi \eta t}{m} \right) + C' \]

Given the initial conditions, the integration constant \( C' \) is

\[ C' = \frac{m}{6\pi \eta} \left[ \frac{qE}{6\pi \eta} - w_0 \right] \]

In the y-direction the force balance is of a similar form to the x-direction force balance -- the difference being the force of gravity is substituted for the electric field force (note the sign convention, movement downward is taken to be positive).

\[ F_g - F_\eta - F_i = 0 \]

Assuming that the particle does not have velocity in the y-direction as it is ejected from the applicator and that the level of the applicator represents \( y = 0 \), then the initial conditions at \( t = 0 \) are \( \frac{dy}{dt} = 0 \) and \( y = 0 \). The relevant relations are given.

\[ w = \frac{dy}{dt} = \frac{mg}{6\pi \eta} - C_y \exp\left( -\frac{6\pi \eta t}{m} \right) \]

and

\[ y = \frac{mg}{6\pi \eta} t - \frac{m}{6\pi \eta} C_y \exp\left( -\frac{6\pi \eta t}{m} \right) + C'_y \]

Where:

\[ C_y = \frac{mg}{6\pi \eta} \quad \text{and} \quad C'_y = C_y \left[ \frac{m}{6\pi \eta} - 1 \right] \]

It is recognized that viewing motion in the x and y direction independently is not entirely accurate. The magnitude of the relative velocity in both directions affects the Reynolds Number which affects the Drag Coefficient. The relative velocity in the y-direction is a small fraction of the relative velocity in the x-direction.\(^{67}\) The result of making the

\(^{67}\) Oglesby and Nichols, p. 82.
assumption is negligible in the x-direction. In the y-direction, the drag force will in fact be greater than that predicted by the y-direction equations, therefore y-direction calculations can be thought of as a worst case limit.

With equations for particle motion in the x and y direction, we can look at the relative effects of factors like:

1. Tube exit velocity or initial particle velocity
2. The Electric Field
3. The particle charge
4. Gravity
5. Downdraft velocity
6. Sidedraft velocity
7. Particle size

The Basis for Comparison
Any relative analysis needs a stake in the ground, a benchmark. For the analysis to come, I have chosen values representative of typical, lower and upper values for the various parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Low Value</th>
<th>Typical</th>
<th>Upper Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exit Velocity (m/s)</td>
<td>4</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>Electric Field (V/m)</td>
<td>20,000</td>
<td>30,000</td>
<td>60,000</td>
</tr>
<tr>
<td>Particle Charge (% of Saturation)</td>
<td>10</td>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td>Gravity</td>
<td>Moon's</td>
<td>Earth's</td>
<td>Jupiter's</td>
</tr>
<tr>
<td>Downdraft Velocity (fpm)</td>
<td>0</td>
<td>30</td>
<td>60</td>
</tr>
<tr>
<td>Sidedraft Velocity (fpm)</td>
<td>0</td>
<td>30</td>
<td>60</td>
</tr>
<tr>
<td>Particle size (µm)</td>
<td>5</td>
<td>30</td>
<td>70</td>
</tr>
</tbody>
</table>

* just joking about the gravity.

The intent is to cull out the important from the trivial with respect to particle kinetics. To that end I integrated the equations into a Microsoft EXCEL spreadsheet and performed a sensitivity analysis. The analysis simulates using an applicator to spray a vertical panel that passes in front of the gun in one second. The panel is 10 inches away from the applicator.

The series of graphs that follow will help the reader gain an understanding of the motion of small particles. Each group of graphs looks at one particular variable holding all other factors at typical levels. The line with the positive slope represents the distance a particle travels from the gun to the job in the x-direction. The line with the negative slope represents the distance a particle falls in the same time (assuming a level trajectory). For comparison purposes, as an arbitrary metric I assume that a particle attaches to a job if the following conditions are met:

* A particle travels 10 inches in the x-direction in 1 second or less
A particle travels 10 inches in the x-direction before it falls 4 inches in the y-direction.

The first series of graphs looks at the effect of exit velocity.

At the low end of velocity it looks like the particle travels 10 inches toward the job in about 0.6 seconds; however, it also looks as though the particle falls 4 inches in 0.6 seconds. By the arbitrary metric it is questionable if a particle under these conditions would attach to the job. One would expect that increasing the exit velocity would reduce the time it takes for the particle to travel the 10 inches. It does. At 10 m/s the particle travels the distance in about 0.54 seconds. At 15 m/s the particle travels the distance in roughly 0.5 seconds. Exit velocity does measurably affect the motion of small particles in the normal range of operations. As we continue, we will see if it is a dominant factor.
The next variable to investigate is the electric field. In a subsequent section, the problems with point estimates of the electric field will be explained. For now suffice it to say that the electric field is always significantly higher at the corona tip than it is at the job and that the point estimate are rough approximations. Remember that the electric field affects both the charging of the particle and the conductivity of the particle in the interelectrode space.

Clearly in the range of operation in automotive powder coating, electric field has a larger impact on migration velocity than exit velocity does. At 20 KV/m, the particle would not attach; it would "fall off" the job before traveling 10 inches. As the electric field increases the particle's motion in the y-direction does not change but the particle velocity in the x-direction increases significantly. At 60 KV/m it takes only about 0.35 seconds to travel 10 inches.
Percent of saturation charge is an indication of the dynamics of the charging process. Like the electric field, it is a crude but enlightening point estimate. It too will be more deeply explored in subsequent sections.

Particle charge has a large effect upon migration velocity. At 10% of saturation charge the particle would take 1 second to travel 10 inches. At 100% of saturation charge, it would take roughly 0.35 seconds. Particle charge has no effect upon particle travel in the y-direction.
Excessive downdraft velocity is often cited as a cause for poor transfer efficiency. Let's see if the model concurs.

The model concurs with reality, which is nice. With no downdraft, the force of gravity is slight and the particle barely falls an inch in a second's time. Increasing the downdraft to 60 fpm has a dramatic effect on the travel in the y-direction. Just as expected, at higher downdrafts the particles are swept away to the reclaim before they can reach the job. Note that the travel in the x-direction is not affected.
Sidedraft velocity is a bit of a misnomer but it is an attempt to quantify the effects of items like shaping air or any other kind of air used to assist in blowing particles toward the job. It is recognized that this flow in actuality will form some sort of complex flow field. At the moment we are more concerned with gross effects.

The results are quite predictable. *As sidedraft velocity increases so does the migration velocity.*
The final variable under consideration is particle diameter. The powder coating industry has long recognized that higher particle sizes translate to higher TE. The model will help put the effect of particle diameter in perspective, comparing it with the other process variables.

Within the range of "normal" operation, particle diameter has the largest effect of any variable upon migration velocity and transfer efficiency. The curvature noted with the 70μm particle is due to the inertial exponential term in the solved differential equation for x-direction motion. In most all of the other cases this term has been insignificant. The implication is that for a first order approximation, ignoring the effects of sidedraft and downdraft, migration velocity can be very simply written.

\[
w = \frac{qE}{6\pi \eta} - C \exp\left(-\frac{\text{mant}}{m}\right)
\]

migration velocity = \[
\frac{qE}{6\pi \eta}
\]
The sensitivity analysis has shown particle diameter, particle charging and the electric field to all be significant process parameters. While sidedraft and downdraft also play a big role in TE, they can be decoupled from the other variables and dealt with separately. As we continue it will become clear that particle diameter, particle charging, the electric field and some new variables come together in an interrelated and non-linear way. More knowledge is necessary before we can understand the fundamentals of powder coating.
The Electric Field

The electric field is the key to conventional electrostatic powder coating. Oglesby and Nichols explain the three-fold purpose of the electric field:

1. A high electric field near the electrode with a small radius of curvature causes the generation of the charging ions in an electrical corona.
2. The field provides the driving force that causes these ions to collide with and transfer their charge to the particles.
3. It establishes the force necessary for collection of the charged particulate matter. (p. 31)

Previously, for simplicity, the electric field in the equations was implicitly assumed to be constant. In electrostatic powder coating, the electric field is far more complex. In my discussion of the electric field I will deal with the complexity, but will idealize the analysis somewhat by assuming a point to plane geometry. The point is a representation of the high curvature tip of the gun electrode, and the plane is the surface of the job.

\[ \frac{-dV}{dr} \]

The electric field is defined to be: \( \frac{-dV}{dr} \) Where V represents voltage and r represents position or radius. To estimate the electric field as a function of position, Poisson's equation must be solved. Poisson's equation describes the relationship between electrical potential and the space charge or charge density.

\[ \frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2} = -\frac{\rho}{\varepsilon_0} \]

Where

- \( V \) = electric potential (V)
- \( \rho \) = space charge density (C/m\(^3\))
- \( \varepsilon_0 \) = permittivity of the gas (C\(^2\)/N-m\(^2\))
- \( x, y, z \) = rectangular coordinates (m)

The analytical solution for Poisson's equation in a wire-cylinder geometry has been worked out in cylindrical coordinates by White. In discussions with a number of people familiar with the problem it appears that an analytical solution for the point to plane geometry either does not exist or is very complicated. Instead I have chosen to focus my efforts on developing a numerical solution using a method outlined generally in Perry's Handbook of Chemical Engineering, more specifically by Jack McDonald in "Computer Simulation of the Electrostatic Precipitation Process" and in Crowley's piece, "Electrostatic Fields on PC Spreadsheets".\(^{68,69,70}\)

\(^{68}\) Perry, pp 2-68 to 2-71.
The equations that must be numerically crunched in their two-dimensional descriptive forms are:

\[
\frac{\Delta^2 V}{\Delta x^2} + \frac{\Delta^2 V}{\Delta y^2} = -\frac{\rho}{\varepsilon_0}
\]

\[
\rho^2 = \varepsilon_0 \left( \frac{\Delta V \Delta \rho}{\Delta x \Delta x} + \frac{\Delta V \Delta \rho}{\Delta y \Delta y} \right) + \varepsilon_0 \rho \frac{\Delta V}{b} \left( \frac{\Delta \rho}{\Delta x \Delta x} + \frac{\Delta V}{\Delta y \Delta y} \right)
\]

All the terms in the two previous equations, except for \( b \), have been previously defined. \( b \) is the effective charge carrier mobility in units of \((m^2/V\cdot s)\). It is estimated to be between 1.0 \( \times \) 10\(^{-4} \) and 1.4 \( \times \) 10\(^{-4} \) in both Oglesby and Nichols (p. 43) and *Fundamentals of Air Pollution* (p. 420). I will only loosely describe the calculations, if the details are of interest I refer the reader to Oglesby and Nichols (pp. 39-45) and Crowley's *Electrostatic Fields on PC Spreadsheets*.

The numerical model solves for voltage, electric field, space charge, and current density in the \( x \) and \( y \) directions as depicted in the grid below.

**Point to Plane Idealization for Numerical Solution of Poisson's Equation**

Due to symmetry only two dimensions are required. The three-dimensional solution can be found by rotating the two-dimensional grid solution about the AD axis.

The boundary conditions outlined in Oglesby and Nichols (O&N) (p. 42) for the problem are:

- \( V \) at the corona tip equals the applied voltage (point A)
- \( E_x = 0 \) and \( E_y = 0 \) at points A and B
- \( V = 0 \) on the plate or along line CD
- \( E_x = -\Delta V/\Delta x = 0 \) along line AB
- \( E_y = -\Delta V/\Delta y = 0 \) along lines BC, CD, and AD
- \( \rho = j/\varepsilon E_x \) b near plate

Finally for calculations of voltage and space charge on the boundary lines AB, BC, CD, and AD, it was necessary assume voltage values for adjacent points outside the grid. In these cases, the voltages outside the grid were assigned the same voltage as similarly located points within the grid. (O & N p. 43).
I used a Pentium processor to crunch the equations. Convergence was usually achieved in less than 10 min. I modified the procedure outlined in O & N as follows:

Step 1:
- Assign a value of zero to corona tip in the space charge grid. (The shaded box at point A).
- Assign the tip voltage to the shaded box at point A in the voltage grid. I used -60,000 volts.
- Set EXCEL for manual calculation mode and then iterate until the desired convergence is found.
- When the calculation is completed the Voltage grid will be initialized.

**EXCEL Spreadsheet Calculational Procedure**

![Diagram of EXCEL Spreadsheet Calculational Procedure]

Step 2:
- Assign a space charge value to the shaded box in the space charge matrix. I used a value of 8.8 x 10^{-5} \text{ C/m}^3
- Using a macro, the initialized voltage values are pasted into the Last Voltage grid.
- The figure of merit I used for convergence was epsilon. It is the sum of the squared errors for corresponding points in the Voltage and Last Voltage grid.
- As long as epsilon is above a predetermined limit the macro manually iterates 20 times. After the 20th iteration, the macro checks epsilon and the Voltage grid is pasted into the Last Voltage grid.
- The macro continues until epsilon is sufficiently small.

Step 3:
- The selection of the initial value of the space charge dictates the current density. In practice the initial value of space charge should be selected such that the current density near the plate corresponds with a measured current density. In the absence of measurements I chose a space charge density such that the charge to mass ratio for a 30 \mu m particle under typical conditions would be about 1 \times 10^3 \text{ C/kg}. 
Using the model, graphical depictions for the magnitude of the electric field (E), the space charge density (ρ), the voltage (V), and the current density (J) were generated.
Magnitude of Space Charge (C/m³)

-60 KV and -8.8e-5 (C/m³)
Magnitude of Voltage

-60 KV and -8.8e-5 (C/m3)
Magnitude of Current Density (C/m²)

-60 KV and -8.8e-5 (C/m³)
I have discussed the procedure with researchers from ABB Paint Finishing. They too recognize the importance of modeling the electric field. They concur with the validity of the calculation procedure and the imbedded assumptions. The only major difference is that ABB uses a very expensive finite element program and an expensive workstation to produce similar results.

The primary conclusion to be drawn from inspection of the 3-dimensional graphs is that the electric field and current density are very high at the corona tip and that they drop off precipitously in both the x and y directions. Previously the electric field was assumed to be constant. In terms of electrostatic conveyance, the assumption may be reasonable; for a large portion of the distance between the corona tip and the sprayed part, the electric field is relatively flat. But in the charging zone the electric field changes a great deal and cannot be assumed to be constant. The implications of the drop off are important as we will see in the coming sections on particle charging.
Particle Charging

The charge of a particle plays a big role in its migration velocity; how does a particle become charged?

For corona charging applications that are prevalent in powder coating two charging mechanisms dominate: field charging and diffusion charging. For particles with a diameter greater than 1 μm, field charging is the overwhelming charging mechanism. As particles become smaller than 0.5 μm, diffusion charging begins to dominate. Powder particle size distributions are primarily made up of particles with diameters greater than 1 μm, as a result I will focus only on field charging.

In the following discussion I have taken liberally from the oft cited Industrial Electrostatic Precipitation (White) and Electrostatic Precipitation (O & N)

Three major assumptions are made in the derivation of a tractable field charging relationship:

1. The particles are considered to be spheres.
2. The field from one particle does not modify the field in the vicinity of another particle.
3. The particles and ions are suspended in a region permeated by a constant electric field. (O&N, p. 58)

While on the face of it these assumptions might appear unrealistic, White explains the legitimacy of the assumptions in his text.

