THE DEVELOPMENT AND DIFFUSION OF POWDER COATINGS IN THE UNITED STATES AND EUROPE

A HISTORICAL AND VALUE CHAIN PERSPECTIVE

February 15, 2010

Lukas C. Brun, Ruggero Golini[1] and Gary Gereffi

CENTER ON GLOBALIZATION Governance & Competitiveness

Contributing CGGC researchers:

Caterina Moro[2], Huasheng Zhu[3]

This research was sponsored by the Corporate Partnerships Program of the Environmental Defense Fund and prepared by CGGC. We gratefully acknowledge the comments of our sponsor, Andrew Hutson, and Terry Foecke in improving previous drafts of this report. Thanks also to Rodger Talbert, Sidney Harris, Peter Gribble, and Sam Ruscio who provided an important industry perspective on the development and diffusion of powder coatings in the United States and Europe. Errors of fact or interpretation remain the exclusive responsibility of the authors. We welcome comments and suggestions. The corresponding author can be contacted at lukas.brun@duke.edu.

Final Version: February 15, 2010

1. Università degli Studi di Bergamo
Department of Economics and Technology Management
Viale Marconi 5
24044 Dalmine (BG), Italy

2. Venice International University
School of Humanities and Social Sciences
Globalization Program
Isola di San Servolo
30124 Venice, Italy

3. Beijing Normal University
School of Geography and Remote Sense Science
19 Xinjiekouwai Street
Beijing, 100875, P.R.China

INDEX

FIGURES

EXECUTIVE SUMMARY

CGGC conducted a review of the development and diffusion of powder coatings in the United States and Europe from 1950-2000. Key findings for each section follow.

Section 1: Chronology

Key Findings

- Powder coatings provide environmental and economic advantages over traditional coatings while offering similar or enhanced appearance and performance. Environmental advantages of powder coatings are that they do not release volatile organic compounds (VOCs) responsible for ground-level ozone and also have a reduced solid waste profile when compared to traditional coatings. Economic advantages of powder coatings include operational costs which tend to be less than traditional coating lines.
- Our historical chronology of the powder coating industry highlights its origins in Europe, and its subsequent dissemination and growth in the United States. It began as an application for protecting natural gas pipelines and insulating electrical wiring to being adopted throughout consumer and industrial product end-markets.
- From 1950 to the mid-1970s rapid technological development in powder coatings, powder manufacturing, and application equipment occurred concurrently with product market expansion. After the mid-1970s, technological development entered a slower phase, while product market expansion occurred rapidly. After 1975, the most important innovations occurred in powder coating chemistries. These innovations met the needs of an increasing number specific product markets.
- Market, institutional, and technological factors affect powder coating adoption. Key drivers for powder coating adoption have been the technological development in powder coatings, environmental regulations, and the cost of substitutes. In Europe, the technological development of powder coatings for decorative end-markets was important for powder coating adoption. In the United States, environmental legislation and the cost of substitutes was key for powder coating adoption by product end-markets.
- Key actors in the diffusion of powder coating have been the developers of powder coating formulations (the powder manufactures), who work with product manufacturers and their powder equipment suppliers to ensure in early product testing that the formulations meet their needs. Product manufacturers have at times taken the lead in asking for and promoting powder coating.

Section 2: Value Chain Analysis

Key findings

- The powder coating value chain is most concentrated in powder manufacturing and least concentrated in coating enterprises ("job coaters"). Powder manufacturers capture more than 75% of total sales in the world powder coatings market.
- Actors in the powder coating value chain have key leverage points affecting the conduct of the entire value chain. Although the powder coating value chain is currently producer-driven by powder and product manufacturers, large discount retailers have the leverage to shift the powder coating value chain to being buyer-driven in the future.
- Powder coatings in China face specific challenges for greater adoption. Among these are consistent powder quality, limited chemistries, limited product market experience, environmental standards and practices, and the nature of technological development and adoption in China.

THE DEVELOPMENT AND DIFFUSION OF POWDER COATINGS IN THE UNITED STATES AND EUROPE: 1950-2000

A HISTORICAL AND VALUE CHAIN PERSPECTIVE

INTRODUCTION

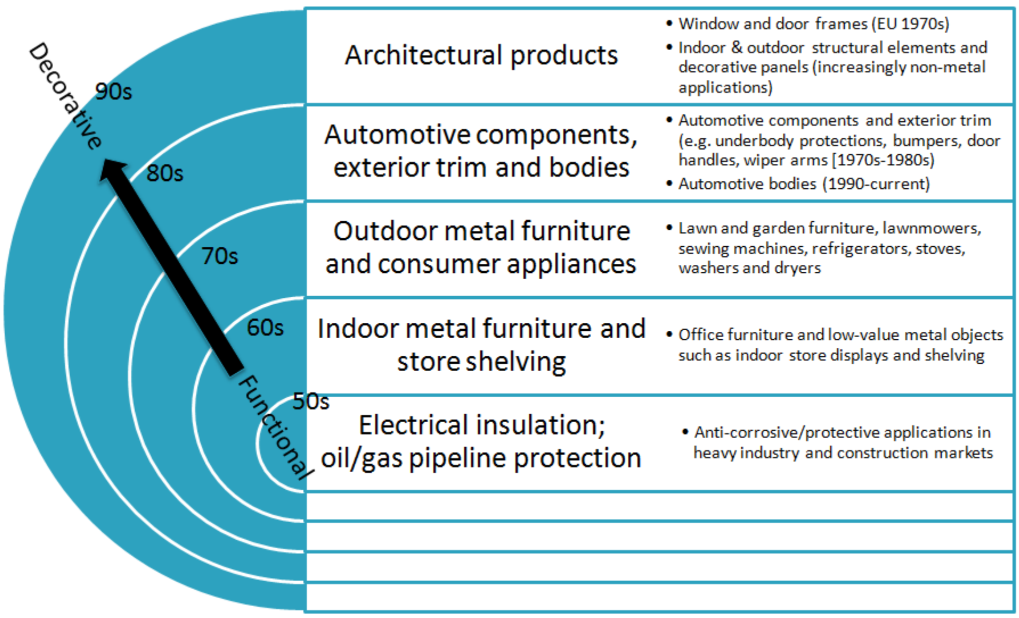
Powder coating is a solvent-free method of coating objects with dry, finely grounded paint particles. The chief benefit of this process is that it avoids the environmental and economic costs of petroleum solvents used in traditional liquid coatings. Powder coatings have been used in the United States and Europe since the 1950s.

The history of powder coatings has been one of expanding use to new product markets as technological developments in powder coatings, manufacturing equipment, and application equipment occurred. [Please see Figure 1.] Part One of the report provides relevant background on powder coatings and summarizes the technological and product market expansions in the United States and Europe from 1950 to 2000. It then develops an explanatory model for powder coating adoption based on the material presented in the chronology. Part Two of the report identifies the powder coating value chain and discusses how key actors affect the conduct and performance of the value chain. We close with some insights about the Chinese powder coating market gained from our review of industry materials and discussions with experts.

BACKGROUND

Powder coating is a dry finishing process in which paint particles are applied with air rather than liquid solvents. Two chief types of powder coatings ("powder chemistries") exist: thermop-

FIGURE 1: POWDER COATING ADOPTION IN PRODUCT MARKETS: 1950-2000



lastics and thermosets. *Thermoplastics* are the original powder coatings and are used for corrosion protection and electrical insulation.

Thermoplastics will re-melt when heated and are applied by placing a heated object in a basin containing powder coating, a process known as the "fluidized bed" process. Thermoplastics made up 10% of United States powder coating use in 2008 [38]. *Thermosetting* powders will not re-melt when heated and are typically applied by a specialized spray process called the "electrostatic spray" process. In this process, the powder coating is applied by electrically charging the powder coating particles and applying them with a spray gun onto pretreated parts in a powder application booth. The paint particles adhere to the parts until they can be cured in an oven, which permanently sets (or "crosslinks") the coating on the part. Thermosetting powder coatings composed 90% of United States powder coating use in 2008 [38].

An important benefit of powder coatings are that they do not use petroleum solvents and therefore do not release volatile organic compounds (VOCs) harmful to the environment. VOCs are organic chemicals that form gases at room temperature and are responsible for ground level ozone and smog. [Please see Figure 2.] Another environmental benefit to powder coating is that the "overspray" (the coating material that does not adhere to the part) can be reused, thus reducing waste. What waste exists can be baked into a solid and disposed of as standard, non-hazardous waste in United States municipal landfills, while standard liquid coatings are considered hazardous waste. From a safety standpoint, powder coatings are safer than solvent-based coatings because they are not flammable and do not expose personnel to solvent fumes. From a quality standpoint, powder coatings are desirable because the durability of the coatings and variation in texture, color, and coating thickness are equal to or better

FIGURE 2: ADVANTAGES AND DISADVANTAGES OF POWDER COATINGS

	Advantages	Disadvantages
Economic	Lower operating costs due to energy savings, labor cost savings, high operating efficiencies, lowered environmental costs & increased plant safety	Capital costs slightly higher than waterborne or high-solids; frequent color changes could entail extensive downtime; operational conditions requiring clean & dry parts
Environmental	No VOCs; reduced energy use; over-spray can be reused; easy disposal	Phosphates & chromates used in part preparation/pretreatment; carcinogenic additives; high-curing temperatures of non-UV and IR-curing powders
Appearance / Performance	High durability and variation in texture, color & coating thicknesses possible	Very thin applications of coatings (less than .001 inches [1 mil]), coating sharp inside corners and heat-sensitive parts have generally been difficult to achieve
Safety	Non-flammable and low spark hazard; personnel are not exposed to solvent fumes	Storage and handling of powder coatings requires special climate controls
Source: *Adapted from* SpecialChem4Coatings, Powder Coatings Center [43]		

than other coating processes. Powder coatings are also cost competitive with solvent based coatings. Product manufacturers have achieved operational cost savings relative to traditional liquid coatings.

While powder coatings are an economically competitive coating alternative to traditional high solvent liquids, they also compete in a variety of product markets against other low-VOC coatings, such as low solvent liquids. [Please see Figure 3.] Traditional liquid coatings are 70% solvents and 30% solids, low-solvent liquids switch this percentage to achieve 30% solvents and 70% solids, while powder coatings are 100% solids. Break even points between various coating types can be calculated using spreadsheets available from industry associations and coating manufacturers. An example from the Powder Coating Institute comparing the operational and capital costs of model traditional and powder coating lines is provided in the technical appendix.

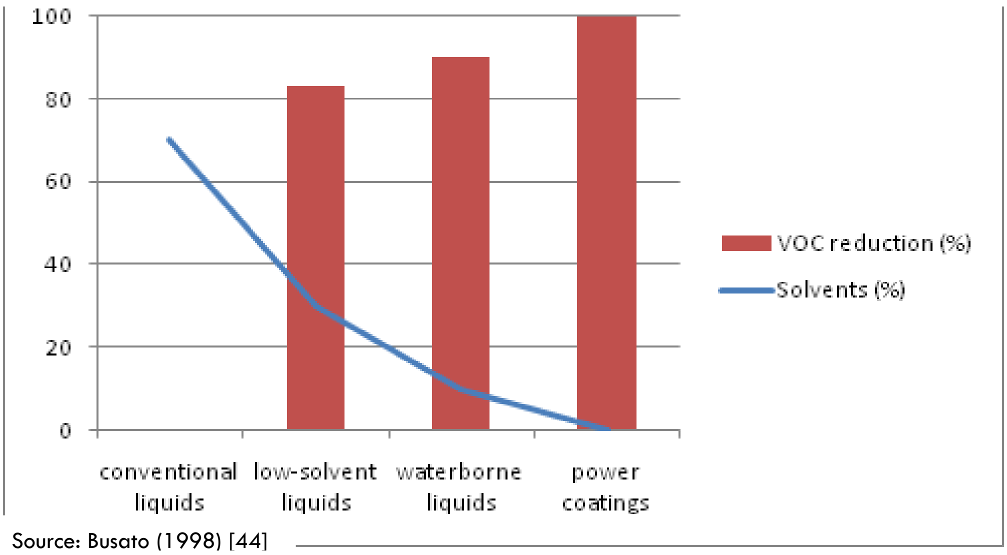
Limitations to powder coatings are operational conditions requiring clean and dry parts, the environmental impact of phosphates and chromates used in part preparation and pretreatment, carcinogenic additives, and relatively high curing temperatures (generally over 300F). Powder coating manufacturers are working to solve these limitations of powder coatings and promising developments have occurred in recent years. A technical appendix is provided for readers wishing to understand additional details about the various categories of powder coatings available and how powder coating is manufactured and applied. A quick review of the appendix may make the remainder of Part One discussing the technological and product market developments in powder coatings from 1950 to 2000 more meaningful.

