GUIDE TO CLEAN TECHNOLOGY

ORGANIC COATING REPLACEMENTS

May 15, 1992

United States Environmental Protection Agency

NOTICE

This *Guide to Clean Technology: Organic Coating Replacements* summarizes information collected from U.S. Environmental Protection Agency programs, peer reviewed journals, industry experts, vendor data, and other sources. The original Quality Assurance/Quality Control (QA/QC) procedures for the reports and projects summarized in this guide range from detailed, reviewed Quality Assurance Project Plans to standard industrial practice. Publication of the guide does not signify that the contents necessarily reflect the views and policies of the U.S. Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

This document is intended as advisory guidance in identifying new approaches for pollution prevention through organic coating replacements. Final selection of a technology will be shop- and process-specific and, therefore, will be done by the individual users of organic coatings. Compliance with environmental and occupational safety and health laws is the responsibility of each individual business and is not the focus of this document.

FOREWORD

Today's rapidly developing and changing technologies and industrial products and practices frequently carry with them the increased generation of materials that, if improperly dealt with, can threaten both public health and the environment. The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. These laws direct the U.S. EPA to perform research to define our environmental problems, measure the impacts, and search for solutions.

Reducing the generation of hazardous solvents at the source or recycling the wastes on site will benefit industry by reducing disposal costs and lowering the liabilities associated with hazardous waste disposal.

Publications in the U.S. EPA series, *Guides to Pollution Prevention*, provide an overview of several industries and describe options to minimize waste in these industries. Their focus is on the full range of operations in existing facilities. Many of the pollution prevention techniques described are relatively easily implemented into current operations without major process changes.

This *Guide to Clean Technology: Organic Coating Replacements* summarizes new commercially available and emerging technologies that prevent and/or reduce the production of hazardous materials during coating replacement. The technologies described in this document and other documents in this series are generally "next generation" clean technologies that often, but not always, represent relatively major process changes, high levels of training, and high capital investments compared to the technologies described in the *Guides for Pollution Prevention*. The waste minimization techniques characterized in the *Guides for Pollution Prevention* should be considered and implemented first. Although some of the clean technologies described herein could be inserted into current operations, they should be considered primarily for major plant expansions or new grass roots facilities.

CONTENTS

SECTION 1

OVERVIEW

What Is Clean Technology?

A *clean technology* is a source reduction or recycling method applied to eliminate or significantly reduce hazardous waste generation. *Source reduction* includes product changes and source control. *Source control* can be further characterized as input material changes, technology changes, or improved operating practices.

Pollution prevention should emphasize source reduction technologies over recycling but, if source reduction technologies are not available, recycling is a good approach to reducing waste generation. Therefore, recycling should be used where possible to minimize or avoid waste treatment requirements when source reduction options have been evaluated and/or implemented.

The clean technology must reduce the quantity, toxicity, or both of the waste produced. It is also essential that final product quality be reliably controlled to acceptable standards. In addition, the cost of applying the new technology relative to the cost of similar technologies needs to be considered.

Why Use Organic Coatings?

The three major classifications of organic coatings based on end use are:

- Architectural coatings
- Industrial finish coatings
- Industrial maintenance coatings.

Architectural coatings are applied on site to interior or exterior surfaces of various buildings. They are applied for protection and appearance, and they cure at ambient conditions.

Industrial finish coatings are applied to factory-made articles during manufacture. Industrial maintenance coatings are field-applied high-performance coatings formulated to resist harsh environments such as heavy abrasion, water immersion, exposure to chemicals or solvents, and/or high temperatures. Alternative clean coating materials are available for all three types of use.

Paint and other coatings are applied to surfaces to enhance corrosion resistance, improve appearance, or both. Examples among the many industries that apply coatings include manufacturers of:

- Automobiles
- Aircraft
- Appliances
- Wood products.

The main functions of automotive coatings are appearance, durability, and corrosion protection. Typical automotive coatings use an undercoat or primer to give corrosion protection and improve durability. The topcoats are formulated to give the desired color and gloss. In some cases, the topcoat is of two or more different layers: a low-solids polyester coat to give the color covered by an acrylic clearcoat for a high gloss finish. Automotive coatings are normally applied on sheet steel, but body parts are increasingly being made from other materials such as plastic, composite, or stainless steel.

The main functions of aircraft coatings are to resist corrosion, fluids and fuels, erosion, temperature extremes, weathering, and impact. Coatings may also assist in providing protection for lighting strike. Coatings must also give the desired appearance. Appearance may be entirely cosmetic or, in the case of combat aircraft, serve as camouflage. Aircraft finishes may be applied over aluminum, titanium, composite, or other substrates.