"To derive the field-charging equations consider an initially uncharged particle of radius $a$ is placed in a corona with a field strength of $E_0$ and an ion density of $N_0$. The particle will immediately begin to be charged by the gas ions, and this action will continue until the repelling field set up by the accumulation of charge on the particle becomes sufficiently strong to prevent any further ions from reaching the particle. The mechanism of particle charging depends basically upon the flow of gas ions to the particles." (White, p. 129)

"The presence of either a dielectric (such as powder paint particles) or conducting particle in an electrostatic field causes lines of electric force to concentrate in the neighborhood of the particle with a consequent increase in the electric field at the particle's surface. This distortion can be modeled." (White, p. 130)

Electric Field in the Vicinity of a Charged Sphere

(White, p. 132)

Electrostatic principles have been used to develop an equation describing the resultant electric field around a charging particle:
\[ E = 3 E_0 \cos \theta - \frac{q}{4 \pi \varepsilon_0 a^2} \]

where

- \( E \) = the resultant electric field
- \( \theta \) = the angle between a point on the sphere and electric field
- \( \varepsilon_0 \) = the permittivity of free space
- \( a \) = the particle radius
- \( q \) = the particle charge

In powder painting we are concerned with the speed with which a particle acquires its charge - will a particle remain in the high electric field of the corona long enough to pick up a sufficient charge? To answer the question the rate of charging is necessary. The rate of charging is initially high and is only limited by the rate at which ions are carried into the particle by the external electric field. As charging proceeds, the electric field resulting from the charge on the particle opposes the external field so that the effective charging area decreases.

The rate of change of charge on a particle with respect to time is defined as the current. The ion current is equal to the integral of the current density times the differential active charging area:

\[ \frac{dq}{dt} = \int_0^{\theta_0} j \, dA = \int_0^{\theta_0} (N_e b E) dA \]

\[ \frac{dq}{dt} = N_e b \int_0^{\theta_0} (3E_0 \cos \theta - \frac{q}{4 \pi \varepsilon_0 a^2}) dA \]

where

- \( q \) = charge on particle \( \text{(C)} \)
- \( b \) = mobility of the ion \( \text{(m}^2/\text{sec-V)} \)
- \( e \) = electronic charge \( \text{(1.6 x 10^{-19} C)} \)
- \( j \) = current density \( = N_o e b E \) \( \text{(C/m}^3 \) \)
- \( \theta_0 \) = limiting angle for charge flow to particle \( \text{(radians)} \)
- \( dA \) = element of area \( = 2\pi a^2 \sin \theta \, d\theta \) \( \text{(m}^2 \) \)
- \( t \) = time \( \text{(sec)} \)

The saturation charge or the maximum particle charge for a conducting particle can be found from equation 6 by setting \( E \) equal to 0 when \( \cos \theta = 1 \) or:

\[ q_s = 12 \pi a^2 \varepsilon_0 E_0 \]
For a nonconductive particle such as powder paint, equation 8 must be modified. \( \kappa \) is the dielectric constant of the powder paint.

\[
q_s = 12 \frac{\kappa}{\kappa + 2} \pi \varepsilon_o a^2 E_o
\]

**Theory at Work tip #3**: The above equation assumes spherical particles with a radius of \( a \). Charging has been shown to be a function of the surface area of the particle. In reality the powder manufacturing process creates jagged particles which have a significantly higher surface area than the idealized assumption estimates. Therefore the saturation charge for a given particle is really only an approximation. Generally the approximation does not pose a problem since a powder with a given particle size charges in a certain way. But what happens when a powder is recycled? As a particle is reworked it loses some of its jaggedness. This translates to lower surface area for a particle that is thought to have the same particle size distribution. The reason transfer efficiency for reworked powder is lower than transfer efficiency for virgin powder is that reworked powder has a lower surface area per particle diameter than virgin powder for the same particle diameter. The saturation charge is reduced.

After some equation processing which is well described in Oglesby and Nichols (p. 61-62), the resulting differential equation of interest, known as the Pauthenier equation, is given by:

\[
\frac{dq}{dt} = \frac{N_o b e q_s}{4 \varepsilon_o} \left( 1 - \frac{q}{q_s} \right)^2
\]

Upon integration with the initial condition of zero charge \((q=0)\) at the start of the process \((t=0)\) the relation is:

\[
q(t) = q_s - \frac{t}{\tau} \quad \text{where} \quad \tau = \frac{4 \varepsilon_o E}{J} = \frac{4 \varepsilon_o}{N_o b e}
\]

**Some Factors Affecting Particle Charging** (Particle size, Exit velocity, Particle exit position)

Pauthenier's equation is useful for understanding the effect of particle size on charging. I have incorporated the equations into an EXCEL spreadsheet to demonstrate the effect of particle size on particle charge. Values for the equation parameters are as follows:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \kappa )</td>
<td>values for dielectric constants for plastic are commonly between 2 and 3. I have used the value of 3. (source: Handbook of Chemistry and Physics)</td>
</tr>
<tr>
<td>( \varepsilon_o )</td>
<td>8.85 ( \times ) 10^{-12} ( \text{C}^2/\text{N-m}^2 ) (source: University Physics, Sears et. al.)</td>
</tr>
</tbody>
</table>
\[ E_0 = 3 \times 10^5 \text{ (V/m)} \] (source: Fundamentals of Air Pollution Engineering, p 420)

\[ N_0 = 10^{15} \text{ to } 10^{13} \text{ (m}^{-3}\text{)} \] (source: Fundamentals of Air Pollution Engineering, p. 417)

\[ b = 1 \times 10^{-4} \text{ (m}^2 \text{ / V}\cdot\text{s}) \] (source: Fundamentals of Air Pollution Engineering, p. 420)

\[ e = 1.6 \times 10^{-19} \text{ (C)} \] (source: University Physics, Sears et. al.)

\[ J = \text{ionic current density is found to be } 5 \times 10^{-3} \text{ (A/m}^2\text{)} \]

Factors prevalent in electrostatic powder coating such as back corona and the extremely high resistivity of the powder need to be taken into account for detailed calculations\textsuperscript{71}; however, Pauthenier's equation can be used in its simple form to gain a basic understanding of particle charging.

While these values are rough estimates, they will help illustrate the relationship between particle size and particle charging.

**Pauthenier's Equation**

Larger Particles Acquire Significantly More Charge

![Graph showing the relationship between particle size and time](image)

Larger particles acquire significantly more charge. More charge leads to a greater migration velocity and higher transfer efficiency.

In the powder coating industry the charge to mass ratio (q/m) is often of interest. Many experts cite a value of $1 \times 10^{-3}$ C/kg as an optimum value.\textsuperscript{72, 73} The following graph illustrates how charge to mass ratio is related to particle size.

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\textsuperscript{73} I. Vereshchagin, et. al., "Optimization of Electrostatic Powder Spraying,", *Journal of Electrostatics*, 23 (1989), p. 189-196. These findings concur with the work of others including Cross.
Smaller particles attain a higher charge to mass ratio under similar charging conditions. In this case the charging conditions are optimized for a 30 μm particle diameter. Smaller particles under these conditions gather excessive charge for their mass and exacerbate a deleterious condition known as back corona or back ionization.

When the electric field \( (E) \) and current density \( (J) \) are approximated with point estimates and in the absence of back ionization, Pauthenier's equation dictates particle charging. The maximum possible charge is given by the saturation charge. Saturation charge is governed by the equation:

\[
q_s = 12 \frac{K}{\kappa + 2} \pi \varepsilon_0 a^2 E_0
\]

It is a function of the dielectric constant of the material, the particle radius squared, and the electric field in the charging zone.

The charging time constant \( (\tau) \) dictates the speed of the charging process. Smaller time constants result in faster charging.

\[
\tau = \frac{4 \varepsilon_0 E}{J}
\]

Increasing the current density \( (J) \) and decreasing the electric field \( (E) \) will increase the speed of charging.

From a practical standpoint, two other factors come into play in the powder charging process:

- the exit velocity of the powder
- the exit position of the powder with relation to the corona tip.
Previous three-dimensional graphs (pp. 58-59) of a representative electric field and its companion current density showed the sharp reduction in E and J both in the x and y directions as a particle moves away from the corona tip. Considering Pauthenier's equation and the equation for saturation charging, the steep drop off in E and J can be a problem.

To maximize particle charge, the saturation charge must be large which favors greater electric fields. To speed the charging process the current density must at least proportionally rise with the electric field to avoid increasing the charging time constant. Therefore, if maximizing particle charge is the goal, it behooves a particle to remain in the small high electric field/high current density area that is very close to the corona generating tip.

Lower particle exit velocities improve particle charging because they allow the particle to remain in the high electric field charging zone for a longer period of time. To generate illustrative graphs of the effect, EXCEL particle dynamic, electric field, and particle charging models were used.

**Exit Velocity Has Significant Effect on Charging**

![Graph showing the effect of exit velocity on particle charging](image)

The increasing volumetric flow rate of air increases the exit velocity in a nearly proportional way.

**Theory at Work tip #4**: Many powder coating operations prefer a gentle blowing of powder to the job as compared with blasting the powder at the job. The reason is that generally a gentle application (lower exit velocities) leads to better charging and higher transfer efficiencies. Keep in mind that the effect of the exit velocity on the distance the particle travels is captured in the exponential term of the migration velocity equation and
is insignificant for most particles. The benefits from improved particle charging outweighs the detriments from decreasing initial velocity.

*Theory at Work tip #5:* One of the reasons that the transfer efficiency of any given applicator is dependent upon the flow rate of the powder is that the flow rate of the powder is dependent upon the velocity of the conveyance air. Higher mass flow rates require higher air velocities to prevent settling and surging. Higher air velocities lead to lower charge-to-mass ratios.

The position that the particle exits the applicator with relation to the corona discharge is also an important consideration. Many corona type applicators have a high voltage needle in the middle of the nozzle exit. In addition corona applicators often make use of deflector tips to spread out the flow of powder in an effort to improve film build uniformity.

The high electric field/high current density charging zone is very close to the corona tip. If a particle is even 1 cm. away from the corona tip in an axial direction, it will be far enough away from the charging zone to create a large difference in the particle charging. The next graph demonstrates the effect.

![Exit Position Affects Particle Charging](image)

The variability of particles' exit positions with respect to the corona generating tip can cause a great deal of charging variability. If uniform charging is a goal, the rudimentary calculations indicate that powder must pass more uniformly through the charging zone. Particle exit velocity and exit position are both important factors in the charging process; they indicate areas for applicator design improvement.

**Understanding Gun KV (kilovolt) Settings and Gun-to-Job Distance**
The Electric Field (E in volts per meter) and the Current Density (J in coulombs per square meter) have a great deal to do with the charging process; understanding these two variables is crucial to understanding the powder coating process. The Electric Field model enables the calculation of the E and J based on some idealized boundary conditions, an assumed tip voltage, and an initial space charge density assumption. The
space charge density is chosen based on real-life current measurements. *In actual applications corona gun KV settings and gun-to-job distance largely determine the tip voltage and the real-life current.*

The role of Gun KV and gun-to-job distance is clarified with a pictorial representation of the voltage-current relationship for automotive powder coating. According to Gerry Crum, Nordson’s Engineering Manager, an idealized but accurate view of the voltage-current relationship is as follows

**Voltage, Current, and Resistance of Corona Gun Process**

Current flows from left to right

<table>
<thead>
<tr>
<th>Constant Source Voltage ($V_0$)</th>
<th>Internal Resistance ($R_s$)</th>
<th>Blocking Resistor in Gun ($R_g$)</th>
<th>Tip Voltage($V_t$)</th>
<th>Variable Resistance between gun tip and the surface of the powder on the job ($R_a$)</th>
<th>Variable Resistance of powder layer and E-coat resistance ($R_c$)</th>
</tr>
</thead>
</table>

The equations describing the current-voltage curves with no back corona are given by:

Current ($I_L$) is measured near the tip. Tip Voltage ($V_t$) is then:

$$I_L = \frac{V_0}{R_s + R_g + R_a + R_c}$$

$$V_t = V_0 - I_L (R_s + R_g)$$

In a simplistic way, before the onset of back-ionization, the two factors determining the electric field and the current density are the gun KV and the gun-to-job distance. Gun-to-job distance determines $R_a$ and unless the gun-to-job distance is very small, $R_a$ is overwhelmingly the largest resistance term. Further, over the range of normal corona gun powder coating operation, (gun-to-job distances of 5 to 12 inches), the resistance increases linearly with increasing distance.

Gun KV is very important to powder coating; it is also one of the most misunderstood variables. The displayed gun KV for most corona applicators is based upon an initial calibration of the gun known as a *load line*. The load line is a laboratory measurement.

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74 G. Crum, Personal Discussion, August, 1994
The load line is based on the measurement of $I_L$ at the gun with the tip voltage measured at no load (infinite variable resistance) and at short circuit (zero variable resistance).

A typical load line is shown:  

![Typical Load Line](image)

*The displayed Gun KV is based on the laboratory derived load line and does not indicate the actual tip voltage.* The Gun KV knob is simply a "gimme more" or "gimme less" knob. Turning the knob all the way in a clockwise direction does not ensure a tip voltage of 100 KVs (as might be inferred from the digital display) all it ensures is that the applicator is providing the maximum tip voltage for the given coating condition, a condition primarily dictated by the gun to job distance. As Gerry Crum observed in the monograph *Understanding Load Lines*, "If the measurement is so hard to make and doesn't represent real operating conditions, why is it bothered with at all? The truth is that it is primarily an advertising number, since bigger numbers are generally assumed to be better". (p. 2) Nonetheless, by regulating the relative amount of current to the gun tip, the Gun KV knob does provide significant control over coating conditions.

The electric field and current density have been shown to be critical variables affecting particle charging. The behavior of the electric field and current density in a powder coating situation has been modeled analytically with Poisson's equation. The short term variables available to the powder coater to enable control of the electric field and current density are:
- the gun-to-job distance which determines the resistance of the system
- the relative control of the gun KV knob.

In the long term, applicator re-design can also independently enhance particle charging performance.

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The previous discussions have ignored back ionization. To holistically optimize powder coating performance requires understanding the subtle and not-so-subtle effects of resistivity and back corona.

**Resistivity and Back Corona**

Much of the previous discussion has had the caveat "in the absence of back ionization". This is unrealistic for powder coating due to the high resistivity of the acrylic, polyester, and epoxy powders. Fortunately the electrostatic precipitation (ESP) industry has recognized the crippling effects of high resistivity particles and back corona. The ESP industry has extensively modeled the problem. They suggest methods for ameliorating the effects of back corona or back ionization.

Resistivity and back corona are closely linked and are dealt with together in most literature. As Oglesby and Nichols put it:

Dust must be capable of conducting the corona current to the passive electrode. If the dust has a high electrical resistivity the corona current will be limited and thereby limit the magnitude of the particle charge, the charging rate, and the electric field. The combined effect of these is to severely reduce precipitator performance.

For a very high resistivity dust, electrical breakdown of the dust layer will occur at very low current densities resulting in a condition called back corona or reverse ionization. (p. 119)

In the ESP industry, typical resistivities range from $10^8$ to $10^{13}$ ohm-cm with anything over $2 \times 10^{10}$ ohm-cm considered to be high. In the case of electrostatic powder coating, resistivities are extremely high; estimates of powder resistivity range between $10^{12}$ to $10^{18}$ ohm-cm.

The high resistivity of automotive powder creates a nearly instantaneous back corona that has been verified by Gary Gorrow of PPG, Sam Rhue of Seibert and Gerry Crum of Nordson and others. What are the implications of high resistivity powder and back corona?