EARLY HISTORY (1950-1960)

Powder coatings were first used to coat heavy duty parts requiring thick coats of protective material, specifically electrical wiring insulation and pipe coatings [4,6,7]. The use of powder coating for applications in which the protective properties of the coating is important is known as the “functional” market. The functional market is distinguished from the “decorative market” in which the color or texture of the coating is most important to the product manufacturer or consumer.

Powder coating was limited to functional markets during the 1950s because of limitations in the powder application technology. The mode of application was the fluidized bed process which allowed only for thick coats of thermoplastic powders (>10 mils, where 1 mil = 1000ths of an inch) such as nylon to be applied to metal substrates [4,7]. The fluidized bed application technology was patented by Erwin Gemmer in

FIGURE 3: VOC REDUCTION AND PERCENT PETROLEUM SOLVENTS, BY COATING TYPE



Source: Busato (1998) [44]

1953 in Germany and in 1958 in the United States. Gemmer was working for Knapsack-Greisham, a German manufacturer of specialty gases (now a part of Hoechst), who saw that alternatives existed to flame-spraying thermoplastic coatings [6,7]. Knapsach-Greisham had a history of using air, rather than petroleum-based solvents, to apply industrial coatings to metal substrates because of the shortage of solvents available in Europe immediately after WWII [9]. Polymer Corp (US) introduced the fluidized bed coating technology to the United States in 1955 under a licensing agreement from Knapsack-Greisham and developed, licensed, and sold the fluidized bed process in the United States [7].

The diffusion of the technology during this period was slow because of key technological barriers. Three key barriers to wider adoption existed during this time were:

1. *limited number of coating chemistries.* Only thermoplastics and one thermosetting epoxy system introduced by Shell Oil in the late 1950s were available [6,7].
2. *powder coating manufacturing limitations.* The milling and blending technology available at the time created a product that had heterogeneous powder particle sizes. Consequently, thin films of powder coatings were difficult to produce [6,7].
3. *coating application.* The fluid bed allowed only for thick coats of powder to be applied to the substrate. This application technology also required a large reservoir of powder to be available to fully immerse the component [6,7].

1960-1970

From 1960-1970, powder coatings began to be used in a greater variety of product markets, particularly in Europe. Key developments during this period were the 1963 invention of the electrostatic spray gun and the development of new powder chemistries and manufacturing methods that gradually overshadowed thermoplastics [6].

Technological Developments. A key event during the 1960s was the 1963 invention and commercialization (by Ransburg [United States] and SAMES/Gema [Europe]) of the electrostatic spray gun, which allowed for thinner coats of powder to be electrostatically applied to components [4,7]. In the powder spray process, the powder is pneumatically fed from a reservoir through a spray gun where the powder gains a low amperage, high voltage positive charge. Clean parts to be painted are placed in a powder booth and electrically grounded so that the charged powder particles are attracted to the parts' surface. The powder remains attached to the part as long as it remains electrostatically charged. Powder spray methods allowed parts to be coated between 2-3 mils rather than the 12-13 mils with the fluidized bed process [4].

A second key development was the "melt mix extruder" that allowed for homogenous powder particle size [6]. The difficulty in the past had been that the ball mill and high-speed mixer technology available for creating powder was not capable of producing fine particle sizes for thermoplastic powders. For thermosetting powders, the difficulty was that variable cooling times of the mix prior to grinding created unstable epoxies. By the mid-60's, technology used in the plastics industry was adapted for powder coating manufacturing. This development in powder coating manufacturing led to the search of new thermosetting powders, particularly in Europe [6].

A third key development was the creation of new coating chemistries that allowed the coating of a broader variety of products. A thermosetting epoxy system was developed in Europe by Shell and a melamine resin system was being developed by Scado [6]. The benefit of these new coating chemistries was that they allowed for thinner application of coatings and, as thermosets became standardized, costs began to reduce. Drawbacks of these early thermosetting powders were that they took a long time to cure (typically 30 minutes at 400F) and could not be used for most exterior applications because of the tendency of epoxy-based coatings to quickly chalk and lose gloss when exposed to ultraviolet rays and sunlight. The search during this period was to find powder coatings that had better exterior durability [7].

Market Developments. The products coated in the United States and Europe during this early period begins to differentiate. The decorative market began to develop in Europe more quickly after the introduction of the electrostatic powder gun than in the United States [4,6]. The primary use of powder coatings in Europe during this time was to cover indoor metal items with little or no visual importance. Examples are store shelving, interior store displays in retail stores, and closet hardware [32]. Metal furniture also was also powder coated during this time in Europe.

In the United States, the powder coatings industry during this period remained largely limited to thermoplastics being used in functional applications requiring thick protective coats. Polymer Corp. (US), for example, was the leading developer and supplier of nylon for electrical insulation used by General Electric and Westinghouse Corporation [4].

Thus, while the electrostatic spray was invented and commercialized in 1963 in both markets, the rate of adoption and diffusion throughout product segments in the two markets was different. In Europe, powder coatings became established as a "viable and commercial decorative compliance technology" (6, p.317), while United States sales of powder coating were virtually non-existent.

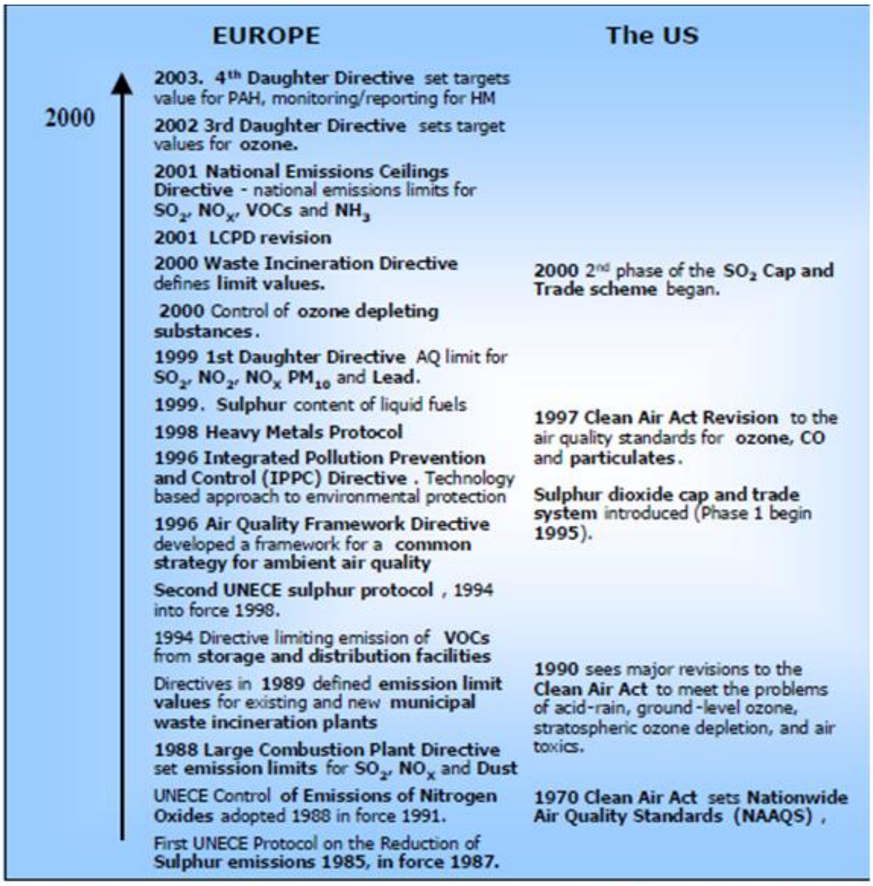
Four causal mechanisms for this difference in response can be identified: environmental regulations, lead firm resistance in the United States, the cost and availability of solvents after WWII, and corporate culture.

Environmental regulations play a key role in the adoption of powder coatings. Two types of environmental regulations are relevant: air pollution emission controls limiting VOCs and waste disposal regulations. Formal regulations in European countries on VOCs lagged those in the United States. In the United States, the Los Angeles Rule of 1966 and the Clean Air Act of 1970 regulated VOCs, while in Europe, country-level regulation of VOCs only began in the 1980s [11]. Regulatory anticipation, however, may have played an important role in the early adoption of powder coatings in Europe. The Los Angeles Rule of 1966 limiting VOCs had a broad effect throughout the world coatings industry to evaluate substitutes for traditional coatings, specifically including powder coatings [1].

European legislation on solid waste disposal relevant for liquid coating overspray disposal was not enacted in Europe during the 1960s. However, a general push to reduce pollution in the Rhine River – where most northern European

industrial production occurs – began in the 1960s. The 1963 Berne Accords among Germany, France, Luxembourg, the Netherlands, and Switzerland created a formal organization to investigate ways for reducing industrial pollution in the Rhine [39]. These Accords, reflective of an emerging movement to reduce pollution in Europe, may have led European companies to calculate that it was in their best interests to adopt cleaner practices and limit the threat of severe air and waste regulations from national governments.

FIGURE 4: AIR EMISSION REGULATIONS IN THE UNITED STATES AND EUROPE



Source: Watkis et al (2004) *A Comparison of EU Air Pollution Policies and Legislation with Other Countries*

A second factor was the prevalence of a solvent-based industrial infrastructure in the United States (US). Lead coatings companies and product manufacturers in the United States had invested heavily in the industrial infrastructure necessary to make and use liquid coatings [33]. This infrastructure was extensive and supplying the world with consumer and industrial goods. Replacement of this infrastructure with a relatively untested technology would have been prohibitively expensive and risky. One industry expert stated that it "was as simple as that" for why coating and product manufacturers in the United States didn't adopt powder coatings to a greater extent during the 1960s [33].

Meanwhile, in Europe, the price and limited availability of solvents immediately after WWII led to the build-up of an industrial coating infrastructure less reliant on petroleum solvents. Recall that powder coatings were developed as a substitute for petroleum-based solvent coatings by German-based Knapsach-Greisham. The limited availability and additional expense of solvents in Europe may have led to a greater willingness by European coatings manufacturers to conduct research and development in alternative coating technologies. As chemistries and applications for powder coating developed, European manufacturers may also have been more willing to experiment and adopt alternative coating technologies on their products than their counterparts in the United States because of reduced investments in liquid coating application infrastructure.

This causal mechanism also helps explain the reference by industry experts about the role of corporate culture to understand the difference between the United States and Europe in the adoption of powder coatings during the 1960s. Industry sources have stated to us that European coating companies and product manufacturers have a greater preference for clean technology than do their counterparts in the United States. "They just do things differently over there" stated one expert. "They will mess about with a technology until they get it right, while we in the United States will look at a technology, and if not immediately useful will throw it aside. We have to be hit over the head with regulations before we do anything." [32]. An independent preference for clean technology by European coating manufacturers and product manufacturers may exist; however, it is equally likely that this preference is partially derived from the economic and regulatory incentives European companies had in adopting powder coatings. Given that the level of investment in liquid coatings was less in Europe, they could afford to "mess about" with an alternative coating technology to "get it right." Looming regulations may have been the extra push needed to increase their preference for powder coatings. This discussion about the factors influencing the adoption of powder coatings is continued and more fully developed in Part 2 (pp. 27-30).

In Europe, the price and limited availability of solvents immediately after WWII led to the build-up of an industrial coating infrastructure less reliant on petroleum solvents.

These four causal mechanisms help explain why Europe was an early adopter of powder coatings. The adoption and diffusion of powder coatings during the 1960s in Europe was led by producers and consumers of powder coatings ("bottom-up"), while in the United States, the adoption and diffusion of powder coatings – other than in the thermoplastics/functional market – was to be driven by regulations ("top-down"). In the absence of high oil prices and investment in liquid coatings, the use of solvent-based coatings continued in the United States until their costs increased during the 1970s oil shortages and environmental regulations made their use more problematic.

1970-1980

This period is characterized by the development of new thermosetting powder and application technology in the early 1970s, the rapid development of powder coating use in Europe by the late 1970s, and the adoption of powder coatings in the United States in a relatively narrow set of product categories.

Technological developments. The technological development of powder coatings in the early to mid-1970s resulted in the basic powder coating chemistries used today. In 1970, a paper given by Erwin Gemmer at the International Conference on Plastic Powder Coatings in London listed the available powder coating chemistries as nylon (thermoplastic) and epoxy and vinyl (thermoset) powders. By 1975, the available chemistries expanded to fast curing epoxy, polyester, epoxy-polyester hybrid, polyester urethane (polyurethane), and acrylics – the chief families of powder coatings available today [7]. [See sidebar on families of powder coatings].