Appliances are often referred to as "white goods" due to the traditional color of the coating applied. However, a wide variety of colors are now applied to appeal to consumer tastes. Coatings are applied to protect the underlying metal from water, salt, detergent, and other common corrosive agents at temperatures in the range of about 0°C to 100°C. The substrate is typically steel sheet.

Wood products such as furniture, siding, and doors are coated to increase durability and improve appearance. Exterior coatings must have greater weather resistance than coatings on items intended for interior use. Color or clear coatings may be chosen depending on the type and quality of the wood substrate and the intended end use.

In addition to the specific examples discussed above, coatings are used in a wide variety of other industries and applications. The coatings may provide temporary or long-term protection of wood, metal, and plastic surfaces. This wide range of applications indicates the cross-industry applicability of clean coating material technology.

Pollution Problem

Classical organic coating materials are dilute solutions of organic resins, organic or inorganic coloring agents, additives, and extenders dissolved in an organic solvent. The organic solvent gives the coating fluid the necessary viscosity, surface tension, and other properties to allow application of a smooth layer of liquid coating solution.

The liquid coating is brushed, rolled, sprayed, flowed, or otherwise applied to the surface. As the organic solvent evaporates, the organic resins polymerize to form the desired dry film.

Environmental concerns and increasing costs of organic chemicals and transition metals are leading to changes in the formulation of organic coatings. Coating makers and users are seeking alternative materials to reduce or eliminate waste of hazardous solvents and paint residues, particularly coatings using pigments containing metal compounds.

Typical coating solvents include methyl ethyl ketone, methyl isobutyl ketone, toluene, and xylene. The coloring agents can be inorganic pigments containing hazardous metals such as cadmium, chromium, and lead. Mercury chemicals have been used as a paint preservative, although this use is declining. This guide describes application of clean technologies for replacement coating materials that eliminate or reduce solvent use. In many cases, the new coating also reduces paint waste, which in turn reduces waste of hazardous metals.

Solution

Coating technology relies on covering a substrate material with an organic film having the desired protective, mechanical, optical, aging, and adhesion properties. Conventional organic coating technology uses dilute solutions of alkyd, polyester, epoxy, polyurethane, acrylic, vinyl, or other resins in a volatile organic solvent. Not too many years ago coating materials relied on organic solvents to promote desired flow characteristics so the coating could be applied. The solvent would then evaporate allowing the resins to polymerize and cure to form the dry coating. Recent years have seen expanded use of clean technologies.

Clean technologies based on physical methods now exist for materials that reliably apply coatings but which contain little or no volatile organic solvent. There are four general classes of clean technology for organic coating materials:

- 100% dry solids materials that completely eliminate the solvent by using a dry resin formulation
- 100% reactive liquids that use a liquid coating material but do not rely on any volatile organic solvent
- Water-dispersed or water-soluble polymer systems that substitute water for some or all of the volatile organic solvent

- High solids polymer systems that reduce the amount of organic solvent needed by increasing the concentration of reactive resin in the solvent.

The clean technologies can also prevent pollution by increasing the efficiency of use for the coating, thus reducing paint waste.

What's In This Guide?

This application guide describes **clean technologies that can reduce waste by the use of alternative organic coating materials.** The objectives of this application guide are to help identify potentially viable clean technologies to reduce waste by using alternative organic coating materials and to provide resources for obtaining more detailed engineering information about the technologies. We address the following specific questions:

- What alternative organic coating technologies are available or emerging that reduce or eliminate pollution?
- Under what circumstances might one or more of these alternative coating systems be applicable to your operations?
- What pollution prevention, operating, and cost benefits could be realized by adapting the technology?

Other Questions About Investment Decisions

Other aspects affecting the decision include:

- Might new pollution problems substitute for the old?
- Are tighter and more complex process controls needed?
- Will product quality and operating rates be affected?
- Will new operating or maintenance skills be needed?
- What are the overall capital and operating cost implications?

This guide covers several clean coating replacement systems that are applicable under different sets of product and operating conditions. If one or more are sufficiently attractive for your operations, the next step would be to contact vendors or users of the technology to obtain detailed engineering data and make an in-depth evaluation of its potential for your plant.

Who Should Use This Guide?

This guide is intended for plant process and system design engineers and for personnel responsible for process improvement and process design. Process descriptions within this guide allow engineers to evaluate options so that alternative coating materials can be considered for existing plants and factored into the selection of new coating materials.

Sufficient information is presented to select one or more candidate technologies for further analysis and in-plant testing. This guide does not recommend any technology over any other. It presents concise summaries of applications and operating information to support preliminary selection of clean technology candidates for testing in specific processes. The level of detail allows identification of possible technologies for immediate application to eliminate or reduce waste production.

A list of keywords is provided to help you quickly scan the technologies covered.