One attribute of powder coating with a high resistivity powder is the reduction of the particle charge. White explains:

Severe back corona produces a positive ion discharge at the collecting electrode (assuming negative corona from the wires) which tends to neutralize the negative ions from the discharge electrode. Under this latter condition, particle charge is greatly reduced, and positive and neutral particles may be present in numbers approaching or even exceeding the negative particles.

The charging of particles under these conditions has been treated quantitatively by Pauthenier. The presence of both positive and negative ions in appreciable numbers means that it is impossible for suspended particles to gain anything even approaching the normal saturation charges. The situation is further aggravated by the concentration of the discharge into streamers and by the low operating voltages characteristic of back corona. The net result is that the average particle charge is greatly reduced, and that positive, negative, and neutral particles are present. The extent of the lowering of the average particle charge depends upon the severity of the back discharge. ... Needless to say, the

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precipitator under these circumstances is scarcely more than a relatively expensive settling chamber, and the electric power used is a complete waste. (pp. 150-151)

In Mizuno's article *Review of Particle Charging Research* Pauthenier's quantitative treatment is elucidated:

Field charging theory must be modified when high resistivity dust with $\rho_d > 2 \times 10^{10}$ ohm-cm is encountered to produce back corona. Originally developed by Pauthenier the equation states:

$$q(t) = \frac{q_s (1 - e^{-\gamma \tau'})}{(1 - \alpha^2 e^{-\gamma \tau'})}$$

where:

$$q_s = \alpha q_i$$

= degraded saturation charge

$$\alpha = \frac{(1 - \gamma)}{(1 + \gamma)}$$

= charge degradation factor

$$\gamma = \frac{b + N_+}{\sqrt{b - N_-}} = \sqrt{\frac{J_+}{J_-}}$$

$$\tau' = \frac{\varepsilon_0 E}{\sqrt{J_+ J_-}}$$

= charging time constant

In these equations:

$b$ = ion mobility for positive and negative ions

$N$ = the number density of positive and negative ions

$J$ = the current density of positive and negative ions

Experiments have shown that charge degradation by more than 50% of the Pauthenier saturation charge are possible with high resistivity particles.  

Note in the above equations that the presence of positive ions generated by the back corona affects both the saturation charge ($q_i'$) and the charging rate, characterized by $\tau'$.  

Mazuda notes in his article *Resistivity and Back Corona* some data regarding the relationship between resistivity and the term $J_+/J_-$ (where $J = J_+ + J_-$) in some of his experimentation.

<table>
<thead>
<tr>
<th>Resistivity Range</th>
<th>$J_+/J_-$ Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>below $10^{13}$ ohm-cm</td>
<td>10% to 20%</td>
</tr>
<tr>
<td>beyond $10^{14}$ ohm-cm</td>
<td>greater than 30% to 40%</td>
</tr>
</tbody>
</table>

Graphically the effect of increasing resistivity in terms of Pauthenier's modified equation is implied by looking at the effect of increasing $J_+/J_-$ on charge to mass ratio ($q/m$).

Higher Resistivities Lead to Poor Charging
(higher J+/J- implies greater resistivity)

Many sources cite a minimum charge to mass ratio for effective powder coating of around 1 to $5 \times 10^{-4}$ C/kg.\textsuperscript{80,81} Higher resistivity reduces the saturation charge of a particle and increases the charging time constant in accordance with Pautenier's modified equation. The effect is significant and can result in extremely poor powder coating performance.

High resistivity particles also reduce the voltage drop from the electrode tip to the grounded surface of the job thereby reducing the electric field. Oglesby and Nichols describe how:

If dust is present on the collection electrode surface, the voltage-current curves will be altered by the voltage drop in the dust layer, which is given by

$$V_d = j \rho t$$

Where

- $j$ = current density
- $\rho$ = resistivity
- $t$ = dust layer thickness....

High dust resistivity can result in large voltage drops and high electric fields within the dust layer itself. The field in the deposit can be computed as

$$E = j \rho$$

If the resistivity of the dust is very high, the voltage drop across and the electric field in the dust layer can be exceptionally large even at low current densities, and breakdown can occur... If this occurs, a condition of back corona develops and the voltage-current curves of the precipitator depart from the normal curves characteristic of a pure resistive effect.

\textsuperscript{80} J. Hughes, "Optimizing Powder Plant," \textit{Finishing}, July 1982, p. 16.
When a back corona condition develops, the character of the voltage current curves changes. Increases in voltage beyond the onset of back corona result in an abnormally rapid increase in current. (pp. 120-121)

When back corona develops, positive ions begin to flow back toward the gun electrode. While this flow of positive ions in the negative direction contributes to the current density, the increased current will not result in a concomitant increase in particle charging rate and saturation charge. In fact, as Pauthenier's equations for high resistivity particles point out, the increase in \( J_+ \) reduces the achievable saturation charge as seen by \( \alpha q_s \). In effect, the positive ions "cancel" the desirous negative ions.

**Before Back Corona**

**After Back Corona**

\[
\text{Gross current } I_L = \text{Negative flow} + \text{Positive flow} \\
\text{Effective current} = \text{Negative flow} - \text{Positive flow}
\]

The current increase is a measurable phenomenon and will be explored further in a subsequent section.
In addition to lowering particle charge, the charging rate, and the electric field, the high resistivity/back corona combination can adversely effect the surface appearance of the job. In Masuda's words from *Resistivity and Back Corona*:

At the onset of back corona... the breakdown of this layer occurs many times, ejecting dust particles to produce the pinholes called "orange peel" or "moon-craters", and finally stops to turn into a stable glow-corona. ... dust deposition can generally continue until a certain thickness is reached, at which the positive ion emissions become so active that all the oncoming particles are positively charged and repelled back into the gas space. This is called the 'limiting thickness' and has a great importance in the case when dust resistivity is extremely high, say beyond $10^{15}$ ohm-cm (e.g. electrostatic powder coating) (p. 343)

High resistivity and back corona are bad things. The next logical question is: can anything be done to improve the process and if so what are the ramifications?

**Lowering Resistivity - Industry Reflection**

One approach that the electrostatic precipitation industry has taken to lower resistivity is to condition the dust or powder. Since plastics are insulators, charge will not travel through the particle as it does with conductive materials such as carbon black. Therefore at the relatively low temperatures existing in powder coating applications, the primary mechanism for charge mobility is via the surface of the powder particle. This phenomenon has been given the stunningly inventive moniker - *surface conduction*. If a conductive substance can be coated on the outside of insulating particles then the particles would be *conditioned*. Improved surface conduction leads to lower resistivity.

For years the electrostatic precipitation industry has wrestled with and experimented with various conditioning substances to lower resistivity of particles to below the magical value of $2 \times 10^{10}$ ohm-cm. One of the most ubiquitous conditioning substances is water. At typical electrostatic coating temperatures, water readily adsorbs onto powder particles. As a Seibert technical manual explains:

The moisture content of a powder is inversely related to its specific resistivity and therefore, its ability to acquire and hold a charge (charge decay rate). So, fine powders tend to hold more moisture and more charge (in fact too much charge) than courser powder particles (charge/mass ratio).(p. 42)

As an aside, the Seibert passage raises some interesting and controversial issues around charge decay rate, the appropriate amount of charge and the charge to mass ratio which I will deal with shortly

Data from Seibert, White, and Oglesby and Nichols indicate that the surface coating of water on particles can lower resistivity by as much as 3 orders of magnitude. Still, if the initial resistivity is on the order of $10^{17}$ ohm-cm, conditioning with water only reduces resistivity to about $10^{14}$ ohm-cm.

Other conditioning substances have been investigated. One that has been applied in the electrostatic precipitation industry is $\text{SO}_3$, which is not without its problems.
"There is some reluctance on the part of plant personnel to use SO$_3$...SO$_3$ is an effective oxidizer and strongly attacks tissue" (O & N, p. 139)

The point here is not that SO$_3$ is "the" conditioning material but rather that many possible materials might be potential conditioning materials. It is likely that a substance exists that could be coated on powder particles to provide resistivities in the range of 10$^9$ ohm-cm.

If lower resistivity powders were available, would it be wise to use them? After discussions with Sam Rhue (Seibert), Gerry Crum (Nordson), and Max Helvey (EvTech) (Summer 1994) the answer is not clear.

Industry experts' arguments against a lower resistivity powder are:

1. Too much charge on the particles. Charge to mass too high. Too much charge on the job will cause worsening back-corona and reduce the maximum thickness of the powder coating.
2. Lower resistivities will reduce the force of attraction of powder to the job.

Industry experts' arguments for a lower resistivity powder:

1. The electrostatic precipitation industry advocates lower resistivity for improved collection efficiency.
2. Anecdotal automotive evidence tends to confirm that lower resistivity powders improve TE and film build.

Armed with the knowledge of the basics of powder coating physics and some experimental evidence, I will explain why lowering powder resistivity is clearly beneficial.
A Graphical Description of Resistivity and Back Corona

Back corona occurs because negatively charged ions cannot get to ground. Measuring the image current from the workpiece to ground illustrates the relationship between ions and back-corona.

![Graph showing workpiece current and coating time](image)

At point A, the corona gun is turned on and no powder is blown at the surface. At point B, the powder flow is initiated; the current drops off as ions flock to the slower moving particles and the space charge is altered. At point C back-ionization becomes significant. The increase in charge reflects an increase in the ion population due to back ionization. At point D the self-limiting thickness is achieved. Particles no longer attach to the job. Finally at point E, the powder is switched off and free ions are once again able to reach the surface.

Many studies have been done citing the importance of measuring the workpiece to ground current.\(^{82,83,84}\) One uniform observation was the usefulness of the measurement for quantifying back-ionization. Various studies showed that back-ionization severity was well described by the time to back-ionization which is essentially the time between points B and C in the graph. Higher gun KV's would result in shorter time to back-ionization and at the extremes would result in poor coating performance.

From a coating perspective, the problem is that there are too many ions on the surface of the job. There are two ways to solve the problem.


• increase the rate that charges can travel to ground
• reduce the rate of charge arrival
High resistivity problems are associated with the inability of the charges to travel to ground. The reduction of the rate of charge arrival is primarily an applicator design issue and will be dealt with in later sections.

**Rate of Charge Decay**
As a job is sprayed, due to high resistivity, ions accumulate on the surface. The sprayed part retains the particle charge for an extended period of time. However, over time, even without heating, the surface charge will decay and in the limit all the charge will bleed off to ground. In this way charge decay for an electrostatically painted vehicle is analogous to an RC circuit where the powder layer represents the resistor and the charge build up on the surface represents a very big capacitor.

**The RC Circuit**

![Diagram of RC Circuit]

The dynamic behavior of the RC circuit is describe by:

\[ C \frac{dv}{dt} + \frac{v}{R} = 0 \]

Whose solution is:

\[ v(t) = V_0 e^{-\frac{t}{RC}} \]

The time constant \( \tau \) is then:

\[ RC = \tau \]

White (p. 326) has defined the time constant for electrical relaxation as being

\[ \varepsilon_0 k \rho = \tau \]

which is analogous to RC

where:

\[ \varepsilon_0 = \text{the permittivity of free space} \]
\[ k = \text{dielectric constant of the powder layer (3 per White pg. 326)} \]
\[ \rho = \text{resistivity of the powder} \]

Measurement of the electrical relaxation time constant is a superior method for determining resistivity. Traditionally resistivity of a powder is measured by applying a
high voltage across a small packed sample of powder and recording the current.\textsuperscript{85} The approach yields a "laboratory resistivity" which sometimes does not correlate well with coating system performance.\textsuperscript{86} A second approach is to record the decay of the electric field of a charged plate of powder. This technique was used extensively by Jill Nichols at the General Motors Technical Center to measure the resistivity of various powders. The technique is superior to the laboratory measurement because it more closely approximates the experience of the powder on a coated surface.

In the Fall of 1994 Jill Nichols collected resistivity data for a number of powders including a PPG Acrylic powder. Using an electric field inducing and measurement device she charged a dish of powder and observed the electric field decay. If the charge decay model were an accurate depiction and if resistivity remained constant, a classic exponential decay should have been observed. As the graph shows, this was not the case.

![Electric Field Decay](image)

A little research showed that the PPG Acrylic powder's behavior was not extraordinary but expected.\textsuperscript{87} When powders are electrostatically charged and sprayed onto a surface they do not possess a fixed resistivity; as the electric field decays, the resistivity increases and the rate of charge decay is reduced.

The resistivity at any small segment of the curve can be approximated by manipulating the charge decay equation as follows:

\[
\rho = \frac{(t_2 - t_1)}{\left( \frac{E_1}{E_2} \right) k \varepsilon_0}
\]

From the equation and a series of experiments the following data was produced at 70% relative humidity:

<table>
<thead>
<tr>
<th>Powder Type</th>
<th>1 min.</th>
<th>5 min.</th>
<th>20 min.</th>
</tr>
</thead>
<tbody>
<tr>
<td>PPG Acrylic</td>
<td>9.29 x 10^{12}</td>
<td>1.72 x 10^{13}</td>
<td>5.61 x 10^{13}</td>
</tr>
<tr>
<td>PPG Polyester</td>
<td>3.95 x 10^{13}</td>
<td>7.28 x 10^{13}</td>
<td>2.99 x 10^{14}</td>
</tr>
<tr>
<td>DuPont Acrylic</td>
<td>4.79 x 10^{14}</td>
<td>6.30 x 10^{14}</td>
<td>2.27 x 10^{15}</td>
</tr>
</tbody>
</table>

The data uniformly shows increasing resistivity with time. It also demonstrates the difference in resistivity among different powder types.

Taking the idea one step further, powder coaters may want to consider measuring the electric field decay of an actual sprayed part, to truly measure "real-life" resistivity. Considering the tremendous but subtle role that resistivity plays in powder coating, an on-line measurement of electric field decay would be an interesting process development tool.

**Strength of Particle Attraction to the Job**
One of the potential drawbacks of lowering resistivity of the powder is that the particle will have insufficient charge to adhere to the surface of the job. If that were the case, the charge would bleed off the particle so quickly that the powder would fall off the job before the job reached the cure ovens. A simple force balance shows that when the force of gravity (mg) is greater than the normal force (μqE) then the particle will fall.

**Forces Relevant to Particle Adhesion**

\[
\text{where: } \mu = \text{coefficient of static friction.}
\]
J. Cross et. al.\textsuperscript{88} put the minimum charge for adhesion at $3 \times 10^{-4}$ C/kg. By substituting a typical value for the electric field of $3 \times 10^5$ V/m, $\mu$ is constant and found to be about 0.1 which is reasonable.

Determining if a particle will fall off a job then depends on the charge on the particle (q) and the electric field (E). The initial charge depends on the particle diameter, the initial particle velocity, the degree of back ionization, the gun voltage, and the gun to part distance among other things. The rate of charge decay depends primarily on the particle resistivity. The electric field depends primarily on the gun voltage, the gun to part distance, and particle resistivity. Particle adhesion is yet another example of the interrelated nature of powder coating parameters. Various source peg the minimum powder resistivity for good adhesion at about $1 \times 10^{10}$ ohm-cm.\textsuperscript{89}, but testing should be done to confirm the assertion.

**Resistivity - an Interim Summary**

The issue of resistivity is difficult to understand but crucial to powder coating performance. A brief review is in order.