The United States and Europe during this period differ in the types of powder coatings demanded and available in their markets. In the United States, epoxy, polyurethanes and acrylics were chiefly used, while in Europe, epoxy polyester hybrids and pure polyesters were chiefly used. Acrylic coatings were practically unknown in Europe during this time [7]. Powder manufacturers in each of these markets produced specialized powders only for their markets, a practice which continued through the

1980s when homogenization of the powder coatings market in the United States and Europe occurred [7].

The coating manufacturing and application equipment also developed during this period. Production methods allowed for greater control and classification of powder particle size (classification mills) [6,8]. Application equipment improvements included the development of the electrostatic fluidized bed systems, and powder feeding systems for electrostatic spray, which allowed for more consistent powder flow and spray patterns. The triboelectric gun, a new way of applying electrostatic charge to powder coating was patented in Germany in 1973 [6]. It began its modest penetration in the market during the 1980s when it was sold by Siemens (Germany) and GEMA/Ransburg (Switzerland) in Europe [36] and Nordson in the United States. Use of the tribo-gun has been limited to Northern Europe by operating conditions requiring stable humidity and low temperatures [18].

Market developments. Up to this time, powder coating in the United States was limited to thermoplastics like nylon for electrical and pipe coatings, and the thermosetting powders used to coat small metal components. During the 1970s the market for powder coatings developed in three main categories: general metals, appliance, and automotive markets [6]. In general metals, powder coating replaced porcelain enamel and liquid coating in lighting fixtures, indoor metal furniture, outdoor lawn and garden furniture, and tractors [6, 32]. In the appliance market, powder coating replaced porcelain enamel on external surfaces in refrigerators and dryers. Powder coating also replaced paint in oven range panels, microwaves, and refrigerators, and metal plating on refrige-

Five main families of thermosetting powders

Epoxy powder coatings exhibit inherent toughness, corrosion resistance, chemical resistance, flexibility, adhesion, and abrasion resistance. Epoxy powder is normally used where a tough durable film is required and the product will not be exposed to direct sunlight for long periods of time. An epoxy coating will form a chalk like appearance on the surface with lengthy exposure to sunlight. Epoxies make up approximately 7% of world powder production.

Polyester powder coatings feature characteristics of long-term exterior durability, high performance mechanical properties and heat resistance. Polyester powder is widely used for decorative components where good resistance to the ultraviolet rays from sunlight is important. Many automotive trim components and other exterior components are coated with polyester powders. Most coatings used on buildings use TGIC-polyester powders which raise environmental and health concerns. TGIC-free polyester powders are available. Polyesters make up approximately 36% of world powder production.

Epoxy-polyester hybrid powder coatings are epoxy powders with a high percentage of polyester resins (sometimes approaching or exceeding 50%). These powders are similar to epoxies with improved resistance to yellowing in sunlight and weatherability. Hybrid powders are considered the backbone of the powder coatings industry and make up 51% of world powder production.

Polyurethane powder coatings have excellent gloss retention and long-term resistance to humidity and corrosion in thin film applications. They provide good all around physical and chemical properties and have a good exterior durability. Polyurethanes make up less than 2% of world powder production

Acrylic powder coating is specified where the decorative requirements and resistance to ultraviolet rays from sunlight for a longer period of time is critical. They have good gloss and color retention on exterior exposure and have heat and alkali resistance. Acrylics make up approximately 3% of world powder production

Source: adapted from engineershandbook.com and Akzo Nobel Complete Guide to Powder Coatings (1999) [18]. Data from Powder Coating and Finishing Magazine 2007 Annual Edition as cited in [17]. Additional information about the families of powder coatings is provided in the technical appendix.

rator and dishwashing machine racks [6]. The growth of powder coating in the consumer appliance market was at least partially due to the energy crisis. For example, one Whirlpool plant had to shut-down its porcelain enamel operation during the 1973 oil crisis, a procedure that caused the bricks used in high-temperature enameling furnaces to crack as they cooled. When they tried to start up after several days of disuse, they found that it was prohibitively expensive to replace the enameling furnaces. Rather than rebuilding the enameling furnaces, they shifted production to other plants until a powder coating line was installed [34].

Manufacturers also began requesting powder coating for their products during the early 1970s. Snapper Lawnmowers in January 1971 approached Glidden (US) about how it could powder coat its lawnmowers to achieve a more durable finish. Snapper Lawnmowers began powder coating its products within the year. [34]. Singer Sewing Machines in 1974 converted from a two-coat conventional liquid line to powder coating. This was an important event in the powder coating industry, according to one industry observer, because it signaled that powder coatings had achieved a suitable level of consumer and manufacturer acceptance. Singer also began promoting powder coatings to other manufacturers in the United States [12], illustrating the business-to-business diffusion of powder coatings within product markets.

In the building sector, the protection of reinforced steel bars (“rebars”) with fusion bonded epoxy [FBE] powder coatings occurs by 1973 in the United States [30]. The primary use of powder coated rebars is in protecting highway bridge decks from de-icing salts [30]. This product sector would only develop in Europe in the late 1980s because of a lack of agreed upon standards in the UK and Europe [31]. In the European architectural product market, companies like Scado BV in the Netherlands and Landshut in Germany developed powder coated aluminum for outdoor architectural applications [10]. These polyester powders contained TGIC [triglycidyl isocyanurate], a known carcinogen, but are used because the acrylic alternative creates compatibility problems with other generic types of powder coating [25].

In the automotive industry, powder coating was used on underbody parts [6,13,14]. Ford and GM experimented in the United States with the use of powder coatings on automotive bodies in the early 1970s, but this use did not develop beyond the experimental stage because of “inconsistent film thickness, difficulties with metallics, and the many tricks inherent in repairing powder paint” [23, p.35]. For example, Ford’s Paint Division in Mt. Clemens, Michigan coated Ford Pintos with a single layer of acrylic powder coating but found that field tests failed because of corrosion [26]. Greater success was found for automotive components and underbody parts. In the United States, the automotive industry coated coil springs with thin-film epoxy powder coating in the early 1970s because it allowed for both flexibility and durable corrosion protection in a very demanding environment [13]. Coil springs were followed by an increasing number of automotive parts that needed to be both lightweight (for increased fuel efficiency) and have high resistance to corrosion [14]. For example, in 1975 Ford used powder coating for catalytic converters because superior durability, corrosion resistance, and heat stability [22]. In Europe, exterior trim such as bumpers, door mirrors and handles, and windshield wiper arms were being powder coated – automotive parts that wouldn’t be powder coated in the United States until the 1980s [14]. The emphasis on lighter components to increase the fuel efficiency of cars (in the wake of the oil embargos of the 1970s and resulting higher fuel prices) also allowed for the progression of powder coating into new automobile component product markets. [Please see Figure 5: powder coatings in the automotive industry timeline.]

A key driver in the United States for expansion into these product segments was the Clean Air Act of 1970 [6,7]. The passing of the Act created expectations in the industry for massive growth. For example, it was estimated in 1972 that the North American market would grow from roughly 60 million pounds in 1971 to 230 million pounds in 1980 (about a 40% annual growth rate) and consume half of the world's total production of powder coatings by 1980 – figures that would only be reached a decade later [6]. This expectation within the powder coatings industry in the United States was driven largely by the assumption that solvent-based automotive body topcoats would be replaced by powder coating [7]. The effect was that relatively small companies with market niches in powder coating, such as Polymer Corp, Dexter Corp, Hysol, and Armstrong, found themselves competing against major liquid coatings manufacturers like Sherwin-Williams, DuPont, Glidden, and Ferro (US) [4]. Once it became apparent that powder coating would not pose a dramatic threat to liquid automotive topcoats, however, many of the larger companies re-focused to develop liquid coatings to be more environmentally efficient [6].

1980-1990

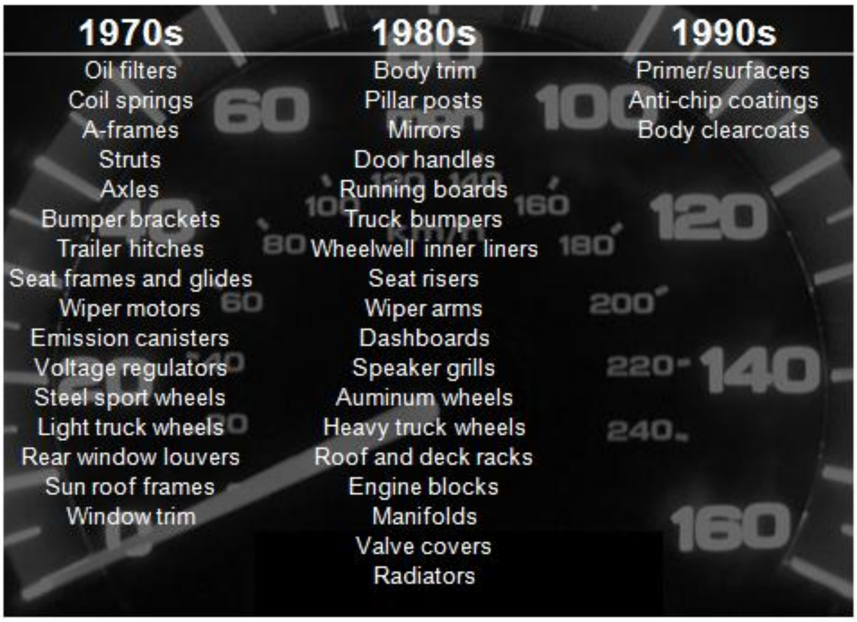
The 1980s were characterized by a large European market and rapid growth in the United States as product markets increasingly adopted powder coatings. During this period, both technological developments and product market expansion occurred in powder coatings.

Technological developments.

Powder coatings used almost exclusively in Europe had a rapid growth phase in the United States during the 1980s [7]. These polyester and hybrid formulations allowed the expansion of powder coatings into outdoor product markets needing enhanced UV and weather protection [7]. Problems with these formulations, however, were that their performance ratings were below the standards of the architectural market in the United States [25] and also contained TGIC. This period also saw developments in lower temperature curing, formulation advances that increased the use of additives to achieve specific performance requirements, and the development of acrylics and thermoplastic blends [6,8]. Powder formulations chiefly used in the United States also become available in Europe [7], specifically for the construction market using reinforced steel.

Coating manufacturing also developed during this period. Design improvements in the extruder permitted better dispersion, shorter dwell times, and improved cooling methods. Computerized color control systems allowed for better and faster color matching. Automation improved the

FIGURE 5: POWDER COATINGS IN THE AUTOMOTIVE INDUSTRY TIMELINE



Source: Sal Lovano (1996) Automotive Applications for Powder Coating consistency and quality of powders, while laser particle size instrumentation allowed for fast adjustments and the creation of small, customized powder lots [6,8].

The application equipment during this period became increasingly standardized, computerized, and automated. Powder collection systems improved and became more efficient as they began utilizing compact cartridge filters. In general, the powder application equipment became more standardized, efficient, and lower in cost.

A 1993 paper presented at a London colloquium by Ernst Timmerman (current president of the German Research Society for Surface Treatment), reviewed the development of the powder coating industry during the 1980s and investigated what barriers remained for adoption in a greater variety of areas. The paper states that the development of the market during this period occurred as a result of four factors: stricter environmental laws and regulations; increased energy costs; increased labor costs; and progress in powder chemistries and application technology [16]. Technological barriers remained in powder coating production processing and film formation. Powder coating production barriers were the inability to achieve a high gloss finish, special effect metallic coatings, and recoating in multi-layer systems. Development of storable and low-temperature powders, new hardeners, additives, weatherproof clear coats, and thin-layer powders were needed at the time. Processing developments needed were listed as increased first-application efficiency, film thickness control, optimization of electrostatic and tribo-guns, improvement in color change technology, powder coating of plastics and wood, and coil-coating with powder materials [16]. Many of these barriers would be overcome in the next decades.

Market developments. The market in the United States developed rapidly during the 1980s. As an example of market developments in the United States, industry organizations, journals, and industry consulting organizations specializing in powder coatings emerged during this period. For example, the Powder Coating Institute was founded in 1981. Powder Coating Magazine was established in 1990. The specialized industry consulting organization Powder Coating Consultants was established in 1988.

An important market development in United States during the 1980s was the replacement of porcelain enamel on the tops and lids of washing machines by Whirlpool (and its Sears Kenmore brand) at its Clyde, Ohio plant [6,15]. Although expensive porcelain enamel on external surfaces had been replaced with powder coating in refrigerators and dryers in the 1970s, the adoption of powder in washing machines was an important event because it signaled that powder coatings had achieved a satisfactory level of performance in a large and demanding consumer product segment. The benefit to the washing machine industry was significant savings over porcelain enamel. [Please see Case History I on pg. 16.]

In the automotive market in the United States, use of powder coatings in automotive components expanded throughout the 1980s to exterior applications like window frames, roof rails, wiper arms; aluminum wheels; and interior applications like seat risers and mirrors. The use of primer/surfacers for automotive bodies also developed during this period. Primer/surfacers are used to improve the appearance of succeeding layers of coating, and provide chip and corrosion resistance for the entire vehicle body [14]. GM began using a powder coating primer on its S-10 small pick-up truck plant in Shreveport, LA in 1980 [26] and eventually introduced it to its passenger vehicles in the early 1990s [2]. This expansion to essentially all aspects of automotive components (but not automotive body topcoats) increased the automotive market share of powder coatings to the position it currently holds, at roughly 12-15% of the powder coating market in the United States [14]. [Please see case history II on pg. 17.]

In the building sector, construction using reinforcing steel "rebars" with fusion bonded epoxy (FBE) powder coatings expands to Europe from its wide use in the United States. Regulations are adopted by 1988 in the UK and Europe about the use of reinforced steel in construction. FBE rebars are rapidly expanding in Europe for a wide variety of uses, including sea defenses, chemical plants, culverts, railway bridges, and piers that contrasts with its traditional use in the United States as a way to protect bridges against de-icing salts [30].

1990-2000

Technological developments.

Technological developments during the 1990s occurred in coating chemistries, coating manufacturing, and coating application. Coating chemistries in the 1990s developed to use silicones, metallics, and new ultraviolet curing methods. Performance and application additives for specialized characteristics and functionalities developed during this period, as well as the improvements in polyester coating chemistries [8]. Research into powder coatings for non-metallic substrates such as glass, ceramics, plastics and wood occurred, and commercial powders become available for these substrates for the first time in the late 1990s. Akzo Nobel, for example, states in its 1999 powder coating guide, that it has commercially available powder coatings for these non-metallic substrates [18].

Coating manufacturing saw improvements in mixing and computerized particle control. Ferro (US), for example, introduced in 1995 a new powder coating manufacturing process eliminating the melt-mixing (extrusion) process, lowered temperature processing, and the use of carbon dioxide as a solvent. The entire manufacturing process is controlled and monitored by a computerized control system [8]. This manufacturing process has not seen broad commercial use because of cost and control issues [32].

A new coating application method, the powder slurry process, developed in England [35]. In the powder slurry process, water is used to disperse very fine powder coating particles (1-5 micrometers). The result is a very smooth and thinly coated surface that combines the advantages of powder coating and liquid coatings. BASF Coatings (Germany), for example, uses a powder slurry process to apply primer to automobile bodies at a German Mercedes-Benz plant [26]. Fast color change also becomes possible with the development of cyclone systems that can change colors in minutes in contrast to high-volume production systems that can take up to an hour or more to change. Lean systems (color on demand) also became commercially available [8,19].

Market developments. The market development from 1990-2000 exhibits diffusion into additional product markets, the increasing scale of items that are powder coated, and the ability to coat items with non-metallic substrates. A major regulatory development in the United States was the 1990 passage of amendments to the 1970 Clean Air Act. The amendments further regulated pollutants and expanded the role of the federal government in monitoring and enforcing air regulations [28]. The effect of the 1990 regulations was to spur industry to further reduce or substitute use of solvent-based coatings [29]. Solid waste regulations had also become more stringent with the 1976 Resource Conservation and Recovery Act (RCRA), its 1984 amendments (HSWA), and the 1980 Comprehensive Environmental Response Compensation and Liability Act (CERCLA or "Superfund" Act). Waste from solvent-based coatings is considered hazardous waste under these laws. The effect of these regulations was that both the emission and disposal of solvent-based coatings became increasingly difficult and costly for industry. The result was that manufacturers using solvent-based systems had increasing incentives to find alternatives to high solvent liquid coatings.

Powder Coating Case History – I

The Whirlpool Corporation

Whirlpool Corporation (US) is a major producer of consumer appliances with production facilities of household laundry dryers in Marion, Ohio. In 1985, the decision was made to replace the finishing of dryer drums and bulkheads. The existing e-coat process was unable to keep up with production levels at the plant and a new 10-warranty program raised concerns that the existing coating would not be able to perform adequately. A major customer for Whirlpool, Sears (Kenmore brand), determined that a white interior drum was a strong customer preference over the existing dull gray electro-deposition coating (also known as electro-coat or "e-coat"). Since a stable white e-coat did not exist, powder coating was investigated as an alternative to e-coating dryer parts.

The consumer appliance market is driven by customer preferences. Appliances represent a large investment for the consumer, which means that a high quality product is essential for customer satisfaction. Responsiveness to consumer demands and concerns is a critical factor in the manufacturer's success, and appliance manufacturers are constantly monitoring how customers view the product and seek to find ways to improve the quality of the product.

Powder coating was selected as a replacement for e-coating because it provided the required wear characteristics and the desired aesthetic appearance. That powder coating would also meet any EPA restrictions was a positive factor for powder coating, but not a decisive one. Marion, Ohio was not a high pollution area and environmental regulations were not rigorously enforced.

An epoxy powder was selected as the replacement for the e-coating of the dryer drum, bulkhead, and door liner. Three powder coating lines were built at the Marion Plant. Two were for the dryer parts and one for coating microwave ovens. An extensive new facility was built for the coating lines with a new pretreatment system, oven, and conveyor in a new 43,200 square foot building. The three lines were ready to go on line after 15 months.

The new lines experienced several technical problems, particularly in the application of the coating. The thickness of the coating was impossible to control and left parts with a range of coating from 2.7 to 7 mils. In addition, the overspray overloaded the recovery system and distorted the blend of virgin and reclaimed powder. The heavy powder load resulted in additional time for cleaning and maintenance, replacement costs for worn-out gun and pumps parts, and clogged filters. In addition, the excessive volume of powder in the booth also created health and safety concerns for personnel due to a spark hazard. So, while the project goal of achieving a pleasing white finish that met the ten year lifetime warranty standard was reached, the cost of powder coating was much higher than anticipated.

Marion's sister division in Clyde, Ohio had been powder coating washing machine tops and lids with a different type of powder gun and experienced none of the problems reported at the Marion Division. The powder gun that the Clyde plant used had the ability to control voltage with an internal cascade power supply with standard 110 volt power. This eliminated the need for stiff high voltage cables that can cause voltage fluctuation. The result of better voltage control was the ability to consistently deposit powder in the specified 2.5 to 4 mils and reduce the volume of powder sprayed on the part during the first pass. The net effect was to reduce the spark hazard to personnel, the costs of spare parts, and a better blending of virgin and reclaimed powder. The Marion Plant has fully implemented these changes throughout its coating lines and is now satisfied with the performance of powder coating.

Source: adapted from Michael T. Hartings (1992) "Liquid to Powder: An Investment for Style and Quality" Powder Coating 1992 Conference Proceedings

Powder Coating Case History – II

Big Three Ventures in Powder Coating

Powder coating in the US automotive sector has had a start-stop relationship. The automotive sector was an early and important customer for powder coatings in the early 1970s for coil springs, catalytic converters, and other functional parts which required coatings that could survive harsh operating conditions or in underbody components for which UV exposure or decorative quality was not important. As experience developed in the automotive market, additional automotive components have been powder coated over time (see automotive timeline). Yet auto-bodies – the single largest parts of cars that need coating – remained an elusive segment for powder coatings.

Auto-body paint is an important selling point for automobiles. There are actually five layers to a modern automotive coat, the electro-deposition coating for anti-corrosion (e-coat), a primer/anti-chip coating, a base coating giving the vehicle its color, and the clear coat that provides durability, UV protection, and a high gloss finish. A good finish is one of the first things that attract customers to an automobile and a key indicator of vehicle quality throughout the life of the car. There is an industry saying that "the paint sells the car." Painting cars is also expensive. The capital required for a new paint shop makes up 30-50% of the capital investment of a new plant.

After passage of the 1970 Clean Air Act, expectations in the powder coating industry was that powder coating would replace solvent-based top coating, leading to rapid growth in the market. General Motors and Ford experimented with powder-based top coats in the early 1980s (followed by experiments in Japan by Honda and Toyota in the mid-late 1980s) but were unsatisfied with its performance. Solvent-based systems – despite their very high VOC emission profiles – remained dominant with plants adding expensive emission abatement systems to remain in compliance with regulatory standards. These abatements systems, while effective in reducing VOC emissions, created new issues for car manufacturers. The plant's energy consumption increased, leading to the greater emission of greenhouse gasses, while the emission abatement systems added costs to the production facility. Economically feasible alternatives had to be found.

In response to the 1990 Clean Air Act Amendments which expanded the role of the federal government in enforcing clean air standards, GM, Chrysler, and Ford formed the Low Emissions Paint Consortium (LEPC) in February 1993 to conduct joint research and development in low-emission paint technologies. The LEPC agreed to reduce per vehicle VOC emissions to 1.5 VOC units (from pre-emission control levels of 18.5 for enamel and 50 for lacquer) and focused on the development of a powder coating clear coat to help achieve these goals.

The direct benefit of the LEPC to the Big Three was that they could capture the cost savings of an environmentally compliant painting system rather than expending nonproductive capital on factory emission controls which were expensive and unlikely to meet more stringent pollution controls. The pooling of resources among the Big Three automakers also minimized development costs. The Consortium selected ABB Paint Finishing Systems to be the design and construction partner. This pattern of working closely with product manufacturers, coating manufacturers, and equipment manufacturers in a relational manner to develop a powder coating system that overcomes the technological, manufacturing, and business issues has been characteristic of the powder coatings market in the automotive industry. PPG has a strong relationship in developing and supplying powder primers to Chrysler; Siebert Powder Coatings is the key powder supplier to GM; and DuPont and BASF have strong relationships with European automobile manufacturers.

Source: Adapted from Bevin Barberich (2004) "Application of Color Powder Paint in the Automotive Industry"; Charles M. DeWitt (1995) "A Holistic Approach to Automotive Powder Coating"; and Kevin Biller (2006) "OEM Automotive Powder Coatings".

The markets in the United States and Europe are, by the 1990s, increasingly homogenous as the powder chemistries developed in each market become more widely available in both markets. In the automotive market, primer/surfacers and anti-chip coatings are adopted by major European, Japanese, and US manufacturers, while body clear-coats finally becomes used by a European manufacturer (BMW). GM and Chrysler expand use of powder primer/surfacers throughout their assembly plants in the United States by the mid-1990s [26]. BMW installs a powder clear topcoat line in 1998 for its 5- and 7-Series vehicles in Germany [26]. This is hailed as “arguably the most significant breakthrough in the history of powder coating technology” because these vehicles “require some of the highest standards for appearance and durability in the industry” (26, p.3). One interesting side note is that foreign-based automobile companies manufacturing in the United States were able to negotiate compromises on VOC emissions, in addition to tax abatement and labor concessions, as part of their site selection packages with local and state governments. Thus, “they are not forced to comply with the prevailing EPA strictures that the domestic automakers face. The Hyundai, Mercedes, and Honda plants in America thus won’t have to take a serious look at powder for the foreseeable future” (26, p.3). Product markets for powder coatings continue their expansion in the United States and Europe. Powder coating for easy-open cans for food and beverages are evaluated by Nordson (US) in the 1990s as a way to cover metal scores (the cuts through the steel) in two and three piece cans, while BASF Paris and Sexton Cans (US) evaluate the use of powder coatings for non-food (aerosolized) cans. Limitations to the use of powder coatings in the canning market are high line speeds and thin film requirements [2].

The architectural market, which developed from coating window and door frames in the early to mid-1970s, expands to structural beams and paneling for both internal and external use. TGIC-free powders become available by 1991 for exterior applications in Europe, but their greater adoption in the United States was limited because they are rated below the “five-year Florida” [AAMA 2604] performance level required for external applications in the United States by the American Architectural Manufacturers Association until the mid-1990s [25]. This product segment is unique because of its scale and use in both interior and exterior environments, requiring specialized powder coating chemistries. The availability of a wide number of colors, improvements in applying powder coating to aluminum profiles and sheets, and increased quality of powder coatings for external applications were decisive for the increasing importance of powder coatings in architecture. Environmental regulations were the “driving force” for the use of powder coatings in this market segment [10].

Similar scale issues arise in the marine market where shipping containers and ship components can be very large. Akzo Nobel notes in its 1999 powder coating guide that items can be powder coated up to 10 meters (~33 feet), although size limitations are theoretically only subject to the size of the powder application equipment (powder booths) and curing equipment limitations [18].