- High resistivity is inherent in powder coating. Many sources put powder resistivities in the $10^{13}$ to $10^{17}$ ohm-cm range.
- High resistivity creates back corona.
- The presence of back corona modifies the Pauthenier equation to account for the generation of positive ions.
- The modified Pauthenier equation shows that back corona significantly reduces both the saturation charge and the speed of particle charging.
- The highly resistive powder layer on the job reduces the voltage drop from the corona tip to the job. This reduces charging efficiency by reducing the electric field in the charging zone.
- Back corona creates surface disruptions.
- Charges on powder particles travel on the surface of the particle.
- Coatings such as a thin film of water, can be added to the powder surface to enhance charge mobility and reduce resistivity.
- Industry experts' fear that lower powder resistivities will result in higher charge-to-mass ratios, worsening back corona, and particle adhesion problems.
- Industry experts' fears are misplaced.
- Lower resistivity will enable charge to travel to ground faster. It results in a faster charge decay. It delays the onset of back corona.
- Real-life resistivity is dynamic. In the presence of high electric field the resistivity is lower. As the charge decays and the electric field lessens, the resistivity increases.
- Powder coaters can take advantage of the dynamic resistivity. If powder resistivity could be lowered to the range of $10^{11}$ or $10^{12}$ ohm-cm, or perhaps even


lower, back corona would be less severe but particles would retain enough charge to adhere to the job. As the charge decays, resistivity increases and limits further decay. If the powder retains sufficient charge for 10 to 30 min. it will remain on the surface of the job.

Experimenting with reduced resistivity powders should be a primary focus of any powder coating development work.

**Reducing the Arrival Rate of Ions**

Reducing the arrival rate of ions to the surface of the part will also help reduce back corona and its affiliated nefarious effects. The arrival rate of ions is primarily a function of the applicator design. Currently there are two basic types of commercially available applicators: corona and tribo charging. In addition the principle of induction has been proposed as charging mechanism to be factored into applicator designs. From the previous discussions on charging it seems that the ideal applicator would provide a charge to mass ratio of $1.0 \times 10^{-3}$ (C/kg) to every particle, independent of particle size. The perfect applicator would also eliminate excess free ions.

A corona gun, the industry standard, is not a perfect applicator. According to Hughes, only about 0.5% of all of the corona generated ions actually attach to particles. The remaining 99.5% of the free ions end up accumulating in the bulk of the deposited powder layer, contributing to back corona.\(^{90}\) In addition the preceding discussion shows that the corona gun charging process produces highly variable particle charging, far from a consistent $1.0 \times 10^{-3}$ (C/kg) charge to mass ratio.

Tribo charging guns were invented to compensate for inherent problems with corona guns. Tribo guns rely on the triboelectric effect. When a particle collides with the inner surface of the conveying tube of the gun, a charge is imparted to the particle. The magnitude and sign of the charge is dependent upon both the powder and the tubing material. Since no corona is used to charge the particles, free ions are eliminated. The primary drawback with tribo guns is their erratic and inefficient charging mechanism. Pneumatically conveyed particles must collide with the walls of the tubing to be charged. The collisions are essentially random events that only a fraction of the particles undergo. Another problem is that when particles collide with the walls, some stick. The triboelectric effect only occurs between dissimilar materials; therefore, over time, tribocharging continually degrades \(^{91}\).

John Hughes, Senior Lecturer in Applied Electrostatics from the University of Southampton is a strong advocate of a third charging mechanism for powder coating, induction charging. Induction is simplistic and pictorially illustrated.

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Induction Charging

Negative Electric Potential

- if negative charges are free to move (low resistivity)
- then they will bleed off the particle giving the particle a net positive charge

Positive Electric Potential

- force of gravity (mg)
- balances
- electrostatic force (qE)

When the force of gravity balances the electrostatic force, the particle will levitate and then can be pneumatically conveyed. Since mg = qE and since g and E are constant, then the charge to mass ratio (q/m) will be constant and independent of particle size. No free ions are generated because no corona is generated. This principle has been used as a separation technique for particles of different resistivities.\(^2\)

To my knowledge no commercial powder coating applicators make use of induction charging. For induction charging to be successful particles must first obtain a charge and then possess low resistivity so that charges can migrate relatively freely. While it might be a technical challenge to harness induction charging in a viable commercial device, the potential pay-off in terms of uniform charging and elimination of excess free ions is great.

Summary

Much of the physics and technology related to powder coating has been reviewed. Clearly powder coating is comprised of a number of interrelated and non-linear variables. I will summarize the technology discussion by looking at key variables in the powder coating process and briefly describing how the physics and technology of powder coating explain common powder coating observations.

- **Mass Flow:** Corona guns usually coat from 50 to 250 grams/min of powder. Exceeding 250 grams/min. results in very poor transfer efficiency. Generally, due to the nature of the jet pump and frictional characteristics of the delivery system, the only way to deliver increasing mass flow rates is to increase the volumetric flow rate of air. In short, higher mass flow rates require higher exit velocities. Higher exit velocities translate to poorer charging efficiencies.

- **Particle Diameter:** *Particle diameter is the single most important variable in powder coating.* Diameter is inversely related to migration velocity, but it is a squared term in the saturation charging equation; so the net effect is that larger particles have higher transfer efficiencies. This agrees with common knowledge. Particle diameter is used to approximate particle mass via the assumption of spherical particles. Particle diameter is important in determining the length of time a particle stays in the high electric field/high current density charging zone.

- **Particle Size Distribution:** Even though particle charging and transport are largely dictated by particle size, particle size distributions are quite broad. Literature states that powdered particles should have a Log-Normal distribution. (White, pp 60-63) My analysis of a number of very different particle size distributions from a number of sources indicates that an approximation of a Normal distribution (bounded by zero) is more accurate and useful. As a rough estimate, a typical particle size distribution (mean of 40μm and standard deviation of 15 μm) might look like this:

  **Particle Size Distribution**
  volume basis

![Particle Diameter (μm)]

Current particle size distributions represent known, accepted and substantial variability.
• **Exit Velocity**: When powder systems are set up, a major concern is surging. Jet pump pressures are set to minimize velocity without surging for a given mass flow rate of powder. *Minimum exit velocity is not an independent variable; it is a function of the delivery system and the mass flow rate.* Exit velocity largely determines the time a particle spends in the high electric field charging zone. Smaller particles tend to stay in the zone longer than larger particles and obtain a higher percent of their saturation charge. The time for this charging is on the order of milliseconds. A second, less pronounced effect is the inertial effect on the motion of the particle. High exit velocities will cause large particles (> 50 μm) to travel a considerable distance (inches) before reaching terminal velocity.

• **Gun to Part Distance**: Gun to part distance plays two major roles. As shown in the transfer efficiency equation, shorter gun to part distances result in higher TEs. This make sense; the particle has less distance to travel. For corona gun applicators, gun to part distance also sets the characteristic resistance of the system. Larger distances result in poorer charging. But because they result in poor charging, the onset of back corona is delayed. *If gun to part distance is too small, excessive back corona results in poor TE and surface appearance. If gun to part distance is too large, poor charging and the large travel distance result in poor TE.*

• **Gun KV Settings**: The Gun KV setting is a relative control knob. The actual tip voltage is a function of the applicator design and the coating conditions. Maximizing gun KVs at small gun to part distances can result in excessive back corona. In these cases, reducing gun KVs can actually improve transfer efficiency, an effect which has been anecdotally noted in some GM powder installations. In the absence of back corona, reducing gun KV settings will reduce charging performance and the conveying force of the electric field.

• **Downdraft Velocity**: In today's systems a downdraft is necessary to prevent small fines from floating in the coating booth. The downdraft is set to evacuate from the coating chamber the particles that did not attach to the job. Unfortunately analysis shows that higher downdraft velocities sweep smaller particles away resulting in poorer transfer efficiencies.

• **Sidewraft Velocity**: Any air used to assist particles toward the job will only meet with marginal success. With downdrafts and sidedrafts, the flow pattern is anything but simple. Sidedrafts may be beneficial in the initial stages of a particle's flight but as the air flow approaches the job, it is likely that flow pattern will become complex and sidedrafts will be a detriment.

• **Length of the Job**: Although conceptually simple, in reality this is difficult to model. It assumes a constant conveying electric field, which is unrealistic for an automotive powder coating operation. For a single gun, the influence of the electric field is practically only about 0.5 to 1 meter. In the model, without the force of the electric field and in the absence of a sidedraft, a particle would rapidly come to a halt.
However in practice, multiple oscillating corona guns, continually increase and decrease the electric field that a particle "sees".

- **Line speed**: In the TE model the corona guns are assumed to be fixed. If this is the case then the actual line speed value can be used in the TE equation. In automotive powder coating operations this is roughly 0.15 m/s. The TE equation confirms common industry knowledge that increasing line speeds will result in lower transfer efficiency.

- **First pass transfer efficiency**: For the purposes of illustration, the models and equations presented have been combined to provide a rough indication of transfer efficiency by particle size. The overall first pass TE in this situation is 65%

  **Transfer Efficiency by Particle Size**

  ![Graph of Transfer Efficiency by Particle Size](image)

  Again the prediction confirms years of observation, smaller particle sizes have lower transfer efficiencies. As a result, fines build up in the reclaim system such that reclaim is always richer is smaller particles than the virgin from whence it came.93

- **Humidity**: The industry debates the role of humidity, with no clear consensus. Humidity presents a trade-off. Higher humidity (70% RH) will cause particles to pick up a considerable amount of moisture on the way from the applicator to the job. The water is a conditioning agent and significantly lowers the resistivity of the particles. The charge on the particles can decay faster and delay the onset of back corona. The predicted result is improved transfer efficiencies and thicker film builds. The anecdotal result concurs. When GM's Shreveport, LA powder coating operation loses control of its humidity in the coating booth (and as a Gulf state they only lose it one direction) film builds increase significantly. High humidity has two negative consequences. Wet powder creates handling problems in the reclaim and delivery systems and the moisture on the powder must be driven off in the cure ovens.

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The thoughtful technologist can apply the basic relationships to every day operations. The insight is valuable both for solving day-to-day problems and for creating a vision for the future.

A Technology Roadmap for Powder Coating - Decoupling and Reducing Variability

In 1992 John Hughes wrote an article Powder Coating -- will it ever change?94. In the paper he states that both tribo charging and corona charging methods are "hopelessly inefficient" with charging efficiencies limited to 60%. According to Hughes, the charging efficiency of 60% translates to a deposition efficiency (aka 1st pass transfer efficiency) of 60%. While some might dispute the 60% figure there is a good deal of consensus in the industry that 1st pass transfer efficiency is fundamentally limited and certainly doesn't approach even 90%, a limit at which excess powder could economically be disposed of instead of reclaimed. As Hughes puts it:

"...there seems to be little evidence of this fundamental problem (poor charging efficiency) being addressed in a logical, scientific manner."(p. 96)

I posit that from a technological standpoint, the two fundamental problems with automotive powder coating are:

- The process parameters are highly coupled and non-linear. This makes the process especially difficult to segment and understand.
- The process has excessive variability in many areas, some of which can be reduced.

The following recommendations, based on the insight gained from the work presented, strive to decouple the process and reduce variability.

#1 Reduce the mean particle size to around 20 μm and reduce the variability of the particle size distribution. Currently particle sizes average about 30μm. Imagine for a moment what the powder coating process would be like if every particle was 20μm. The powder coating system could then be designed around a 20μm particle. Charging variability would be greatly reduced. Transfer efficiency would be increased. Fines would be eliminated from the handling system and reclaim system. Surface appearance would improve due to the mean particle size reduction.

At the very least, current particle size distributions should be cycloned and sieved to substantially remove all particle of less than 10 μm. Since smaller particles are nearly inert in the process and end up recirculating in the recycle system, what is the point in using an automotive powder coating facility as a big and expensive sieve?

The most efficient people to perform the particle size distribution shift are the powder suppliers. In the past suppliers have complained that the capital equipment to carry off such a reduction, combined with the reduction in yield would make powder with a tight distribution prohibitively expensive. They are not correct. Does it make sense to provide a product of which 10% or more is unusable and in most cases detrimental to the production process? Of course not. The reason material suppliers are unwilling to

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provide an improved product is that they live in a profitable and uncompetitive world -- nothing is forcing them to.

I have called communism and separation equipment suppliers like Micron Powder Systems. They sell equipment that can deliver tight particle size distributions with a mean of 20μm. According to Micron Powder Systems, for best performance, their equipment should be dedicated to a product line with a minimum efficient scale. Hypothetically, for about $250,000, they could provide equipment producing at least 100,000 lbs. of powder per month. Increased volumes would obviously increase powder manufacturers' profitability by spreading out the fixed cost. Yes, powder manufacturers' yield would be reduced, but if yield is the only concern why not just throw a few pounds of sand into the mix? The sand would have nearly the same coating performance as the powder fines and it would cost the powder manufacturers much less per pound.

I caution the automotive powder coaters to remember the business analysis. Unless the LEPC really pushes this idea or unless competitors like Seibert and EvTech are allowed to sell into the market it is unlikely that the current suppliers will budge. The obstacles are not technical, they are architectural.

#2 Push for applicator re-design. Corona guns are the proven standard. Tribo-charging guns are fundamentally too erratic. In the short term applicator designers should be encouraged to investigate methods for improving corona application devices. Sames has made a large stride in this direction with their introduction of the powder bell. (The bell will be thoroughly explored in the section Understanding Manufacturing). Essentially the bell forces powder to pass more uniformly and more slowly through a much larger high electric field/high current density region. While carved out from the rib of the solvent based bell, it is effective nonetheless, providing a wider film build coverage at higher mass flow rates. With a little imagination, even greater improvements can be made. The technical analysis showed that exit position and exit velocity play a big role in charging uniformity. Corona applicator manufacturers should focus efforts on reducing exit position variability and exit velocity.

The use of any corona device creates tremendous coupling and non-linearity in the powder coating system. The electric field is very non-linear. It serves a charging function and a conveying function. The corona guns links gun-to-job distance with the charging process, the powder resistivity, and the overwhelming impacts of back corona. An operator or engineer, turns up the gun KV to increase film build. In some cases film build increases; in some cases film build decreases (it would decrease with short gun to job distances, low relative humidity, creating excessive back corona). In addition most corona devices contribute excessive, pernicious free ions to the coating process.

Induction charging provides a "clean" answer if it can be commercialized. Induction charging provides a constant charge to mass ratio, which for a uniform particle size of, for example, 20 μm means a single, easily controlled charge to mass ratio. Induction charging eliminates the electric field. Induction charging allows for much closer gun to job distances. By eliminating free ions and providing uniform controllable charge, back
corona can be controlled. Since induction charging requires lower resistivity powders (Hughes), charge decay on the surface of the job will improve and reduce back corona.

*Induction charging reduces charging variability and decouples the powder coating process.* But again the LEPC must factor in the business analysis. ABB Paint Finishing or eNexus may recognize the benefits of induction charging, but they need encouragement to investigate it and LEPC support to turn it into a dominant design.

### #3 Pursue the development and investigation of low resistivity powders.

*Because resistivity does not explicitly show up in the saturation charge equation, the migration velocity equation or Pauthenier's equation, many in the industry do not understand and therefore discount its role in the powder coating process.* It is often confused with the dielectric constant or the electric permittivity of the powder (which does show up in Pauthenier's equations). The previous work shows the intricate and detrimental role of high resistivity powders.