SUMMARY OF CHRONOLOGY

The review of the history of powder coatings leads to several conclusions about how powder coatings developed from a relatively minor functional coating in the electrical and pipe insulating market to its current position in the coating market as the “predominant coating over the next 5-10 years” (20, p.26). In the early years, basically from its invention in the 1950s to the mid-1970s, the coating chemistry, manufacturing, and application technology had to develop. Functional applications, where coating characteristics other than appearance are important, came first, followed by decorative applications.

The pattern that repeats itself throughout this development phase is a technological development in the coating chemistry, powder manufacturing, or application equipment, followed by the commercialization of the new coating by coatings manufacturers, limited testing and application by product segment manufacturers (in cooperation with powder and equipment manufacturers), followed by narrow product line adoption (ex. small pick-ups), and then to full adoption within the broad product segment (all passenger vehicles). This process tended to take place over years, rather than months, as product manufacturers became comfortable with the use of the new coating technology in their product segments, and received information from their customers about the performance of the coating.

After the mid-1970s, this basic dynamic still takes place but higher solvent costs and environmental regulations become an important driver in the substitution of liquid, solvent-based systems. The major manufacturing and application technologies had, by this time, been developed and the area of development for this relatively standardized equipment and application technology was to become computerized and automated – a trend that continues today. Also by the mid-1970s, the major powder chemistries had become mature, leaving further development in the area to be increasingly specialized to narrow product segments, while powder coating as a whole becomes suitable to be used in an ever broader array of product segments.

The history of the expansion of powder coatings in the United States and Europe indicates that the key actors have been the developers of powder coating formulations (the powder manufactures), who work with product manufacturers (and their powder equipment suppliers) to ensure in early product testing that their formulations meet their needs. Product manufacturers had at times taken the lead in asking and pro-

FIGURE 6: POWDER COATING DEVELOPMENTS AND PRODUCT MARKET EXPANSION, 1950-2000

	Coating Chemistry and Materials	Coating Manufacturing	Coating Application	US Product Markets	European Product Market
50s	Polyamides/vinyls	Milling/blending	Fluid bed	Electrical wiring insulation and pipe coatings	Electrical wiring insulation and pipe coatings
60s	Epoxies, polyolefins	Extrusion	Electrostatic spray	Electrical wiring insulation and pipe coatings	Store shelving, interior store displays, closet hardware, indoor metal furniture
70s	Polyesters, hybrids, melt flow and fluid handling additives	Classification mills	Cyclone and cartridge booths, tribo spray	General metals (lawn/garden furniture, lighting fixtures, tractors), appliance (refigerator,dryer,stove boxes), and automotive components (anticorrosive/underbody); reinforced steel "rebars"	Outdoor architectural applications; automotive exterior trim such as bumpers, door mirrors and handles, and windshield wiper arms
80s	Acrylics. Thermoplastic blends, appearance additives	Small lots, computer color control	IR cure, thin film, compact systems	Washing machine tops&lids; exterior components and primer/surfacer	Rebars
90s	Silicones, metalics, UV cure, PVDF, improved polyseters, novel curatives and binders, performance/application additives	Bonding, slurries, particle control	Slurries, automation, fast color change, charge shaping, novel feed systems	Auto (primer/surfacers and antichip widespread); food and aerosol cans; architectural market	Automotive body clearcoat; tgic-free architectural apps

Source: Adapted from Kiefer (2004) [8] with product market expansions by CGGC researchers.

moting powder coating.

Three key drivers appear to affect the adoption of powder coatings: market factors such as the cost of coating products with powder coatings relative to alternatives; institutional factors such as environmental regulations and perhaps corporate culture; and the level of technological development of powder coatings to achieve the functional and decorative characteristics desired by product manufacturers and their customers. The role of these factors and actors in powder coating adoption will be further discussed on pages 27-30 developing an explanatory model for powder coating adoption.

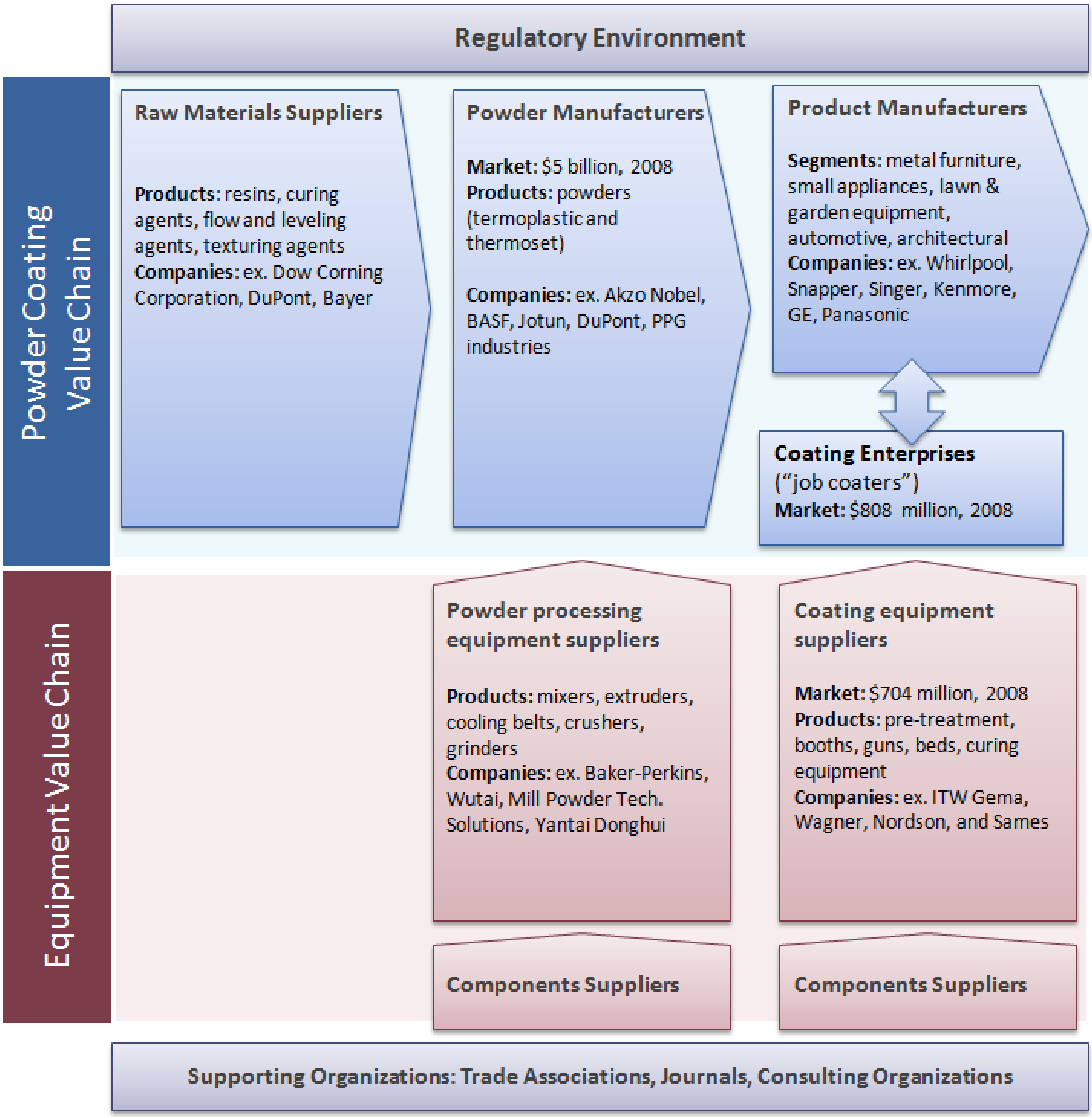
PART 2: ANALYSIS OF THE POWDER COATING VALUE CHAIN

The purpose of this section is to provide an analysis of powder coatings from a value chain perspective. Specifically, it will investigate the role of lead firms and market forces in driving the innovation and adoption of powder coatings in the United States and Europe by asking four key questions:

What does the powder coating value chain look like? Who are the lead firms in each segment?

The powder coating value chain (Figure 7) consists of raw material suppliers, powder manufacturers, independent powder coating enterprises "job coaters", and product manufacturers.

FIGURE 7: POWDER COATING VALUE CHAIN STRUCTURE



Powder manufacturing and application equipment manufacturers (and their component suppliers) enter the powder coating value chain at specific points. Other relevant organizations and institutions are trade associations, trade journals, private consulting organizations, and the regulatory environment.

Powder coating was a $6.5 billion industry worldwide in 2008. Powder manufacturing was a $5 billion industry worldwide in 2008. Equipment manufacturing was a $704 million industry worldwide, while independent coating enterprises were an $808 million industry in 2008 [37]. Powder coating as a whole makes up approximately 6% of the total coating world market and approximately 30% of coatings used in manufacturing and commercial applications [38]. The value chain is most concentrated in the powder manufacturing segment and least concentrated in the coating enterprises ("job coaters") segment. Details on each segment of the value chain are provided below.

Raw Material Suppliers

Raw material suppliers provide the resins, curing agents, pigments, extenders and additives necessary to produce powder coatings. Dow Corning, DuPont, and Bayer are examples of large raw material suppliers.

Powder Manufacturers

Powders manufacturing is the most concentrated portion of the industry in the powder manufacturing segment, with the top 25 major powder manufacturers accounting for 80% of the world powder coatings market. The main players identified in the global powder coating market are Akzo Nobel, BASF, Jotun, DuPont, PPG, Rohm and Haas (DOW group) and Caparol (DAW).

All of these companies are multinational corporations producing both liquid and powder coatings. Their revenues from coatings (liquid and powder) are an important part of their total sales, especially for Akzo Nobel and PPG. These companies serve a globalized coatings market, but have higher than average sales in Europe.

These companies commercialize different brands of the most common thermoset powder types: epoxies, polyesters, hybrids, and acrylics. Their broad product range and the high product quality allow them to supply customers in both the decorative and functional coatings product markets. A major challenge for companies is to extend the applicability range of powder coatings to wooden or plastic product surfaces.

In addition to these large multinational coating companies there are thousands of medium and small powder coating producers (ex. Absolute Powder Coating, Powder Buy the Pound, LLC, EPC Powder Manufacturing, Innotek Powder Coatings). These companies usually have a limited market area and may also sell powder coating equipment and accessories.

Product Manufacturers

Product manufacturers are consumers of powder coating and are divided into specific product segments. The most important product segments for powder coatings have historically been metal furniture, household appliances, and functional products like electrical wiring and pipeline protection. Product manufacturers in an ever-increasing set of products have adopted pow-

FIGURE 8: SAMPLE OF TOP POWDER COATING MANUFACTURERS

Name	Total turnover (bln)	Employees	Headquarter	Internet site
Akzo Nobel nv	$ 21.5	60,000	Europe	www.akzonobel.com
PPG Industries Inc.	$15.85	44,900	US	www.ppg.com
DuPont Coatings & Color Technologies Group	$ 30.53	60,000	US	www.dupont.com
BASF Coatings AG	$ 87.22	96,924	Europe	www.basf-coatings.com
Jotun	$ 1.92	7,200	Europe	www.jotun.com

Source: CGGC research

der coatings. [See figures 1 and 6 for summary]

Coating Enterprises

Coating enterprises (or "job coaters") are outsourcing partners of manufacturers who do not have the technological expertise or equipment necessary to coat their products or pre-cut "blanks" in-house. There are thousands of job coaters around the world and they are usually small and medium companies that operate regionally. Thomas Research reports 1,427 powder coating services of which 675 are defined custom manufacturers.

Powder Processing Equipment Suppliers

The equipment necessary to produce powder coatings has been specialized over time from manufacturing processes in the plastics, chemical, pharmaceutical and even cement industries. Key standardized equipment suppliers are Baker-Perkins, Thermo Scientific, Wutai, Mill Powder Technology Solutions, and Yantai Donghui Powder Processing Equipment Co. These companies provide from "one to all" necessary equipment and the technical assistance to set-up the plant. Finally, for big and customized plants there are specialized engineering & contracting companies.

Coating Equipment Suppliers

Some coating equipment is specific to the powder coatings industry, while other equipment is sold for broader applications. For example, the washing systems or the curing ovens can be used in other industrial processes with minor modifications. Some equipment, however, is specifically designed for powder coating such as the electrostatic spray guns and powder application booths.

Two main categories of coating equipment suppliers exist: components sellers and system integrators. Components sellers provide customers with specialized equipment such as guns, booths or ovens needed for a powder coating line. System integrators are service-oriented companies that usually buy components to build standardized batch or customized turn-key systems. Some of the main companies in this market are ITW Gema, Wagner, Nordson, and Sames.

Regulatory Environment

The regulatory environment has been a key driver of powder coating adoption in some markets. Two types of regulations are relevant: air emissions standards limiting volatile organic compounds (VOCs) and solid waste regulations limiting the type and quantity of industrial waste that can be released by industry. In the United States, the 1970 Clean Air Act and its amendments were an important force in powder coating adoption by industries using liquid and enamel coatings. The various solid and hazardous waste regulations adopted over the years (RCRA, HSWA, and "Superfund") were also important drivers for the adoption of the technology. Environmental regulations, however, are not a necessary condition for powder coating adoption. The European example indicates that powder coating adoption and diffusion among product segments can occur in weak air and waste emission regulatory environments.

Supporting Organizations

Supporting organizations for the powder coating value chain consist of industry organizations, specialty trade journals, and private consulting organizations. These organizations provide forums for information exchange and provide a reservoir of technical knowledge in powder coatings for other actors in the powder coating value chain.

What are critical points in the value chain?

Key leverage points exist in the powder coating value chain. By leverage points, we mean portions of the value chain over which specific actors have unequal power in influencing the conduct of the entire value chain. A summary of leverage points by key actors in the powder coating value chain are summarized in Figure 9.

Research and Development Powder manufacturers conduct the overwhelming share of research and development in the powder coating value chain. In the pre-1975 era, research and development tended to occur in the manufacturing and application equipment sector and by powder manufacturers. After this period, innovation in all three areas tended to be marginal, while powder coating chemistries became increasingly able to meet the needs of specific product markets. This ability by powder coating companies to refine powder coating chemistries to meet the needs of specific applications, operating conditions, substrates, and product markets led to the growth of powder coatings.

Customization and technical assistance Powder suppliers collaborate with customers to develop a customized product, particularly for high value products or products for which the coating is an important part of the product (e.g. marine, automotive, architectural markets). This customization enhances the powder suppliers' bargaining power because it is more difficult for the customer to switch to another supplier. If the coating is not a very important feature of the final product (e.g. basic functional requirements like for cars underbody) the product manufacturer can more easily switch suppliers and constrain them to compete on a price base.

Equipment suppliers also provide technical assistance to product manufacturers to customize and optimize equipment.

Access to markets Product manufacturers possess a large base of retail and wholesale customers for their products. These customers provide information to product manufacturers about their level of satisfaction with the product. In turn, product manufacturers decide whether the current technical specifications of their products – including the type of coating used – best meet the needs of their customers. As a result of this control, product manufacturers have the ability to determine product specifications and set the price of their goods. This control of access to markets by producers is characteristic of a producer-driven value chain.

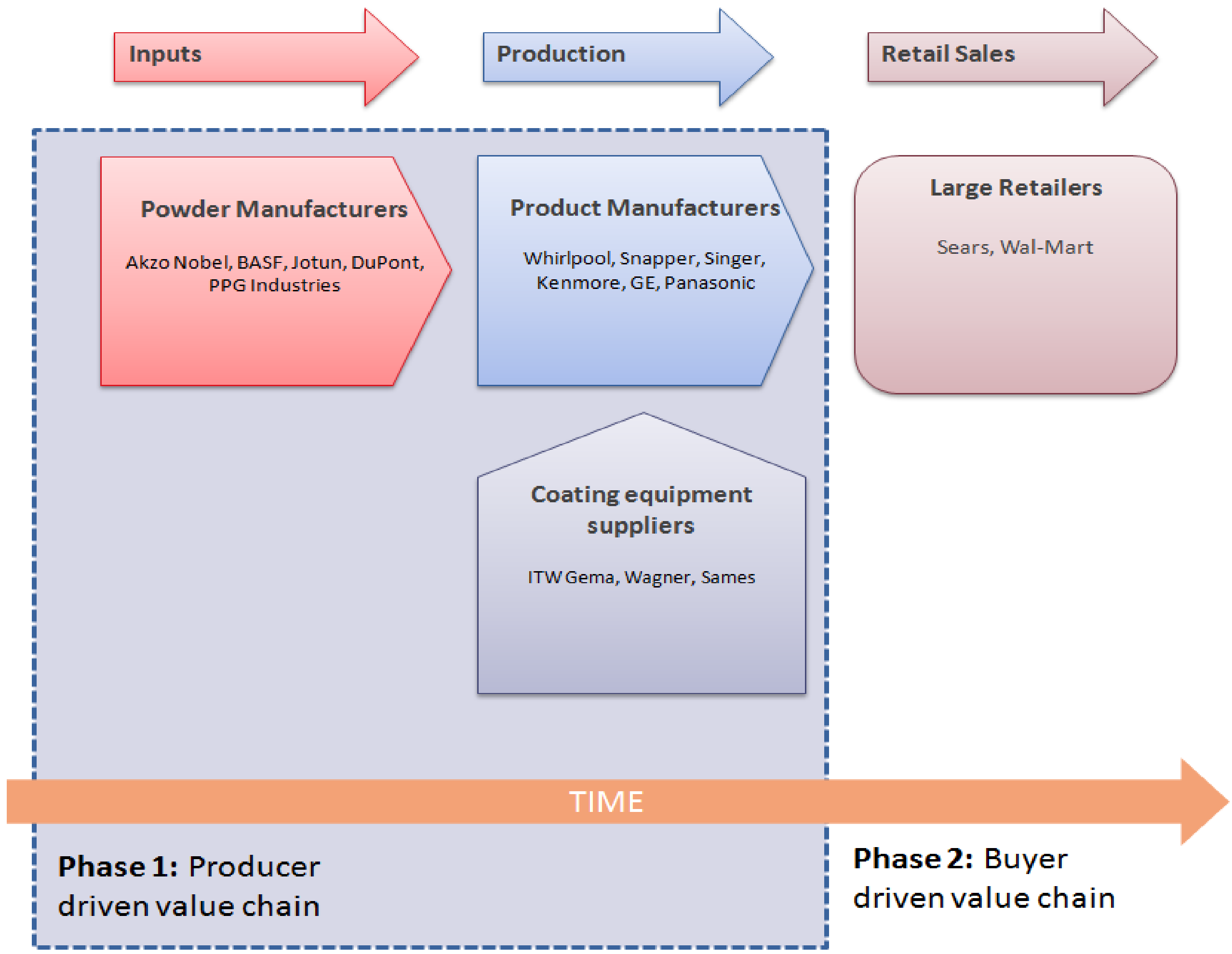
The producer-driven value chain is contrasted with buyer-driven value chains in which buyers control access to markets. In buyer-driven value chains, producers manufacture according to buyer specifications and become price takers. Their base of customers narrows to a few wholesale customers and they use the buyer's distribution network to access retail customers. This dramatic shift of power in product markets has resulted from the rise of large retailers – particularly in the United States – with massive purchasing volumes able to take advantage of (and demand from) product manufacturers' economies of scale and scope to reduce prices. The shift in power from producers to buyers presents buyers with tremendous opportunities to shape value chains to meet their specifications and price levels. Buyers have the ability to be major players in technology adoption by fully exerting their leverage on value chains, particularly their leverage in market access, purchasing volumes, brand name recognition, and economies of scale and scope. A fuller discussion of the differences and consequences of producer-driven and buyer driven value chains than can be offered here is available in Gereffi (1999) [40].

Buyers have the ability to be major players in technology adoption by fully exerting their leverage on value chains.

FIGURE 9: POWDER COATING LEVERAGE POINTS

Leverage Points / Value Chain Actors	Input	Production		Retail Sales
	Powder Manufacturers	Equipment suppliers	Product manufacturers	Large retailers
Research and Development	Large powder manufacturers are continuously investing in R&D to maintain high profit margins in new products in an industry where older powder products have very low margins. Major areas of research are in higher quality (e.g. resistance to hostile environment, new aesthetic qualities) and lowering their customers process costs (e.g. lower curing temperature).			
Customization and technical assistance	Powder suppliers collaborate with customers to develop a customized product, particularly for high value products or products for which the coating is an important part of the product (e.g. marine, automotive, architectural markets). This enhances the powder suppliers' bargaining power since is more difficult for the customer to switch to another supplier. If the coating has a lower importance on the quality of the final product (e.g. basic functional requirements like for cars underbody) the product manufacturer can more easily switch suppliers and constrain them to compete on a price base.	Equipment suppliers provide technical assistance to product manufacturers to customize and optimize equipment		
Access to markets			Product manufacturers who own or control the distribution channels of their products can specify price and product specifications that best meet their retail and wholesale customers.	Large retailers can dictate price and product specifications (e.g. type of coating used) to product manufacturers, particularly in product segments where branded manufacturers do not control distribution and sales networks.
Purchasing volumes			Product manufacturers who purchase large quantities of powder may receive discounts or preferential contracts from powder manufacturers.	Large retailers can use their purchasing power to negotiate preferential contracts from branded and non-branded product manufacturers
Brand name recognition			Companies with a highly recognized brands (e.g. Whirlpool for white goods) may leverage this to increase bargaining power over retailers and maintain control of price and product specifications	Large retailers have well known brands can use it to negotiate preferential contracts with branded and (especially) non-branded suppliers.
Economies of scale and scope	Large powder manufacturers have international product and sourcing networks and have achieved economies of scale in producing powder coatings. This permits them to achieve market power in the powder coatings market		Product manufacturers have international production and sourcing networks and are able to achieve economies of scale in manufacturing . This permits product manufacturers to reduce per unit costs and/or increase product quality	Large retailers can pressure product manufacturers to reduce costs and/or improve quality thus capturing the gains from manufacturer's economies and scale

FIGURE 10: POWDER COATING VALUE CHAIN DEVELOPMENT



The extent to which the powder coating value chain has shifted from a producer-driven to buyer-driven value chain is a testable proposition. Figure 10 illustrates this hypothetical development in the powder coating value chain. Phase 1 illustrates a producer-driven value chain controlled by product manufacturers, powder manufacturers, and coating equipment suppliers. In Phase 2, large retailers drive the value chain as a result of their control over retail sales.

The preliminary evidence gathered from industry experts about the relative role of producers and buyers in the powder coating value chain suggests that the shift from a producer-driven value chain to a buyer-driven value chain has not occurred. The market dynamic in place is still very much the collaboration and coordination among the three key actors in the producer driven model.

Purchasing volumes Product manufacturers purchasing large quantities of powder may receive discounts or preferential terms from powder manufacturers. Large retailers may also use their purchasing power to negotiate preferential contracts from branded and non-branded product manufacturers.

Brand name recognition Companies with highly recognized brands (e.g. Whirlpool for white goods) may leverage this to increase their bargaining power over retailers, thus maintaining control of price and product specifications. Large retailers with highly recognized names may also negotiate preferential contracts with branded and (especially) non-branded suppliers.

Economies of scale and scope Large powder manufacturers have international product and sourcing networks and have achieved economies of scale in producing powder coatings. This permits them to achieve market power in the powder coatings market. Product manufacturers have international production and sourcing networks and are able to achieve economies of scale in manufacturing. This permits product manufacturers to reduce per unit costs and/or increase product quality. Large retailers can pressure product manufacturers to reduce costs and/or improve quality thus capturing the gains from manufacturer's economies of scale.

How does adoption occur? What are the factors and actors important to the adoption of powder coatings?

The chronology presented in Part 1 identified factors and actors relevant to the adoption of powder coatings. An explanatory model for powder coating diffusion is provided in Figure 11.

The dependent variable is technology adoption, in this case the decision by product manufacturers to choose powder coating rather than non-powder coatings. The framing of the dependent variable as a dichotomous variable is somewhat forced since powder coating can replace - and compete against - a variety of coatings. Powder coating has replaced standard liquid and spray enamel coatings, but also competes with other low-VOC coatings (so called "green coatings") like low-solvent liquid coatings, waterborne liquid coatings, and electro-coating in a variety of product markets. The chronology focused on companies and product categories that shifted from non-powder coatings to powder coatings, and placed outside the scope of inquiry how companies in specific product categories and the coatings industry diversified beyond powder coatings to meet new market, institutional, or technological conditions. This is admittedly a limitation of the current research.