Essentially the high resistance of the powder will not allow charges on the particle to bleed to ground quickly enough to prevent back corona. Back corona severely reduces charging performance in the conveying force of the electric field. As we saw in the migration velocity sensitivity analysis, both percent of saturation charge and magnitude of the electric field play major roles. *High resistivity leads to back corona which severely reduces migration velocity and in turn reduces transfer efficiency.*

Since there appears to be some skepticism about the role of resistivity on powder coating, the LEPC or their designees (e.g. ABB Paint Finishing, materials suppliers) should conduct carefully controlled experiments to convince themselves of the role of resistivity. One possible reason the industry has not embraced resistivity as an important consideration, in spite of decades of research and consensus in the ESP, is that previous flawed experimentation has led researchers to conclude that it is not a significant variable. Some pitfalls to avoid while performing future testing are:

- Watch out for confounding factors such as particle size distribution. All powders tested should have the same particle size distribution. If they don't initially, sieve them until they do.
- Particles should have roughly the same surface area. Do not compare sharp, jagged edged particles (higher surface area) with particles that have rounded surfaces. Use microscopy to subjectively evaluate the surface area.
- Use "real-life" resistivity as a measure not "laboratory resistivity". Perform replicates. Characterize particle resistivity at different levels of relative humidity. Tests, such as those performed by Jill Nichols at the GM Tech. Center, are straightforward and relatively rapid tests. Ensure that powders tested for resistivity differences have statistically different resistivities. Perform T-tests.
- Run carefully controlled statistically designed experiments. Important independent variables should include resistivity, humidity, gun to job distance, exit velocity, gun KV and mass flow. Important response variables include film build, 1st pass transfer efficiency, and appearance.
Set the experiment design space so that it is similar to production conditions. Avoid very low film builds and very high film builds that are approaching the self-limiting thickness; non-linearity will become a major issue.

Once the industry has convinced itself of the value of lower resistivity powders, powder manufacturers should focus on developing low resistivity powders. Recent work at the General Motors Technical Center shows that different kinds of powder have significantly different resistivities (PPG acrylic @ about $1 \times 10^{13}$ ohm-cm, DuPont acrylic @ about $5 \times 10^{14}$ ohm-cm). Work in the ESP indicates that conditioning is a useful technique for lowering resistivity. It should be straightforward for materials suppliers to coat particles with a conditioning substance after the particles have been sieved.

**#3a Investigate coating in a high humidity environment.** An adjunct to lowering the resistivity of powders is to coat in a high humidity environment. Higher humidity coating environments will cause a thin film of water to coat on the particles as they enter the coating chamber. The thin film should serve as a conditioning agent and allow charges to more readily escape from the particles once the particles land on the job.

An added benefit from high humidity coating is dirt/dust reduction. "It has been recognized that painting operations appear to suffer fewer rejects due to particle contamination when the relative humidity of the air is high"\(^95\).

High humidity coating is not without its problems. The added particle moisture must be-driven off in the cure ovens. This could lead to longer cure times and/or appearance problems. Also the fine particles with high moisture content could wreak havoc in the reclaim system and potentially even the virgin delivery system as high moisture content powder particles increase system wear and impact fusion.

Despite potential problems, the opportunity should not be discounted. A few rapidly conducted experiments could determine what the potential opportunity of high humidity coating could have in terms of film build, first pass transfer efficiency and appearance.

**#4 Decouple the powder coating process from the line; optimize coating time. Bring cars to a stop. Eliminate the reclaim systems.** Historical forces caused powder coating to be modularly adapted to the automotive painting process. Coating time is therefore coupled to line speed. The first pass transfer efficiency equation shows how.

\[
TE = 1 - \frac{d}{l} \frac{v}{w}
\]

where:
- \(d\) is the gun to job distance,
- \(l\) is the effective length of the job,
- \(w\) is the migration velocity, and
- \(v\) is the line speed

and coating time is ratio of the effective length of the job to the line speed. If a line speed of 0.15 m/s (about 30 ft./min) has a transfer efficiency of 65%, reducing the line speed in half to 15 ft/min would theoretically increase transfer efficiency to 83%.

The above calculation assumes migration velocity remains ostensibly constant, which in the presence of back corona, may not be a great assumption. Once again the interrelated nature of the powder coating process is highlighted, and for the equation to hold, the system would have to be optimized. Nonetheless the opportunity is large and clear.

The auto industry has accommodated the physics of the paint curing process by providing two very expensive cure ovens for each paint operation. Why not provide two or three powder coating booths to dramatically increase powder coating efficiency and potentially eliminate reclaim systems? Picture a system that decouples the coating time from the line speed.
- A job is whisked into one, two, or three coating booths.
- The job comes to a stop.
- An optimized number of applicators sprays powder at the job in a precise pattern.
- Transfer efficiency is dramatically increased to the 85% to 95% range. This assumes that the particle size distribution is far more uniform than it is today.
- The job is re-integrated into the flow of work and enters one of the two cure ovens.
A simple set of experiments in the GM Technical Center or ABB pilot facilities would demonstrate the viability of decoupling the powder coating time from the self-imposed constraint of production line speeds.

**#5 Eliminate downdraft, purge after coating is complete.** In current systems a downdraft of approximately 60 ft/min is necessary to purge fines that would otherwise be suspended in the air. In most operations the downdraft operates while the applicators are blowing powder at the job. The previous sensitivity analysis showed downdrafts are detrimental to transfer efficiency.

I advocate coating the jobs first and purging the booth after the necessary coating time has elapsed. In that way the particles' path to the job is not impeded by an unnecessary downdraft. The purging process will be decoupled from the coating process. Of course the intrinsic safety of the decoupled system would be paramount, but if safety constraints were not binding then enhanced transfer efficiency could result.

Again verification of the premise should pose little problem in the GM Tech Center or other testing facilities. If safety considerations permit, simply turn off the downdraft while coating and compare result with panels coated normally. The transfer efficiency for smaller particle sizes (and therefore the entire particle size distribution) on vertical surfaces should be most affected.

**#6 Consider implementing electric field generation for conveyance purposes only.** Remember that the electric field serves two purposes in the powder coating process; it is a primary factor in particle charging, but it is also important in particle conveyance. In current corona systems, the corona gun determines the electric field. *The resulting*
electric field seen by the particle is anything but uniform; the numerical solutions to the point-to-plane geometry presented in previous sections, combined with multiple oscillating applicators, create a varying and non-linear force for particle conveyance.

Envision a system where a pre-charged particle enters a coating chamber with a minimum of aerodynamic force and is exposed to a uniform electric field whose sole purpose is to convey the particle to the job. A series of large, flat high voltage plates would provide the necessary field. Corona, which depends on a surface with a high radius of curvature, could be reduced or eliminated through careful design.

There may be a myriad of practical reasons why such a system would cause problems but the potential for improved migration velocity uniformity and possible reduction in coating time makes it an option worth investigating.

#7 Drastically reduce gun to job distance. With corona gun systems it is impractical to reduce the gun to job distance much below 5 inches. At small distances the system resistance is comparatively low and at typical gun KVs, current density and electric field are quite high. With a low resistivity powder, high current densities/electric fields are desirous, but with high resistivity powders, the high current densities/electric fields result in extremely poor coating performance due to rapid, excessive back ionization. In terms of the transfer efficiency equation, reducing gun to job distance should improve the transfer efficiency, but in actuality it has such a deleterious effect on particle charging that the reduction in migration velocity more than offsets the reduction in gun to job distance and the net effect is a reduction in transfer efficiency. Reducing gun to job distance to less than 5 or 6 inches, with current corona charging systems, would degrade coating performance due to back ionization.

Another problem with reduced gun to job distances is a lack of pattern width. The detailed relationship between pattern width and gun to job distance will be thoroughly explored in the subsequent section on manufacturing. In practical powder coating terms, a lack of pattern width translates to poorer film build uniformity for any given number of applicators.

With the current dominant powder coating design it seems silly to reduce gun to job distance; however suspend disbelief for a moment and think past the dominant design. What if a non-corona based system were used and pre-charged powder were to be ejected from a re-designed applicator whose purpose was to provide a wide film build pattern? If this were the case then according to the transfer efficiency equation, reducing gun to job distance should significantly improve transfer efficiency. With a non-corona system, the gun to job distance is no longer linked to the charging process and the migration velocity is no longer dependent upon it. Therefore the closer the gun is to the job, the higher the transfer efficiency. For instance, in a non-corona system, if a gun to job distance of 8 inches results in transfer efficiency of 65% then a gun to job distance of 3 inches would theoretically improve transfer efficiency to 87%.
The idea of reduced gun to job distances is not as far-fetched as it first appears. Tribocharging system transfer efficiencies are improved by reducing gun to job distance. I invoke tribocharging as an example of the only commercially available non-corona system. Use of tribocharging illustrates the potential of reducing gun to job distance in the future. Without dwelling on the point I want to make clear that I do not advocate the use of tribocharging except in instances where Faraday Cage problems are impossible to handle by other means. Tribocharging's fatal flaw is its inefficient and erratic charging process which fundamentally limits its capability. Regardless of the shortcomings of tribocharging, an ideal and fully optimized powder coating system of the future will likely have much shorter gun to job distances than current systems.

#8 Decouple powder delivery process. Replace jet pump delivery with auger delivery. Install mass flow sensors. Where possible use short, straight runs of hose.
My assignment when joining Chrysler was to develop a mass flow sensor for pneumatically conveyed powders. The results from my work are contained in a LEPC confidential report (cleverly titled Mass Flow Measurement of Pneumatically Conveyed Particles. January 24, 1995). The work showed that the current delivery system is highly coupled and that the delivery system induces a great deal of short term and long term variability. Since mass flow and exit velocity play a role in the coating process, decoupling and reducing variability appear to be in order.

The problems inherent in the system can be best conceptualized by describing events as a delivery system is "tuned in" and then run.
• Fluidization air pressure in the delivery hopper is set.
• Tubing length and configuration is set.
• Jet pump transport air is set. The mass flow rate of powder is measured and the flow pattern is visually inspected for surging.
• Assuming the mass flow rate was lower than the setpoint, the jet pump transport air is then increased until the desired mass flow rate is achieved.
• Unfortunately increasing the mass flow rate seems to cause a great deal of surging.
• Atomizing air on the jet pump is increased to eliminate surging.
• But increasing the atomizing air puts backpressure on the jet pump and reduces the mass of powder delivered by the jet pump, so the transport air has to be increased.
• After a few iterations surging is eliminated and the mass flow rate is at setpoint.
This kind of delivery system is extremely sensitive to changes in system pressure and the inherent frictional characteristics, changes in either will induce mass flow variability. Further, since no online sensor has been commercialized for automotive powder coating operations, the only way to infer the mass flow rate is to measure the final film build. Of course the final film build is dependent upon MANY other strong factors; so at best, film build is only a gross indicator of mass flow.

In practical terms the potential and largely unknown problems are many.
• When multiple guns fire, the head pressure on the powder inlet of each of the jet pumps is less than it was for each single gun as it was fired. Since calibrations are only done one gun at a time, operations people have no way of knowing how much
lower the flow rate is. One study involving experimental mass flow sensors, showed the production flow rate to be only 55% of the calibrated flow rate.

- Increasing the frictional characteristics of the delivery system increases the likelihood of surging for any given volumetric flow rate of air. It is no wonder then that longer and tortuous tubing runs are more prone to surging. Since they are prone to surging, they also require greater atomizing air pressures. Greater atomizing air pressures generally result in greater volumetric flow rates and higher exit velocities for a given mass flow rate.

- As impact fusion and wear take place, the frictional characteristics of the system increase and the efficiency of the jet pump decreases. The net result is a noticeable decrease in mass flow rate over time periods as short as a week.

- The jet pump is an inherently coupled device. Particle velocity and mass flow are linked. Simplistically, to increase mass flow requires increasing the transport air pressure. In the flow regime typical for powder coating, increasing transport air pressure also increases the exit particle velocity.

_I strongly advocate that the LEPC consider decoupling particle velocity from mass flow by making use of a lab tested auger delivery system. I further support investment in the commercialization of a microwave Doppler online mass flow sensor. This will solve many of the industry's problems associated with current systems._

- The auger sets the delivery rate. Unless there is significant settling or leakage then the calibrated delivery rate will be the same as the production delivery rate. The auger is easy to calibrate and is independent of fluidization air pressure.

- The transport air pressure is independently set based on flow characteristics. As the tube lengths become shorter and straighter, less transport air will be required to maintain the same mass flow rates. Less transport air results in lower exit velocities which translates to superior charging.

- The microwave Doppler online mass flow sensor is a window into the process. It shows the flow pattern, which is helpful for system tuning, and will provide an indication of impact fusion and wear problems. Early indication of problems will lead to solid preventative maintenance practices.

Despite the obvious and not so obvious problems with the current dominant design for powder delivery systems, the industry stubbornly clings to modular innovations. The industry appears to eschew the readily commercializable and intrinsically superior auger delivery systems and microwave Doppler mass flow measurement in favor of jet pump delivery and differential pressure measurement systems. If mass flow measurement and delivery is truly important, I would urge the LEPC to look past the sales hype and reconsider their investments in jet pump delivery systems and differential pressure measurement systems; the current systems are fundamentally flawed.

**#9 Install load cell before and after coating process to track TE online.**

Understanding of the powder coating process would benefit greatly from a few online process measurements. At least in a development setting like the Prove-Out facility or at the GM Tech Center, it would be very useful to know first pass transfer efficiency as the part is being coated. Calculation of transfer efficiency requires knowing the mass of
powder that attaches to the job and dividing that value by the mass of powder that is sprayed.

In the system of the future a PC could be used to numerically integrate auger delivery flow rates for each job. The problem then remains determining the mass of powder that has attached to the job. In a stationary system for instance, the job would rest on a load cell. As power was sprayed and attached to the job, the engineer or production worker could view the increase in mass of the job over the coating time. Subtracting the final job mass from the initial job mass would provide the mass of powder that stuck to the job.

\[
\text{Online 1st Pass TE} = \frac{\text{Final mass of job} - \text{initial mass of job}}{\text{Sum of all auger deliveries}}
\]

Online TE would enable development engineers and production personnel rapid response capability and better intuitive understanding of the powder coating process. Without online measurement, an engineer can typically wait anywhere from 2 days to 2 weeks to find out how TE responded to changes in testing conditions.

**#10 Measure workpiece to ground current.** As previously mentioned, the workpiece to ground current curve is extremely useful for understanding the impact of back corona on the coating process. Time to back corona can be used as a response variable in statistical experimentation and would be very useful for process optimization. Other researchers have shown how the workpiece to ground current curve was related to gun KV, gun to job distance, charge to mass ratio and transfer efficiency. (see discussion on p. 76)

![Diagram: Measuring the Current from the Workpiece to Ground](image)

Measuring the Current from the Workpiece to Ground

Probably the biggest benefit from measuring workpiece to ground current would be elevating the general industry awareness of back corona, resistivity and their corrupting

100
effects. The curve provides pictorial, online evidence that can quickly link back corona problems with obvious coating problems like poor TE and low film builds.

**#11 Measure electric field decay of painted jobs.** An electric field indicator set a fixed distance from a job and linked to a PC could provide online resistivity measurements and could potentially be used as a non-contacting film build indicator. The online measurement would provide the best value for "real-life" resistivity. It would serve as a process measure.

Assuming that the time from the end of coating, until the job passes under the sensor is fixed, then the initial electric field under a set of production coating conditions, will be a function of the thickness of powder applied. It might be possible for an array of electric field sensors or scanning electric field sensor to provide online non-contacting thickness measurement.

**#12 Continue to provide industry leadership.** The earlier business analysis highlighted the many roadblocks to significant change. The one, potentially cogent force, in favor of step change improvement is leadership. The LEPC should step-up its sponsorship and encouragement of research in the areas listed above. The LEPC should divert resources that are now used for "fire-fighting" and invest in fundamental process understanding. With a strong theoretical understanding experimenters can execute better, more insightful experiments and end their reliance on the sometimes questionable research and development of the multitude of suppliers. Superior research will reduce technological and strategic uncertainty and lead to a superior powder coating process.