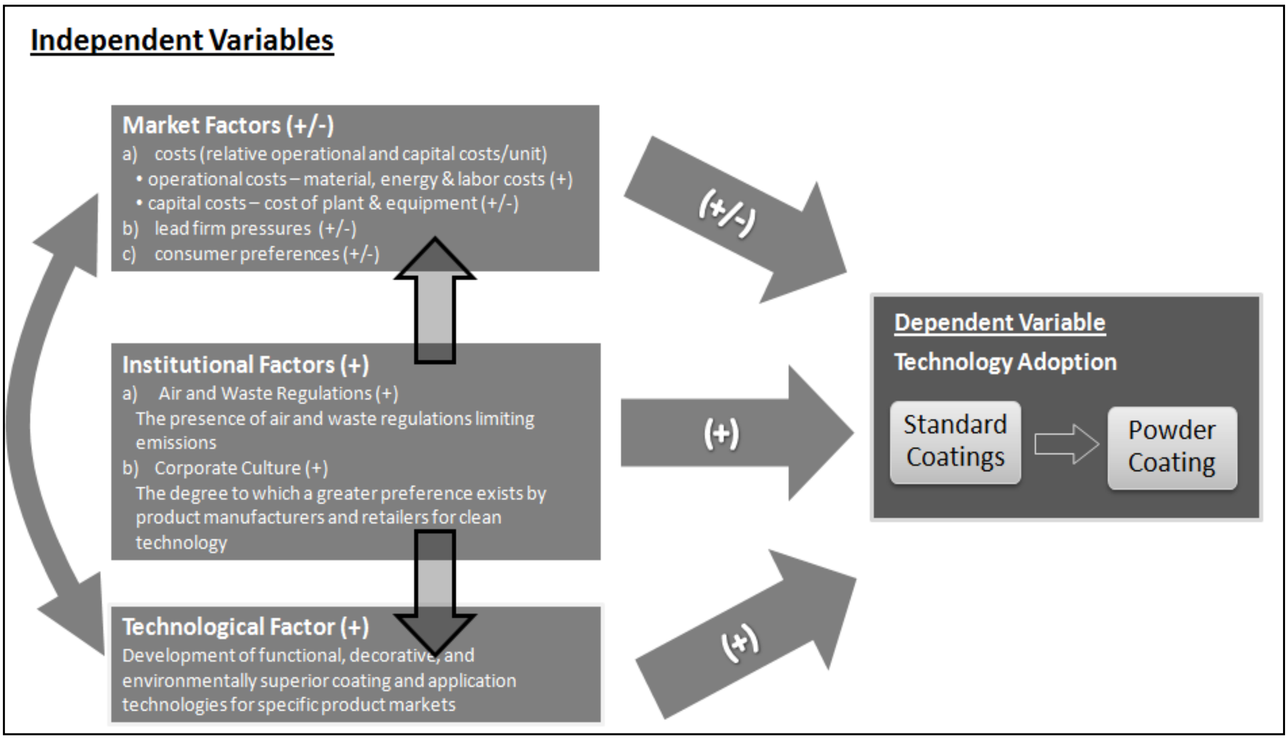
The independent variables explaining technology adoption are in three categories. The first category is market factors, by which we mean the per-unit operational and capital costs, lead firm pressures and consumer preferences. The second category is institutional factors comprised of environmental regulations and corporate culture. The third category is technological factors, specifically, the development of powder coatings over time to be suitable for an expanding range of product markets. The remainder of this section provides additional detail on each category of independent variables and how they interact with one another to affect the adoption of powder coatings.

Market factors – Market factors consist of the costs of powder coating an object relative to the cost of alternative coatings, lead firm pressures, and consumer preferences.

Costs refer to the per-unit operational and capital costs of a powder coating line relative to non-powder alternatives. Operational costs are the per-unit material, energy, labor, and maintenance costs of a coating line. By capital costs, we mean the cost of the plant and equipment infrastructure required to coat products. Break-even points for powder coating and its alternatives can be calculated for both operational and capital costs.

The chronology pointed out that the per-unit coating cost was an important factor in product manufacturers' adoption of powder coatings. In many instances, powder coating was a financially competitive operational alternative to traditional coating methods such as high solvent liquids or spray enameling. In fact, the high cost or limited availability of petroleum solvents at times became the overriding factor for adopting powder coatings. Examples of this dynamic in the chronology were in the consumer products market. However, extensive capital investments in traditional coating infrastructure inhibited the adoption of powder coatings in the United States. In Europe, the capital investment in a solvent-based coatings industrial complex was less due to historical factors, thus allowing European manufacturers to adopt powder coating to a greater extent. We denote the role of operational costs in Figure 11 with a (+) to indicate that reduced per-unit material, energy, labor, and maintenance costs of powder coating had a

FIGURE 11: EXPLANATORY MODEL FOR POWDER COATING ADOPTION



positive effect on the adoption of powder coatings. Capital costs are denoted as (+/-) to indicate the conditional effect of infrastructure costs on the adoption of powder coatings. The effect of capital costs on the adoption of powder coatings is conditioned on the extent of existing investment in non-powder coating infrastructure.

Lead firm pressure refers to the role of coating suppliers, product manufacturers, and large retailers in adopting powder coatings. Coating manufacturers had a key role in promoting powder coatings to product manufacturers as technological barriers were overcome in specific product markets. We termed this dynamic "supplier push." The role of coating suppliers is mixed, however, because some coating suppliers in the United States who had invested heavily in traditional liquid coatings resisted powder coatings until regulatory changes pressed them to include them in their product portfolio. Thus, the role of coating suppliers on powder coating adoption is mixed, depending on the level of investment in non-powder coatings and the regulatory environment.

The effect of lead firm product manufacturers was also mixed. Some product manufacturers heard about the benefits of powder coatings and approached their coating suppliers about transitioning from other types of coatings to powder coating, a dynamic we called "demand pull." Examples of this dynamic provided in the chronology are outdoor equipment and consumer appliance product manufacturers. In other cases, however, product manufacturers evaluated and rejected powder coatings because they failed to meet performance or aesthetic requirements. The automotive industry's experimentation with a powder coating topcoat is an example of this dynamic. We denote the effect of lead firms as (+/-) to reflect the mixed historical role of lead firms in adopting powder coatings.

Co*nsumer preferences* had a mixed role in powder coating adoption. In some cases, consumer preferences led to the adoption of powder coatings because the functional or decorative characteristics that consumers wanted from their products were only achievable with powder coatings. These preferences were monitored by large retailers who pressed their product manufacturers to meet them. The chronology notes that consumer appliances fell in this category. In other cases, however, consumer preferences inhibited the adoption of powder coatings because the functional or decorative characteristics they wanted were not yet possible with powder coatings until further technological development occurred. This was particularly true of the automotive body topcoat market and exterior architectural market in the United States until very recently. We denote the effect of consumer preferences as (+/-) to reflect their mixed effect on the adoption of powder coatings.

Institutional factors – The institutional factors identified as important to the adoption of powder coatings are environmental regulations and corporate culture.

The *regulatory environment* refers to the presence (and strength) of air and waste regulations in a geographic area. Relevant air regulations are limitations on the emission of volatile organic compounds (VOCs). In the United States, the Clean Air Act of 1970 and amendments to the Act in 1990 affected the rate of adoption of powder coatings by limiting the permissible amount of VOCs that could be emitted by industry. In Europe, limitations of VOCs developed during the 1980s and 1990s; however, industry sources state the Los Angeles Rule of 1966 affected the coatings industry in both the United States and Europe.

Waste regulations were also relevant for the adoption of powder coatings. Discarded high solvent liquid coatings can be environmentally harmful, while leftover powder coatings become environmentally neutral if baked into a solid. In the United States, for example, discarded high solvent liquid coating is considered hazardous waste, while powder coatings can be disposed in most municipal landfills if properly prepared. The waste regulations affecting the coatings industry in the United States are RCRA, HSWA, and the Superfund Act of 1980. The industry literature suggests that waste regulations had a supporting role in pushing the adoption of powder coatings by product manufacturers, while air regulations were the most important regulatory driver.

In Europe, the effect of waste regulations on the adoption of powder coatings is more tenuous. The 1963 Berne Accords were entered into force by countries surrounding the Rhine River to reduce water pollution. Since most of industrial production in Northern Europe occurs around the Rhine, the adoption of the Berne Accords may have increased the willingness of European coating companies to develop clean coating technologies and influenced the adoption of waste reducing technologies by European product manufacturers.

Corporate culture was identified by industry experts as a factor contributing to the faster adoption of powder coatings in Europe than in the United States. By corporate culture we mean the degree to which a greater preference exists by coating companies, product manufacturers and retailers for clean technology independent of market, regulatory, or technological factors.

The difficulty with corporate culture as an explanatory variable is that it is at least partially determined by market and regulatory factors. For example, a greater willingness to adopt powder coatings by European coating companies and product manufacturers may have occurred because of historical limitations on the availability of solvents and reduced investments in solvent-based coating lines – market factors we attributed to operational and capital costs. In addition, regulatory efforts to clean up the Rhine in the 1960s where most of Northern European industrial production occurs, may have affected the willingness of European coating companies to invest in powder coatings and the preference of European manufacturers for powder coatings. In the United States, the absence of either solvent limitations or regulatory pressures permitted the unabated use of traditional liquid and spray enamel coatings until the twin forces of environmental regulations and the 1970s energy crises motivated product manufacturers to adopt more environmentally efficient coatings.

Thus, while differences in corporate culture may have a role in explaining the adoption of powder coatings, it is difficult to determine the extent to which this variable is independent of factors more directly tied to the profit maximizing motive of firms. We are skeptical, in short, about the extent to which this preference is derived independently from market and regulatory factors. To the extent that a preference among companies for clean technologies exists, however, it would positively contribute to the adoption of powder coatings. We denote corporate culture with a (+) to reflect this relationship.

Technological factors This variable refers to the development of powder coatings and manufacturing and application equipment necessary to meet the requirements of product manufacturers (and their customers) in specific product segments. Technological development by powder coating manufacturers and equipment suppliers occurred because they saw the opportunity for increased sales once the technical barriers of powder coating in specific product markets were overcome. Technological development also occurred as a result of foreign direct investment. For example, the availability of powder chemistries typically available only in one market became available in both the United States and EU as mergers and acquisitions among large coating manufacturers took place in the early 1980s. This allowed expansion into decorative applications in the United States that had generally only been available in Europe; while in Europe, functional applications in the construction market expanded as a result of coatings developed in the United States becoming available. We signify technology factors with a (+) to denote the relationship between technological development and powder coating adoption.

Interaction among variables As with any complex phenomenon, the independent variables explaining technology adoption of powder coatings interact with one another as well as affecting the dependent variable. Institutional factors affect both market and technological factors. For example, air and waste regulations required manufacturing plants to become compliant with new standards or face fines. Capital investments to either modify existing infrastructure or replace coating lines with more environmentally efficient methods were the result of air and waste regulations. Regulations also affected the technological development of powder coatings. The automotive industry, for example, worked closely with coating companies to develop regulatory compliant powder coatings for a variety of applications for cars. The institutional corporate culture variable was influenced by regulatory and market factors. The preference for powder coating was at least partly affected by air and waste regulations and by the high cost or limited availability of solvents. Technological factors were affected by market factors and vice versa. For example, technological advancements in powder coating application equipment (the electrostatic spray) reduced the operational costs of powder coating metal products. The operational and capital costs of powder coating, in turn, affect the level of demand for additional technological development in other product markets. Market factors interact with all variables, including each other. For example, material costs are partially determined by the level of technological development of powder coatings. Energy costs are partially determined by the regulatory environment, while the capital costs are also a function of technological development.

What are critical factors for successful adoption?

Once the decision to powder coat a substrate or product has been made, the repeated advice heard from industry experts and stated in the industry literature was the importance of coordinating three key players in the powder coating value chain: the powder coating manufacturer, the product manufacturer, and - depending on whether the coating line is in-house or a job coater - the powder application equipment manufacturer. Highly specific assets must be invested in at this point, and coordinating with these value chain actors is important to ensure that the powder chemistry, powder application equipment, and actual powder application process (i.e., pretreatment, application, and curing) meet the needs of the product manufacturer, and ultimately, their customers. An independent technical advisor with long-standing experience in powder coating should be considered to ensure that choices made are appropriate for the intended use of the product. Costly mistakes can be made at this point, and industry experts repeatedly stated the importance of proceeding prudently at this stage.

A second and related point is that spot market transactions for purchasing powder coating may not be the most cost effective strategy in the long run. Powder chemistries can be manipulated in ways to reduce their costs (for example, adding extenders or using heavy metals) but which also reduce their coverage, technical effectiveness, or compliance with environmental standards. These manipulations may also not be immediately apparent. Ensuring that the powder chemistry meets the needs of the product manufacturer and their customers is important in successful adoption of powder coating substrates in specific product markets. A relational corporate strategy with well-established powder coating companies should be strongly considered to avoid high monitoring and oversight costs.

Challenges of the Chinese Market

CGGC conducted phone interviews with industry experts and extensively reviewed material on the history and development of the powder coating market for its report on the US and European markets. During our interviews and review of written material, we discovered what the industry sees as challenges specific to the Chinese market. We touch on those issues here.