Even with a good first order understanding of the physics of powder coating, extensive experimentation and optimization will be necessary to suck the value out of the non-linear and interrelated process. Many powerful experimentation and optimization tools exist, some of which will be described in the section on manufacturing. To make the most out the experimentation, the LEPC should hire a full-time process-oriented statistician and spend a good deal of time training her in the physics and business of powder coating.

With the $20MM Prove-Out facility, the LEPC faces a choice. Without an increased level of leadership, the incremental forces will hold sway and the Prove-Out facility will become an evolutionary facility. Progress will come in small incremental steps; low risk yields low return. The LEPC could choose a riskier but potentially more profitable approach. Stray from the dominant design, understand the process, and plot a more aggressive path forward. The Prove-Out facility embodies a tremendous opportunity to cash in on decades worth of research and development in the electrostatic precipitation industry. Opportunities like this are rare. Create competitive advantage.
Understanding Manufacturing

It looks good on paper, but does it work?

In the context of my thesis, I am focusing on one aspect of "Manufacturing", the ability to translate equations, theories and ideas into viable processes and products. Ten years of manufacturing experience in conjunction with my tenure at M.I.T., have exposed me to a vast number of models and techniques that help to frame and resolve manufacturing related problems. The tools taken together are an impressive collection of some of the most recognized buzzwords of our time. The following are a sampling:

- Just-In-Time (JIT)
- Preventative Maintenance (PM)
- Design for Manufacturing (DFM)
- House of Quality
- Total Quality Management (TQM)
- Statistical Process Control (SPC)
- Systems Thinking
- Statistical Design of Experiments (DOE)
- Linear and Non-linear Optimization

Detailed review of just one of the ideas, like JIT, is fodder for multiple books. My intent in this section is to focus on a specific example, and use the example to demonstrate the power of two tools: Design of Experiments and Non-linear Optimization.

The Powder Bell

In September of 1994 I was asked to evaluate the functionality of a new corona applicator known as a powder bell. Sames had recently introduced the electrostatic powder bell touting a number of features:

- "Very high transfer efficiencies of approx. 85%.")
- "Powder flow of > 500 grams per minute"
- "Remarkable thickness consistency of +/- 10%" 96

Like many new technologies a certain amount of folklore was associated with the powder bell. The unit was rumored to provide superior appearance because of its "softer pattern", reduce Faraday Cage effect, and provide superior TE when compared to a corona gun, "first pass transfer efficiency of a powder bell ranges from equal up to 20% better than that obtained with a powder gun operating under exactly the same conditions."97. The LEPC wanted someone to separate the fact from the fiction.

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96 Taken from Sames Sales Brochure for the SRV 037 Electrostatic Powder Bell, 1994.
The powder bell is a prime example of a modular innovation. Sames intended, and industry users wanted, an improved applicator, but it had to fit within the current architecture; the powder bell had to be a "drop-in". As a modular innovation, vast chunks of technological and strategic uncertainty associated with the bell would be eliminated. Still, some degree of uncertainty remained about the powder bell.

Very simply, decision makers wanted to use bells if they worked, but if bells didn't work, well then, they wouldn't be used. My task was to translate the vague desires of the decision makers into a concrete action plan. There are many approaches that could be and were considered.

- install a bell in a location and "see if it works"
- put the onus on suppliers, give them a small contract to install a powder bell system and hold their feet to the fire until the system performs as desired.
- perform pilot testing of the bell until confidence is high enough to install a production system.

What's the right approach?

When faced with a new process or product, I advocate the use of statistically designed experiments in conjunction with non-linear optimization to quickly gather data and generate community consensus. The steps are as follows:

- Identify key process variable
- Identify key response variables
- Perform quick statistically designed screening experiments to winnow down the variables under consideration and to roughly define the window of operation.
- Carefully design and execute statistically design experiments.
- Generate mathematical models.
• Integrate the models into a non-linear optimization package and perform sensitivity analysis.
• Based on the optimization results and sensitivity analysis, propose and test one or more options.

Whether this is done in pilot or production facilities is largely dependent upon the decision makers involved. In the case of powder bells, testing was to be performed in pilot facilities. I will show how this technique was successfully used to evaluate the powder bell.

Because testing was to be performed under laboratory conditions at the GM Technical Center, questions were raised as to the applicability of results in a production situation. To partially address this concern we decided to run nearly identical tests with both single bells and single guns. Since guns were a known commodity, we hoped that decision makers could infer the bell's relative performance by comparing with gun performance under the same conditions. From our results it appears that our approach was reasonable.

The Process Parameters
Before embarking on any testing, the bell testing team queried the technical community to come up with a list of potential key variables. In order to map out a process window we not only had to list the variables but we also had to suggest potential ranges for the variables. We also had to decide upon the variables' amenability for testing and the best way to deal with each of the variables in the GM Technical Center pilot facilities.

A list of the parameters follows along with a brief description of how we dealt with each of them.

1. Mass Flow Rate is generally recognized as one of the most critical variables, but with a high degree of interaction with other variables. For bell testing the range was set to be 200 gram/min to 440 gram/min in accordance with Sames recommendations. The gun ranges were set to be 100 gram/min to 220 gram/min based on previous experience.
2. Applicator KV, as pointed out previously, is a crucial but largely misunderstood variable. Rather arbitrarily, bell ranges were set from 50 KV to 80 KV(max. output) and gun ranges were set from 60 KV to 100 KV(max. output). These were nominal values. The true electric field generated by the nominal settings was not measured.
3. Number of Passes was included as a variable to determine if two passes at half the flow rate would provide better film build than one pass at the full flow rate. In practice it would only be possible to provide one or two passes but there was some curiosity regarding higher numbers of passes.
4. Gun to Job Distance was another critical variable. For both bell and guns the range was to be from 6 inches to 12 inches.
5. Bell RPM was a question mark variable. Some sources indicated that it would be an important variable and other sources said it was of little consequence. It was decided to look at Bell RPM in a separate screening experiment. The range set for the screening experiment was 4000 to 8000 RPM.
6. **Humidity** could not be controlled in the pilot facility. It was to be recorded and taken as a noise variable.

7. **Line Speed** was set at 24 feet per min.

8. **Particle Exit Velocity** is a function of the delivery system. It was taken as a noise variable.

9. **Powder Type** used in all experimentation was DuPont Acrylic.

10. **Orientation** - To simulate bell usage for hoods and roofs, we focused on a horizontal orientation.

11. **Downdraft velocity** was taken as a noise variable. The pilot facility offers little control over air flows in either magnitude or direction. "Squirrelly" air flows were often observed with a velocimeter. Nominally downdrafts were 60 ft/min.

12. **Shaping air** was not used. Thinking that wide patterns correspond to uniform film build coverage, we wished to learn how to obtain the widest pattern possible.

The most important aspect of the exercise was that the community achieved consensus and the variables listed were reasonable.

**The Response Variables**
The LEPC is primarily concerned with three loosely defined variables with regard to powder coating.

1. **Film Build** - The community was attentive to many aspects of film build including the maximum value, the width of the film build profile and the overall shape of the profile.

2. **Appearance** - To investigate claims that the bell offered superior appearance to gun coating, we wanted to pay special attention to appearance. While subjective visual evaluation is the final measure of appearance, we also wanted to look at specific attributes such as orange peel, distinctness of image (DOI), and gloss.

3. **Transfer Efficiency** - Again to verify claims of superior TE we wanted to look closely at this variable. We were primarily concerned with first pass transfer efficiency.

The exact methods used for describing the response variables will be explained shortly.

**The Screening Experiments**
In late September '94, Jill Nichols, Greg New (Sames Technician) and I ran a number of screening experiments on the small scale Spraymation machine. The goal of the experiments was to stress the bell coating process and do it quickly. Along the way we tried to ferret out the relative importance of process parameters. It was important to experiment with larger than normal ranges for the process variables to ensure the consensus ranges were appropriate. Information from our testing allowed us to block out a design space large enough to make the noise of experimentation small. In addition we noted the interrelated and non-linear nature of the system.

Within three weeks, we gathered the necessary information to properly design an experiment in the large scale pilot facility known as the Binks booth. Because of the interrelated and non-linear nature of the system I chose to run two $2^4$ central composite designed experiments with center point replicates-- one for a single horizontal bell and one for a single horizontal gun. Testing was to be carried out on flat panels. The four
Experimental variables were mass flow rate, applicator KV, applicator to job distance, and number of passes. RPMs were found to have no statistically significant effect upon the response variables. For future experimentation the RPMs were set at 7000 RPM.

**Experimental Results**

On November 3, 1994 a small team executed a designed experiment for a single bell spraying a horizontal surface; on November 15, 1994 a companion experiment for a single gun was completed. After panels were sprayed, they were cured in the same oven for 20 to 30 min. After curing they were thoroughly evaluated. The data from the experiment is included in the appendix.

**Theory at Work: Tip #6  Grounding vs. Non-grounding** - During the test we weren't sure if we were getting a "good ground" and so at one point, out of curiosity we coated a particular part (bb and cc in the Sames Bell test) with and without the grounding strap attached. With grounding, the part had a TE of 67% and a max film build of 2.6 mils. Without grounding the TE fell to 38% and max. film build fell to 1.4 mils. **The lesson to be learned is:** make sure the part is grounded.

The results from the testing were enlightening.

**Characterizing Film Build**

To do meaningful quantitative analysis requires clear quantitative descriptions of the data. The biggest question going into the experiment revolved around quantifying film build. Since film build profiles somewhat resemble a normal curve I chose to use normal curves to describe the data. The approach worked quite well.

![Two Normal Curves Fit the Data Well](image-url)

**THE MODEL:**

\[
\text{Thickness} = k \frac{1}{\sqrt{2\pi} \sigma} \exp \left[ -\frac{(x - \mu)^2}{2\sigma^2} \right] + k_1 \frac{1}{\sqrt{2\pi} \sigma_1} \exp \left[ -\frac{(x - \mu_1)^2}{2\sigma_1^2} \right]
\]

- \( k \) = Scaling Factor for 1st distribution (26.0)
- \( \sigma \) = Standard Deviation of 1st distribution (4.12)
- \( \mu \) = Mean of 1st distribution (11.00)
- \( k_1 \) = Scaling Factor of 2nd distribution (36.1)
- \( \sigma_1 \) = Standard Deviation of 2nd distribution (5.94)
- \( \mu_1 \) = Mean of 2nd distribution (21.85)
The film build profile above was taken from screening experiment data and is illustrative of most of the profiles we obtained. To get a profile we measured film build at one inch intervals across all of the 36 inch test panels.

With the profile loaded into a Microsoft EXCEL spreadsheet, a non-linear curve fitting technique was used to fit the data to either one normal curve or two superimposed normal curves, as is the case above. The technique made use of EXCEL's Solver functionality. Briefly the spreadsheet technique works as follows:

- Cells A1-A35 hold the profile position (1-35 inches)
- Cells B1-B35 hold the corresponding film build height for each position (in mils)
- Cells C1-C35 hold the model's calculated thickness based on Column A's values for x
- Cells D1-D35 hold the error term for each position
  
  \[
  \text{Squared error} = (\text{actual thickness} - \text{predicted thickness})^2
  \]

- Initial values are input for \(k\), \(k_1\), \(\mu\), \(\mu_1\), \(\sigma\), and \(\sigma_1\).
- Column D is summed to provide the sum of the squared errors.
- Solver is invoked to minimize the sum of the squared errors by changing the variables \(k, k_1, \mu, \mu_1, \sigma\), and \(\sigma_1\).
- Appropriate constraints are added to control the calculation.
- Visually comparing the actual profile to the calculated profile provides confidence in the fit.

The use of two normal curves provided excellent agreement between model results and actual results but we found that fitting the data to one normal curve was sufficient for our analysis.

Using one normal curve also simplified analysis. The scaling factor \((k)\) of the above equations is actually the area under the film build profile, a number that can also be obtained by numerically integrating the curve. The community defined the width of the film build profile to encompass all of the profile that was at least 50% of the maximum film build. Based on the community's definition, inspection of the unit normal tables shows that the width of the film build profile turns out to be \(2.36 \times \text{the standard deviation of the curve}\). The smoothed maximum (maximum film build) of the curve occurs when \(x\) equals \(\mu\) and the exponential term goes to 1. Therefore, with one simple model the three critical values useful for characterizing film build were quantified:

- area under the curve
- spray pattern width
- maximum film build.

The data could then be statistically analyzed.

**Characterizing Transfer Efficiency**

Transfer Efficiency is often loosely bandied about. In this experiment it is a calculated value that is intended to represent 1st pass transfer efficiency excluding excess powder sprayed before and after the panel is under the applicator. It was expected to serve as a relative measure of 1st pass transfer efficiency.
Transfer Efficiency = \( \frac{\text{Amount on Panel}}{\text{Area (density)(line speed)}} \times \frac{\text{Conversion factor}}{} \) 

Amount Sprayed \( \frac{\text{Flow rate (# of passes)}}{} \) 

- Area is the area under the curve 
- Density is the powder density assumed to be 1.1 g/cc 
- Conversion factor was simply a unit conversion factor.

**Three dimensional film build sketch**

![Three dimensional film build sketch](image)

TE is the mass of powder represented by the shaded area divided by the amount applied in a certain time.

The contrivance served its purpose well. Since density, line speed, flow rate, and # of passes are all independent variables, the equation shows that first pass transfer efficiency is solely a dependent on film build as expressed by the area of the film build profile.

Under test conditions the above equation is very useful for statistical analysis and comparison purposes.

**Characterizing Appearance**

This was one of the most interesting findings of the experiment. Some advocates of bells claimed that bells would provide superior appearance to guns. In addition there seemed to be some mysticism with regard to appearance. *Keeping in mind that panels were all sprayed with DuPont Acrylic and were subjected to very similar cure conditions, experimental data showed that appearance is strictly a function of film build. Higher film builds translate to improved appearance; whether the powder is applied with a gun or bell is immaterial.*

Many instruments measure aspects of appearance. In the final analysis though, the standard against which all of the instruments are measured, is subjective evaluation. To quantify appearance we gathered subjective ratings and objective measurements of Orange Peel, Gloss, and DOI. The first step in sorting out the information was to determine if an objective measure or combination of objective measures could be used for the 'true' subjective evaluation. Luckily DOI had an amazingly good relationship to the subjective measure.
Only those panels found reasonable were rank ordered (1 being the best); the rest were assigned an arbitrary value of 20. DOI's relationship to the subjective evaluation is uncanny. Whoever designed the DOI device did well.

With a good objective measurement in hand I wanted to explore the relationship to film build for both the bell and the gun.
To use the New England vernacular, these curves are "wicked non-linear". In the region of interest, 80 to 100 DOI, both curves are reasonably described by the relationship.

\[ \text{DOI} = 100 - \exp\left(\frac{3.4}{(\text{max. film build})^{0.61}}\right) \]

**Film Build IS Appearance**

- Most appearance related specs are written to provide a minimum of 2 mils.
- Max film build in mils:
  - 1.0
  - 1.5
  - 2.0
  - 2.5
  - 3.0
  - 3.5
  - 4.0

**DOI**
- 70
- 80
- 90
- 100

To reiterate, DOI is the same function of film build for both guns and bells; DOI correlates well with visual surface ratings.