Consistent powder quality

Specialty pigments and additives are expensive and provide incentives for the increased use of powder coating extenders. This reduces the cost of powder coating but also reduces the area that can be covered by a quantity of powder. Substitution of environmentally compliant powder inputs with cheaper heavy metals such as lead also has been reported. “Sometimes the Chinese will play a shell game,” stated one industry insider. “They send you a sample of their powder and it tests great. Then, once you get your product, you realize that it has no relation to the sample they sent.” The effect is increased monitoring and testing costs.

Importing additives and equipment

“The Chinese just won’t import” stated one industry expert. “For example, if they need titanium dioxide as pigment or additive and have to import it from overseas, they’ll find some way around it or just go without.” UN Comtrade data show, however, that China imported 67 million kilograms of titanium dioxide at a value of more than $124 million (USD) in 2007. The perception still exits, however, that China is not as open to imports necessary to producing high-end powder coatings as it could be. A second, related issue is the importation of specialized powder manufacturing equipment components and high-end powder coating application equipment.

Limited chemistries

As a percentage of total production, the domestic Chinese powder coating manufacturing industry is more specialized in pure epoxy and polyester-TGIC powder coatings than the world at large. TGIC-free powder coatings and epoxy-polyester hybrids are not produced as much in China than in the rest of the world, while polyurethanes and acrylics are about equal with world production [17]. The implication is that products needing these limited available powders should ensure the availability of the powders.

Limited product market experience

China has experience primarily in powder coating metal furniture and household appliances since the mid-1990s. These are relatively simple applications of powder coatings that do not require specialized knowledge of advanced chemistries, pre-treatment or curing methods. Learning methods appropriate to specific product markets will be important for China to move to powder coating higher value items.

Environmental standards and practices

Four areas of environmental concern are raised: the use of heavy metal inputs and carcinogenic curing compounds in powder coating chemistries, the use and release of toxic pretreatment chromates and phosphates, reliance on TGIC polyester, and limited environmental standards and practices in China regulating VOCs and waste emissions.

Understanding the importance of pre-treatment and application-appropriate powders

The pre-treatment phase is critical to any successful coating application, but especially for powder coatings. Concern has been repeatedly raised that pre-treatment of substrates sometimes does not adequately occur, either because of technological limitations or as a cost saving measure in China. A related issue is the use of powder coatings inappropriate to the use of the coated object, again either because of technological limitations or as a cost saving measure. The crux of the issue is that both types of errors only become apparent after the coating has been applied, sometimes after the coated product has been sold. The result is increased monitoring costs to ensure appropriate pre-treatment practices and powder chemistry selection.

Chinese powder coating market structure

The powder coating market structure is different in China than in the US and Europe. The most significant difference is that the powder coating manufacturing industry is highly diffuse in China when compared with the US and Europe. Over 2,000 powder coating manufacturers exist, and 98% of them are SMEs with production levels under 1,000 metric tons per year. Only 40 companies in China produce more than 1,000 metric tons per year, of which the 10 large foreign firms produce 20% (142,000 metric tons) of Chinese powder coatings each year, with the largest three producing 100,000 metric tons per year. Other foreign-owned powder coatings firms sharing 42,000 metric tons of annual production are: Valspar, PPG, Orica, BASF, Jotun, Rohm Haas, Tiger Werke, and 3M. Foreign firms have also increased their Chinese market share through mergers and acquisitions. Nippon Paint and Dow Chemical are recent examples of M&A activity in the Chinese powder coating market [17].

Very large manufacturing firms (both domestic and foreign) typically coat their items in-house rather than sending them to job coaters, although an extensive network of job coaters (usually SMEs coating for domestic production) exists.

China also has a large and well developed powder coating manufacturing equipment market. Only 10 of the roughly 600 powder coating manufacturing equipment purchased annually during 2006 in China were imported from abroad [17]. Most of the powder manufacturing equipment is produced in Yantai, Shandong Province. Domestic powder coating manufacturing equipment suppliers include: Hkorl Machinery Co, Yantai Sanli Machinery, Donghui Powder Processing Equipment, and Yantai Ling Yu Powder Processing [17]. Some limitations exist, however, on technologically advanced components for manufacturing equipment.

Domestic production of powder application equipment (booths, guns, integrated and automated powder lines) is more limited than the manufacturing side, particularly in mid-to-high end application equipment that needs to be imported from oversees. Major suppliers are ITW Gema, Wagner, Nordson, and Sames. Domestic producers of medium-to-low-end coating equipment are Yutung Engineering, Liush Machninery, and Fung Yu Group [17].

Nature of technological development

Technological development and adoption in China occurs to a greater extent in partnership with universities and technical institutes than in the US and Europe. Large foreign powder manufacturers have also developed R&D facilities to study and develop powder coating applications for advanced product markets. For example, Akzo Nobel opened the Powder Coatings Technology Center in Ningbo, Zhejiang province to further develop powder coating in automotive, architectural, furniture, domestic appliance, IT, and industrial end-product markets [41].

BIBLIOGRAPHY

[1] De Lange, P. (2004). "A History of Powder Coating" *Paint & Coatings Industry Magazine* Available online at:
http://www.pcimag.com/Articles/Feature_Article/2ad51878aa187010VgnVCM100000f932a8c0 (accessed 10/27/2009).

[2] Misev, T.A, and R. Van der Linde. (1998). "Powder Coatings Technology: New Developments at the Turn of the Century" *Progress in Organic Coatings*, Vol. 34, pp. 160-168.

[3] Lehr, D.W. (1991). Powder Coating Systems (McGraw-Hill, New York).

[4] Maty, J. (2004). "90 Years with PCI: A Retrospective" *Paint & Coatings Industry Magazine*, 20:11 (November), pp. 28-29.

[6] Gribble, P. (1990). "A History of Powder Coating" *in* Seymour, R. and H. Mark (eds). Organic Coatings: Their Origin and Development (Elsevier, New York), pp. 315-321.

[7] Richart, D.S. (1990). "Powder Coating -- Past, Present and Future: A Review of the State of the Art", *Powder Coating*, Vol1:1 (September), pp.16-24.

[8] Kiefer, S.L. (2004). "Powder Coating Material Developments Promise New Opportunities for Finishers" *Metal Finishing*, (January), pp. 35-37.

[9] Brown, J. (1991) Modern Manufacturing Process, (Industrial Press, New York).

[10] Pietchmann, J. and H. Jehn. (2000) "Powder Coatings, Pre-treatment and Quality Controls of Aluminum for Architectural Applications", *Galvanotechnik* Vol 91:9, pp.2560-2567.

[11] Vratsanos, L. (2002). "Meeting the Challenge of Reformulating for the Future", *Journal of Coating Technology*, Vol. 74:929 (June), pp. 61-65.

[12] Azzam, H., (2009). "History of Powder Coating in the United States" Available online at
http://modeanindustries.com/resources/history-of-powder-coatings/ (Accessed 10/27/2009).

[13] unknown author (1994). "Automotive Applications for Powder Coatings", *Paint & Coatings Industry*, (September), pp. 49-54.

[14] Lovano, S. (1996). "Automotive Applications for Powder Coating" *Metal Finishing* (September), pp. 20-24.

[15] Hartings, M.T. (1992). "Liquid to Powder: An Investment for Style and Quality" The Power of Powder: Powder Coatings 1992 Conference Proceedings, (October), (Powder Coating Institute: Alexandria, VA) pp. 129-137.

[16] Timmermann, E.H. (1993) "Changes in the Field of Industrial Electro Powder Coating" (May) *in* IEE, Colloquium on Electrostatic powder coating - latest developments in powder equipments and application" (IEE Press, London), pp. 5/1-5/6.

[17] Shuquan, L. (2008). "China: Powder Coatings Industry" US Department of Commerce Commercial Service, Jul. 2008 Available online at:
http://www.statusa.gov/mrd.nsf/vwNoteIDLookup/NT000AEEFE/$File/X_1662893.PDF?OpenElement
(Accessed 10/27/2009).

[18] Akzo Nobel (1999). "Complete Guide to Powder Coatings", Issue 1 (November) Available online at:
www.interpon.com/NR/rdonlyres/.../GuidetoPowderComplete.pdf (Accessed 10/27/2009).

[19] Allsop, R. (2006). "The Real Cost of Downtime" *Powder Finishing Online* (November) Available online at: http://www.pfonline.com/articles/pfdnordson01.html. (Accessed 10/27/2009).

[20] Hand, K. (2008). "The 2008 Coating Survey" *Powder Finishing* (December) pp. 22-29. Available online at: http://www.pfonline.com/articles/120802.html (Accessed 10/27/2009).

[21] Interpon (1999). "Concise Guide to Powder Coatings", (April) Available online at: http://www.interpon.com/en/Guide+To+Powder+Coatings/Concise+Guide.htm (Accessed 10/27/2009).

[22] Stearns, P.L. (2003). "Powdering up for a Quality Look", *Ward's Auto World*, (August), p. 41.

[23] Brooke, L. (1994). "A New Coat of Paint" *Automotive Industries*, (March), p. 35.

[24] DeWitt, C.M. (1995). "A Holistic Approach to Automotive Powder Coating", MIT Master's Thesis.

[25] Kettley, J.C. (1992). "New Developments in Powder Coating" The Power of Powder: Powder Coatings 1992 Conference Proceedings, (October), (Powder Coating Institute: Alexandria, VA) pp. 41-60.

[26] Biller, K. (2006). "OEM Automotive Powder Coating", *PCI Magazine* Available online at: http://www.pcimag.com/Articles/Feature_Article/cbf6aeb98e85c010VgnVCM100000f932a8c0 (Accessed 10/27/2009).

[27] Harrison, A. (1988). "Tough, Highly Flexible Powder Coatings for Pre-coat Application", Presented at the SME Finishing West Conference (September) *in* Dawson, S. and R. Vishu (eds) (1990) Powder Coating Applications (Society of Manufacturing Engineering, Dearborn, MI), pp. 57-64

[28] USEPA (2008). "History of the Clean Air Act" available at www.epa.gov/air/caa/caa_historical.html (Accessed 10/27/2009).

[29] Bailey, J. (1994) "Where Paint Meets the Environment", *Industrial Paint & Powder*, (November), p. 14.

[30] Osmond, M.F., (1990) "Powder coating the building sector - current trends" *in* Dawson, S. and R. Vishu (eds) (1990) Powder Coating Applications (Society of Manufacturing Engineering, Dearborn, MI), pp. 57-64

[31] Muhlenkamp, M., (1988) "High-performance Powder Coating for Aluminum", *in* Dawson, S. and R. Vishu (eds) (1990) Powder Coating Applications (Society of Manufacturing Engineering, Dearborn, MI), pp. 74-76.

[32] CGGC Staff Interview with Rodger Talbert, Powder Coating Institute *Technical Director*, 9/25/2009

[33] CGGC Staff Interview with Sidney Harris, Editor, *Focus on Powder Coating*, 9/25/2009.

[34] CGGC Staff Interview with Peter Gribble, former technical director of powder coatings at Glidden, Ferro Corp. and Seibert Powder Coatings, 9/25/2009.

[35] Cantor, B., F. Dunne and I. Stone (2004) "Metal and Ceramic Matrix Composites: An Oxford-Kobe Materials Text" (IOP Publishers, Bristol, UK) 2004.

[36] CGGC Staff Interview with Sam Ruscio, Owner/Operator of Tecnital S.eC (Italy), 9/30/2009.

[37] BCC Report (2009) "Powder Coatings: Materials, Technologies, Applications" (January) available online at: http://www.bccresearch.com/report/CHM051A.html. (Accessed 10/27/2009).

[38] Houston, S. (2009) *Executive Director Report*, Powder Coating Institute (May).

[39] 1963 Berne Accords, "Agreement Concerning the International Commission for the Protection of the Rhine against Pollution" available at http://www.ecolex.org/server2.php/libcat/docs/multilateral/en/tre000484.txt (accessed 10/27/2009)

[40] Gereffi, Gary (1999). "A Commodity Chains Framework for Analyzing Global Industries" *Mimeo* available at http://mgtclass.mgt.unm.edu/DiGregorio/cidesi/mexico/gereffi%201999%20global%20value%20chain.pdf (accessed 10/27/2009).

[41] "AkzoNobel Opens Powder coatings Technology Centre in China" *Focus on Powder Coatings*, Vol. 2009, Issue 18 (August 2009), p.5.

[42] Barberich, B. (2004). "Application of Color Powder Paint in the Automotive Industry", MIT Master's Thesis.

[43] SpecialChem4Coatings (2009). "Powder Coating Center." Available online at http://www.specialchem4coatings.com/tc/powder-coatings/ (accessed 2/15/2010).

[44] Busato, Franco (1998). "Development Trends in Powder Coatings for the Twenty-first Century" *Powder Coating Magazine* (February).