**Theory at Work: Tip #7**: Another tidbit to be gleaned from the data is that the sharpest non-linearity occurs around a film build of 2.0 mils. Coincidentally, many appearance related film build specifications are written to protect against a lower limit of around 2.0 mils. Through trial and error, the industry has arrived at a nearly optimum specification; increasing the film build beyond 2.5 mils or so buys very little in the way of improved appearance, but decreasing film build below 2.0 mils results in a significant degradation in appearance.

The end result of the response variable characterization effort was the realization that transfer efficiency and appearance were really only functions of film build. Conceptually we could then focus on film build. Describing film build with a normal curve was a simple and valuable technique.

**The Equations**
The purpose of the experimentation was to generate equations, models that demonstrated the relationships between the independent variables and response variables. Since transfer efficiency and appearance are functions of film build, it was sufficient to provide mathematical descriptions for area under the film build profile and profile width.

In statistical analysis, if enough variables are fit to a model, eventually the R-Squared will become 1, the system will be determinant; however, it is likely that a number of the variables will be statistically insignificant. Statistical analysis is actually a creative process, melding theoretical insight with hard data. In many cases, the statistically
superior model is not as robust as the theoretically superior model. In my analysis I
focused on developing models that were simple and made sense. The equations are:

- Bell area = \(-31.225 + 4.207 \times (KV/Distance) + 0.069 \times (mass \ flow \times no. \ of \ passes)\)
  \(R\text{-squared} \ of \ 0.87\)

- Gun area = \(-4.316 + 0.669 \times (KV/Distance) + 0.12 \times (mass \ flow \times no. \ of \ passes)\)
  \(R\text{-squared} \ of \ 0.93\)

- Gun width = \(3.256 + 0.562 \times Distance + 0.013 \times (mass \ flow \times no. \ of \ passes) + 0.012 \times (KV \times Distance) - 0.242 \times (distance \times no. \ of \ passes) - 0.004 \times (distance \times mass \ flow)\)
  \(R\text{-squared} \ of \ 0.93\)

- Bell width = \(-0.578 + 2.689 \times (distance) + 0.015 \times (mass \ flow \times no. \ of \ passes) - 0.008 \times (KV \times distance) - 0.56 \times (distance \times no. \ of \ passes)\)
  \(R\text{-squared} \ of \ 0.82\)

These equations are very valuable. They link the process to the response. By taking
partial derivatives they can be used to look at the sensitivity of response variables to
process parameter. They show interactions. They show the relative magnitude and
direction of impact that each of the terms has upon the response variables. Above all,
they make sense.

It makes sense that if the KV is increased that the overall amount of powder applied
should go up (area). Further it makes sense that the term KV/Distance is significant.
From Ohm’s Law \(V/R = I\). Previous theoretical discussion explained that the gun to job
distance is essentially a linear resistance term and KV of course is voltage, so the term
represents current. Finally if more powder is thrown at the job as indicated by the mass
flow \times no. of passes term, then more will be linearly applied to the job. The HUGE
caveat to all of this is that these relationships are only valid within the range of
experimentation. Extrapolation is dangerous.

Graphically the relationship between predicted and actual width and area values is
shown:
For the Bell Area note the non-linearity of the fit at the extreme value of 100. Other more complicated but sensible equations were generated that better fit the data but the simple equations sufficed for our analysis. It makes sense that this should be non-linear at the extremes. As the self-limiting thickness is approached, it doesn’t matter how much more powder is thrown at the job or how high the current is.

Actual width values were rounded to the nearest inch. Regression output for the four relationships is included in the appendix.

**Optimization: Guns vs. Bells - Head to Head**

With the equations in hand, it was possible to perform sensitivity analysis and optimization analysis. One of the first questions to answer was: How do bells compare with guns? Two types of optimizations were performed. The first optimization was to maximize TE at a given film build using only one applicator.

EXCEL Solver and the previously described equations were used to determine how the bell and the gun would perform.

<table>
<thead>
<tr>
<th></th>
<th>Gun Optimum</th>
<th>Bell Optimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance (inches)</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>No. of Passes</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>kV</td>
<td>100</td>
<td>80</td>
</tr>
<tr>
<td>Mass Flow (gm/min)</td>
<td>210</td>
<td>249.1</td>
</tr>
<tr>
<td>Area under Film Build curve</td>
<td>32.1</td>
<td>38.5</td>
</tr>
<tr>
<td>Width of Profile</td>
<td>10.0</td>
<td>12.1</td>
</tr>
<tr>
<td>Max. Film Build</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>1st pass TE</td>
<td>79%</td>
<td>80.2%</td>
</tr>
<tr>
<td>DOI</td>
<td>94.3</td>
<td>94.3</td>
</tr>
</tbody>
</table>

Both optimizations called for the minimum distance, one pass, and the maximum KV for that applicator. Future testing may want to look at even closer gun to job distance, if the
goal is to maximize TE at a constant film build. In the optimization process mass flow was adjusted to achieve the max. film build constraint of 3 mils. Some observations are:

- Bells have wider profiles for a given max. film build.
- Two passes do not provide superior TE
- Bells do not offer a significant TE advantage over guns when max. film build is held constant.

Based on these results, bell advocates' claims of superior TE appear to be unfounded. One Sames assertion, "first pass transfer efficiency of a powder bell ranges from equal up to 20% better than that obtained with a powder gun operating under exactly the same conditions," is true but misleading. It compares guns at high flow rates like 300 grams/min with bells at high flow rates. While it is true that TE for bells at these high flow rates is significantly better than TE for guns, it would be unreasonable to install a single gun to deliver 300 grams/min. The more fair capability comparison would be between one bell at 300 grams/min and two guns at 150 grams/min.

In some cases however, bells may in fact provide superior TE. A recent Eisenmann study comparing bells and guns showed differences in the TE as a function of particle size (section 5). Bells provided superior TE for smaller particles and inferior TE for larger particles when compared to gun TE. Regardless, under the test conditions if there is a difference in overall first pass TE it is slight.

A gun versus bell head to head comparison is useful for developing insight but a more practical optimization is for film build uniformity.

**Optimization: Improve Film Build Uniformity**
The name of the game is film build uniformity; improving it will improve surface appearance at any given max. film build. Before launching into an optimization analysis, a simple thought experiment shows that the wider bell profile will provide a uniformity improvement. Wider, flatter profiles are better that narrow, spiky profiles.

Using EXCEL Solver, I put together a model with the following parameters:

- bell position in the reciprocating direction (x) and the direction of job travel (y)
- line speed
- reciprocating speed
- width of reciprocation
- KV, Distance, and Mass Flow for each bell

The model mapped out the 3-dimensional film build for a hood. I then asked Solver to minimize the standard deviation of the film build by changing the above parameters. Two major implicit assumptions in the model were:

- No filling in effect occurs. If the applicator moves, the film build profile will move in a one for one correspondence.
- Applicators are far enough apart so that electrostatic interaction is not a problem.

---

Simulation of 4 bells spraying a 60 inch by 60 inch flat surface.
Each bell is being run at maximum KV (800 KV).
The bell-to-job distance is 7 inches away.
The mass flow is 400 gram/min.
The line speed is 6 inches/sec.
The reciprocating speed is 6 inches/sec.
The total width of reciprocation is 12 inches/sec.

3-D Film Build

The model was helpful in a number of ways:

- It was immediately clear that the model did not like oscillation. This makes sense since at the edges, oscillation will cause the thinner parts of the film build profile to move on and off the hood, increasing the overall standard deviation. This does not say that oscillation is not necessary. As my colleagues pointed out, people respond to contrast in appearance. Without oscillation it is conceivable that the lines of high film build, right next to the lines of lower film build would be readily seen.
Oscillation moves the peaks around and masks this effect. The take away was that if oscillation could be eliminated, it would certainly be a boon to production.

- Guns and bell can be made to have ostensibly the same uniformity, it just takes a lot more guns to get the same standard deviation that a few bells can achieve. The rough ratio is as the manufacturer claims, about 2.5 guns for every 1 bell.

- The model provided a reasonable starting point for verification testing on hoods.
However, it was clear from the first few hoods that cross drafts in the booth were invalidating the first assumption of a one to one correspondence between the applicator and the hood.

The Proof is in the Puddin'
On December 1, 1994, on our eighth try in the Binks Booth with hoods, we were able to produce a very nice film build profile for the hood using only 4 bells. Problems with cross-drafts notwithstanding, we produced a hood with an OVERALL film build standard deviation of only 0.43 and an average film build of 2.7 mils. All this with no oscillation.
The attached graph shows 6 individual, overlaid profiles taken at intervals of 1/4 inches, 17 inches, 25 inches, 31 inches, 37 inches, and 43 inches as measured from the edge of the hood that would be closest to the driver. As can be seen in the graph, measurements were taken at one inch intervals in the cross direction.

The settings producing the profile are:

<table>
<thead>
<tr>
<th>Bell Settings</th>
<th>Bell #1</th>
<th>Bell #2</th>
<th>Bell #3</th>
<th>Bell #4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position from Left edge (inches)</td>
<td>3</td>
<td>19</td>
<td>34</td>
<td>50</td>
</tr>
<tr>
<td>Position in Y-direction (inches)</td>
<td>0</td>
<td>32</td>
<td>0</td>
<td>32</td>
</tr>
<tr>
<td>Distance to Job (inches)</td>
<td>7</td>
<td>7</td>
<td>8.5</td>
<td>7</td>
</tr>
<tr>
<td>KV</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Transport Air (psi)</td>
<td>34</td>
<td>38</td>
<td>21</td>
<td>14</td>
</tr>
<tr>
<td>Flow Rate (gram/min)</td>
<td>350</td>
<td>410</td>
<td>270</td>
<td>210</td>
</tr>
</tbody>
</table>

The model set all of the variables initially. As we observed the impact of the cross draft on the hood (lots of powder spilling off the left side but none spilling off the right side) and measured film builds, we adjusted flow rates. The four bells without oscillation
produced a very nice looking and uniform finish in a pilot operation with poor downdraft control. The bells show promise for production operations.

**Powder Bell Testing Summary, Conclusions, and Recommendations**
Design of Experiments with Non-linear Optimization are a powerful combination of manufacturing tools. Together they can efficiently be used to map out process operating windows or optimize product development efforts. In this case, the LEPC wanted to know if powder bells were a good idea and if they could be used in production. The vague request to "look into the powder bell" was efficiently transformed, using statistically designed experiments into a set of equations. The equations mapped out the relationships between key process variables of mass flow rate, applicator KV and gun to job distance and the key response variables of appearance, transfer efficiency and film build for both guns and bells. Non-linear optimization was then applied to perform sensitivity analysis and answer specific questions. By using these powerful tools the LEPC was able to minimize uncertainty surrounding the powder bell, paving the way for its introduction into operations.

Specific observations and conclusions from powder bell experimentation are:
1. Four bells can replace eleven guns for the horizontal surfaces with equal to or better film build uniformity.
2. For a given powder and adequate cure condition, Appearance and Transfer Efficiency are functions only of film build.
3. The film build profile can be modeled with a normal curve which is described by two parameters, the area and the width of the profile.
4. Although not mentioned previously, in all of our testing the bells never experienced appreciable build up. The gun tips however experienced SIGNIFICANT build up and would be expected to produce powder balls and other defects in operation.
5. Subsequent testing by Pat Schoening has proven electrostatic interaction to be a problem when using a single flight bar. Installation of four bells will likely require two flight bars.
6. With bells, oscillation is probably not necessary.

Experimental findings agree with technological analysis. From a technological standpoint powder bells appear to be a superior applicator to corona guns. Powder bells both reduce exit velocity and exit position variability compared with corona guns. The narrow gap of the powder bell forces particles to pass through the high electric field/high current density charging zone; particles are forced to eject through the corona. The greater cross sectional area of the bell's opening translates to potentially slower exit velocities for the powder bell giving particles more time to reach their saturation charge.
Powder Bell has Superior Design for Particle Charging

Gap is 1 mm
*Since the gap is so narrow and close to the corona, all particles are forced to pass through charging region.*

Rotating disk (diameter of 68 mm)

*High radius curvature at edge of disk provides corona*

Cross sectional area of bell gap is 2.15 cm$^2$

Cross sectional area of 3/8 th inch hose is 0.7 cm$^2$

*The larger cross section translates to lower exit velocities for the bell.*

The superior charging capability enables the bell to handle higher powder flow rates.

From a practical standpoint, the powder bells appear to require less maintenance than current applicators. Since fewer applicators are required for any given setting, there will be fewer applicators to maintain. In addition, the bells appear to run cleaner than guns and will require less cleaning. The bell's inherent cleanliness will likely result in fewer defects such as powder balls.

The powder bell is a good example of a modular innovation. Since it is a corona device, it fits within the current architecture, but its novel design affords a number of significant, incremental advantages. I would recommend that the LEPC rapidly incorporate powder bells in horizontal applications. I would also encourage the LEPC to look at using powder bells in vertical applications and in conjunction with different powder types. Finally as a general recommendation I would hope that the LEPC continues using the efficient and powerful tools of Design of Experiments and Non-linear Optimization as experimentation begins in the Prove-Out facility.
Understanding Site Specific Applications

All of the holistic understanding in the world doesn't mean much if not properly applied in production operations. Production operations are the crucibles where business, technical, and manufacturing issues come together. In my seven month internship I spent most of my time researching business and technical issues of powder coating. While I did not get much of an opportunity to interact with paint shop operations, I would like to briefly acknowledge the importance of considering day-to-day operations in a holistic approach. Superior business strategy, technical prowess, and manufacturing know-how are rendered impotent by poor site specific application.

One of the surest ways for a new innovation to get a "black eye" is to "throw it over the wall" from development to production. Development engineers need to be the linkage between the laboratory testing and day-to-day operations. The innovation advocate must recognize that people are naturally resistant to change and therefore the advocate must communicate effectively to generate consensus. The implementation leader is fighting a paradigm war. A number of methodologies are available to structure the leader's approach to the war.

The Kepner Tregoe Potential Problem Analysis (PPA) has proven a powerful yet simple technique for bringing the stakeholders in an innovation implementation together. For a hypothetical powder bell implementation a PPA might play out this way:

- Stakeholders select representatives to attend a day long PPA session. Typical participants might be: the paint shop superintendent, development engineers, maintenance personnel, shift foremen, selected operations personnel, some onsite engineers, installation personnel, and supplier application engineers. The total number of participants should be less than a dozen.
- Participants brainstorm. They list all of the potential problems associated with the installation and start up of the powder bell.
- Participants then assess the probability of each potential problem occurring. Each problem is assigned a risk ranking of Low, Medium, or High.
- Participants evaluate the impact on the operation if the problem does occur. Each problem is given a seriousness rank of Low, Medium, or High.
- Participants create contingency plans for all problems with Medium or High risk AND Medium or High consequences.

Like most consensus building processes, a PPA is generally a painful and time-consuming process. But it is time well spent.

It has been my experience that an innovation is guilty until proven innocent. A PPA puts the innovation on trial. The open discussion lays bare all of the potential problems with the innovation; principles are allowed to voice their concerns. The innovation leader then builds consensus through the process of assigning risk and seriousness factors to each problem. Instead of becoming paralyzed by the existence of problems, the PPA pushes the group to pro-actively develop solutions to the problems. The PPA ensures that an implementation plan has been thoroughly considered from many different points of view.
It provides an open communication atmosphere. The result is consensus support and a tangible action plan. Leaving a PPA, all of the stakeholders are "on the same page".

Of course a PPA is not the only viable methodology. I only offer it as one that I have seen work. Another more comprehensive methodology is Total Quality Management (TQM) as embodied in Professor Shoji Shiba's book *A New American TQM*. Many methodologies are available; the practitioner should choose methodologies that foster communication and diversity of thought. As a caution... its possible to become overly engrossed with the methodology; remember that success ultimately depends on the people and not the methodology.

Another valuable and often overlooked tool for successful site specific application of a new innovation is the statistically designed experiment. Experiments are sometimes viewed as wasteful and expensive in production operations. In reality the initial cost and time associated with getting the right answer the first time often overshadows the less visible but more expensive incremental tweaking approach that production operations use to move down the learning curve. For example, a simple nine to twelve part experiment, factored into the installation plan for powder bells, will provide structure to the start up. After the analysis from the experiment is complete, operations will have an optimum operating window and documented evidence for the relationships between process variables like Bell KV, Bell RPMs, and mass flow, and response variables like film build, appearance and TE. The experiment provides all shifts with the same starting point and takes some of the mysticism out of process management.

Innovation champions face an uphill struggle in successfully bringing innovations to day-to-day operations. A new innovation will only become accepted at a site as it solves peoples' problems. Since a new installation generally causes more problems than it solves in the short term, it takes time for the innovation to become accepted as the 'new reality'. As trite as it sounds, communication is the key to successful innovation; pay attention to the people.
The Holistic Summary

Established firms struggle with technological change. Chrysler, General Motors and Ford are struggling with the implementation of the environmentally superior but nascent powder coating technology. When framed in terms of Henderson and Clark's architectural innovation many of the obstacles to change become clear. Innovation advocates face an entrenched dominant design of solvent based coating. The dominant design is part of the organization's culture. The organization has erected an architecture composed of strategies, communication channels, simplifying heuristics, and functional silos that cause people to think in terms of the dominant design. In this atmosphere, companies are generally relegated to incremental change.

I have offered a solution. A holistic approach enables a leader to abandoned the dominant design and envision an idealized "perfect coating world". While a perfect coating world may be a nice idealization, it is likely not realizable in the real world; still, the idealization provides a direction for change. In a technology-oriented manufacturing organization, I have segmented the business into four areas:

1. A leader must understand the physics and technology of a process like powder coating. By knowing what makes a process tick, the leader can create a technology roadmap that is bounded by physics and not an organization's culture.
2. A leader must understand how to use a process to make things. Manufacturing methodologies such as Design for Experiments and Non-linear Optimization are powerful tools a leader can wield, if she is aware of them.
3. A leader must understand how to make money from a technology like powder coating. A knowledge of business issues is crucial for grasping the forces driving an industry.
4. Finally a leader must execute. Business issues, process technology, and manufacturing know-how come together in every site specific applications. Ideas are transformed into reality in day-to-day operations.

A holistic approach can enable an established firm to innovate and create competitive advantage.

Business Issues Summary

I focused on the strategic aspects of the automotive powder coating industry. The automotive companies face a choice between incremental improvement or step change improvement, especially with the coming of the Prove Out facility. The preponderance of forces in the greater automotive powder coating industry are driving the industry toward incremental change. If incremental innovation does hold sway, the LEPC will have lost out on a tremendous opportunity to craft a new dominant design in a way that will create competitive advantage.
An External Constraint Upsets the Balance and Forces Change
Will it be an incremental or a step change improvement?

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<th>INCREMENTAL</th>
<th>STEP CHANGE</th>
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<tr>
<td>Strategic Uncertainty</td>
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<td>Strong</td>
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<tr>
<td>Existing web of constraints</td>
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<td>Misuse of financial analysis</td>
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<td>A leader</td>
<td>Wildcard?</td>
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</table>

Uncertainty, uncompetitive material suppliers, and slightly competitive equipment suppliers drive the automotive powder coating industry toward incremental improvement. A few forward-thinking suppliers and discomfort with BMW's clear coat work are moderate forces in favor of a step change. Ultimately either a leader will step up and drive step change improvement or the LEPC will go the slow but sure way of incremental improvement.

Technical Issues Summary
The LEPC wants to determine how to cost-effectively improve film build uniformity, first pass transfer efficiency, and appearance for primer/surfacers applications and for clear coat applications, but innovation has been hampered by the presence of the solvent based/powder coating dominant design. Electrostatic precipitation offers a different more useful analog to powder coating.

Corona related powder coating process variables are highly coupled and non-linear, making understanding and optimization difficult. Using decades of electrostatic precipitation research and development as a foundation I have developed a fairly comprehensive but first order description of the powder coating process. Based on mathematical models for transfer efficiency, point-to-plane electric field, particle migration velocity, dynamic particle charging and other phenomena, it is possible to gain insight into the powder coating process. The insight has enabled the creation of an idealized powder coating process.

Idealized Powder Coating Process
- Particle size distributions would have a mean of 20µm and a standard deviation of 2 to 3 µm. (assumes normal distribution bounded by zero)
- Applicators would be redesigned. In the short term corona based applicators would have reduced exit position variability and reduced exit velocity. In the long term, induction charging type applicators would reduce charging variability and decouple the powder coating system.
• Powder resistivity would be reduced to \(10^{10} - 10^{11}\) ohm-cm. To partially accomplish this, coating might take place in high humidity environments (>70%RH).

• Jobs would be stationary when coated. Coating time would be independent of line speed. It would be set based on the trade off between the fixed costs of multiple coating booths and the variable costs associated with lower transfer efficiencies. If first pass TE could reach the 90% level, reclaim systems could be eliminated.

• The downdraft would be eliminated. The coating chamber would be purged after the job was completed.

• With induction charging, large flat plates would be installed to create a more uniform electric field for particle conveyance.

• With induction charging, gun to job distance could be drastically reduced (<3 inches)

• Auger systems and Microwave Doppler flow meters would be used in place of venturi pumps and differential pressure systems. Mass flow variability would be greatly reduced.

• First pass transfer efficiency would be measured on-line.

• Workpiece to ground current would provide a measure of back corona on-line.

• Electric field decay would provide an on-line measure of "real-life" resistivity.

The LEPC should continue to provide technological direction and leadership to the powder coating industry. In this way they can set the dominant design and drive the industry forward.

**Manufacturing Summary**

A number of manufacturing related models and techniques facilitate the transformation of theories into practice. Statistically designed experiments and non-linear optimizations are powerful, complementary tools for understanding how new products and processes will perform in manufacturing situations.

The LEPC wanted to know if powder bells were a worthwhile investment. Using statistically designed experiments and non-linear optimizations a small team effectively framed the problem, gathered the data, generated equations, ran optimizations and sprayed prototype hoods (with four bells)... all within the span of three months. The pilot work separated the fact from the fiction with regard to powder bells and paved the way for powder bell use in production facilities.

By way of the powder bell example, I hoped to show the power of these techniques and others to solve problems in manufacturing.

**Site Specific Summary**

Successful site specific implementation of an innovation is dependent on the people. An innovation advocate must recognize that he is facing a paradigm war and must somehow win over the stakeholders who include production and maintenance supervision and personnel. A number of methods are available to the innovation champion including Potential Problem Analysis and Total Quality Management techniques. While the methodologies create structured environments for consensus building, they are not replacements for strong interpersonal communications. Outstanding business analysis,
technical knowledge and manufacturing savvy can all be undone by poor execution in
day-to-day operations.

What Now?
If a holistic approach is valuable to established firms struggling with innovation, then
established firms must develop leaders that can take a holistic approach. A holistic
approach cannot be injected into a corporation through consulting reports it must become
a part of the company. And companies cannot even rely on standard financial techniques
to value investments in leadership. The beneficial cash flows resulting from the
investments are too uncertain and strategic to allow for ROI calculation. Building
holistic leadership is a time consuming, difficult and amorphous task that can not be
easily valued. In the end corporate leadership in established firms must decide -- are
holistic leaders necessary?
Leadership

Leaders don't make a big difference. They make all the difference. (Don Davis, Former CEO of Stanley Works)

A holistic approach is difficult; it is also nearly worthless unless there is a leader to drive it. Firms sometimes look to consultants and others for solutions, but while outsiders may be helpful, established firms will ultimately succeed or fail on the strength of their leadership. Leadership and knowledge are the keys to mastering innovation.

"Magic bullet" solutions rarely work. Outsiders and consultants may be able to prescribe a path forward but in takes leadership within an organization to execute change. Most often an organization contracts with a consulting firm to solve a problem. After the consulting firm delivers their elegant analysis in the form of a report, it is briefly given a great deal of consideration. But as time wears on, the impact from the report fades and the organization slides back into the comfortable state of incremental improvement.

Outside consultants can be brought in and clear alternatives can be identified. However, no matter how clear and persuasive a consultant tries to be, some alternatives will not even be understood if they do not fit the old culture, and some alternatives will be resisted even if understood because they create too much anxiety or guilt and sufficient psychological safety is lacking. Even if top management has insight, some new assumptions cannot be implemented down the organizational line because people simply will not comprehend or accept what the new strategy may require. (Davis, 1984). (Schein p 322)

Without internal leadership the initiative will fail.

Occasionally a manager may latch on to an outsider's or consultant's prescription for change and in some cases this is enough to momentarily propel the organization forward. But unless the leader has a holistic understanding of the business and how the "magic bullet" solution fits into the business, the magic bullet will likely become a program-of-the-month. In this case the initiative will also fail; the manager does not have a holistic view of the business. As the business evolves the magic bullet requires adaptation.

In rare instances a leader emerges; a leader with the holistic view of the business. Holistic leaders see the big picture. They not only understand the magic bullet solution and how it fits in the business, but they also have the knowledge and fortitude to implement the solution. In Schein's words the holistic leader needs:

... a clear sense of where the organization needs to go, a model of how to change the culture to get there, and the power to implement the model. If any one of these elements is absent, the process will fail, and in any case, the anxieties that arise from implied change must be actively managed. (Schein p 329)

Holistic leaders are not mythical characters. In the world of automotive powder coating Yogen Rahangdale, Chrysler's Manager of Paint and Energy Management, is a holistic leader. Due in part to Mr. Rahangdale's leadership, in recent years Chrysler has surged forward to become the leader in automotive powder coating installations.
During a personal conversation in July of 1994, Mr. Rahangdale explained the history of Chrysler's involvement with powder coating. Chrysler's early experience with powder was less than successful, but Mr. Rahangdale stressed that Chrysler learned from the mistakes with the initial installation. In subsequent installations, Chrysler has become increasingly successful, moving down the learning curve. Mr. Rahangdale also related that early investments in powder were difficult to justify despite the superior anti-chip performance and emissions improvements. Regardless, Mr. Rahangdale felt strongly that powder was a coming technology, and that environmental regulation would only become stricter in the future. As a result Mr. Rahangdale served as an innovation champion, an advocate for powder coating. From Mr. Rahangdale's perspective, the key to future success, was in understanding and applying powder coating technology. In the face of changing environmental conditions, Yogen Rahangdale was able to look past the solvent based paradigm and see the value of powder coating.

Mr. Rahangdale was able to fend off many of the forces of incrementalism. Mr. Rahangdale and his organization dealt with the technological uncertainty and did not allow early problems or fear of failure deter them. They looked past the simple NPV analysis and intuitively or explicitly took into account the value of the strategic options that investment in powder coating afforded them. Mr. Rahangdale and his group tipped the balance in favor of step change improvement.

Many, including noted economist Lester Thurow, believe that "skilled people become the only sustainable competitive advantage."99 To create more holistic leaders like Mr. Rahangdale, I advocate that established firms must invest in skilled leadership that can take a holistic approach. While firms may be able to lure in holistic leaders from the outside, a far more powerful approach is to cultivate talent from within. Management must be sensitive to the emergence of leadership figures within their organization. Management must then be willing to train the leaders.

The Massachusetts Institute of Technology's Leaders for Manufacturing (LFM) program is an ideal setting in which to nurture and create holistic leaders. In the two year program, future leaders pursue dual Masters Degrees in Management and Engineering. Throughout the program, leadership and manufacturing issues are strong themes that permeate the learning experience. In addition, the two years away from the established firm allows the leader to gain perspective and view the corporation's culture in a more objective way. The LFM program and similar programs that are springing up around the country are valuable resources that technology-oriented manufacture firms should use to create sustainable competitive advantage.

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Established firms must cultivate their leaders. On-the-job training is not good enough; firms must invest in the education of their leaders. Only through knowledge and experience will talented leaders be able to look past dominant designs and make system linkages. "In summary, the most important change of all would seem to lie in top management's renewed appreciation of the people who build and sustain their firms and in their ability to learn and to adapt to changing and challenging circumstances."
(Utterback, p. 223)

Holistic leaders are the answer.
**APPENDIX**

The testing and selected results from the Bell/Gun tests are shown:

**Sames Bell Experiment 11-3-94**

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</table>

Test execution and data collection was a team effort. Special thanks to Dan Burdick, Tim March, Pat Schoening, Jill Nichols. An extra special thanks to Greg New.

The following table will help decipher the cryptic column headings

- **Part** - A convenient label. For the bell test, part cc was exactly the same as part bb except the grounding strap was not used for part cc. For the gun test, gun bell was a bell test run just after the gun test was completed.
- **dist** - Gun to job distance in inches.
- **pass** - The number of passes used.
- **KV** - Bell or gun kilovolts according to control display. 100 was maximum for the gun. 80 was maximum for the bell.
- **air** - Transport air pressure in psi. No atomizing air was used. Hose internal diameter was 0.375".
- **flow** - Linearized mass flow rate in grams per minute. The delivery hopper was placed on a load cell. Loss in weight and time were taken for each test. The calculated flow rate was regressed vs. the air pressure. The relationship was
linear. To minimize variability from loss in weight and stopwatch measurement, regression values were used. The R-squared for this regression was around 0.9.

- area - The area under the film build distribution curve.
- TE - Calculated transfer efficiency.
- OrangeP - An average of 5 orange peel readings.
- Gloss - An average of 5 gloss readings
- DOI - An average of 5 distinctness of image readings
- rating - A consensus visual rank order rating. 1 is the best. Only the top 12 panels were deemed reasonable. Unacceptable panels weren't rated and were arbitrarily assigned a value of 20.
- width - The width of the film build profile in inches. The width was defined to be all of the profile with a film build that is at least 50% of the maximum film build.
- film - The maximum film build of the profile in mils.

Regression Output for the Bell / Gun Experiments

Regressions were performed using Systat 5.1 for the Macintosh.

**Bell Area** regression output. It has a strong R-squared and very high T values

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<th>VARIABLE</th>
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<th>STD ERROR</th>
<th>STD COEF TOLERANCE</th>
<th>T</th>
<th>P(2 TAIL)</th>
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<td>-6.150</td>
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**ANALYSIS OF VARIANCE**

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<th>MEAN-SQUARE</th>
<th>F-RATIO</th>
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WARNING: CASE 1 IS AN OUTLIER (STUDENTIZED RESIDUAL = 5.572)

DURBIN-WATSON D STATISTIC 1.514
FIRST ORDER AUTOCORRELATION 0.049

**Bell Width** has strong R-squared and strong T-values for all of the variables. The low T-value for the constant simply indicates that the constant shown (-0.578) is not statistically different than zero.

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<th>COEFFICIENT</th>
<th>STD ERROR</th>
<th>STD COEF TOLERANCE</th>
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<th>P(2 TAIL)</th>
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**ANALYSIS OF VARIANCE**

129
**Gun Area** has strong R-squared and strong T-values.

**Gun width** is a strong regression.
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