Keywords		
Clean Technology	Paint	Powder Coatings
Pollution Prevention	Coating	High Solids Coatings
Source Reduction	Powder coating	Water-Based Coatings
Source Control	Removal	Ultraviolet (UV) Radiation-Cured Coatings
Recycling	Stripping	Electron Beam (EB)-Cured Coatings
	Depainting	Radiation-Induced, Thermally Cured Coatings
	Debonding	Two-Component Reactive Liquid Coatings
		Water-Based Temporary Protective Coatings
		Vapor Permeation- or Injection-Cured Coatings
		Supercritical CO_2 as Solvent

Summary of Benefits

The clean technologies described in this guide are divided into two groups based on their developmental maturity – commercially available technologies and emerging technologies in advanced pilot plant testing.

Table 1 summarizes the pollution prevention, operational, and economic benefits of organic coating replacement technologies.

You may wish to scan this summary table to select those clean technologies that best fit your operations and needs. Detailed discussions of these benefits and operational aspects for each clean technology are provided in the next two sections of this document.

Table 1. Summary of Benefits of the Clean Technologies for Organic Coating Replacements

Benefits	Available Technologies				Emerging Technologies					
	Powder Coatings	High Solids Coatings	Water-Based Coatings	Ultraviolet (UV) Radiation-Cured Coatings	Electron Beam (EB)-Cured Coatings	Radiation-Induced Thermally Cured Coatings	Two-Component Reactive Liquid Coatings	Water-Based Temporary Protective Coatings	Vapor Permeation- or Injection-Cured Coatings	Supercritical Carbon Dioxide as Solvent
Pollution Prevention:										
Eliminates solvent in coating	●			●	●	●	●		●	
Reduces solvent in coating		●	●					●		●
Reduces solvent for cleaning	●		●					●		
Operational:										
Easy color blending		●	●	●	●	●	●	●	●	●
Easy color change		●	●	●	●	●	●	●	●	●
Can apply thick coat	●	●	●		●	●	●	●		●
Can apply thin coat		●	●	●	●	●	●		●	●
Economic:										
Relatively low or medium capital cost		●	●					●		
Relatively low or medium skill to operate	●	●	●					●		●

SECTION 2

AVAILABLE TECHNOLOGIES

How to Use the Summary Tables

Four available organic coating replacement technologies are evaluated in this section:

- Powder coatings
- High solids coatings
- Water-based coatings
- Ultraviolet (UV) radiation-cured coatings.

Tables 2 and 3 summarize descriptive and operational aspects of these technologies. They contain evaluations or annotations describing each available clean technology and give users a compact indication of the range of technologies covered to allow preliminary identification of those technologies that may be applicable to specific situations. Readers are invited to refer to the summary tables throughout this discussion to compare and contrast technologies.

Descriptive Aspects

Table 2 describes each available clean technology. It lists the **Pollution Prevention Benefits**, **Reported Applications**, **Operational and Product Benefits**, and **Hazards and Limitations** of each available clean technology.

Operational Aspects

Table 3 shows key operating characteristics for the available technologies. These characteristics serve to qualitatively rank the clean technologies relative to each other. The rankings are estimated from descriptions and data in the technical literature.

Process Complexity is qualitatively ranked as "high," "medium," or "low" based on such factors as the number of process steps involved and the number of material transfers needed. **Process Complexity** is an indication of how easily the new technology can be integrated into existing plant operations. A large number of process steps or input chemicals, or multiple operations with complex sequencing, are examples of characteristics that would lead to a high complexity rating.

The **Required Skill Level** of equipment operators also is ranked as "high," "medium," or "low." **Required Skill Level** is an indication of the relative level of sophistication and training required by staff to operate the new technology. A technology that requires the operator to adjust critical parameters would be rated as having a high skill requirement. In some cases, the operator may be insulated from the process by complex control equipment. In such cases, the operator skill level is low but the maintenance skill level is high.

Table 3 also lists the **Waste Products and Emissions** from the available clean technologies to indicate tradeoffs in potential pollutants, the waste reduction potential of each, and compatibility with existing waste recycling or treatment operations at the plant.

The **Capital Cost** column provides a preliminary measure of process economics. It is a qualitative estimate of the initial cost impact of the engineering, procurement, and installation of the process and support equipment. Due to the diversity of data and the wide variation in plant needs and conditions, it is not possible to give specific cost comparisons. Cost analyses must be plant-specific to adequately address factors such as the type and age of existing equipment, space availability, throughput, product type, customer specifications, and cost of capital. Where possible, sources of cost data are referenced in the discussions of each clean technology.

The **Energy Use** column provides data on energy conversion equipment required for a specific process. In addition, some general information on energy requirements is provided.

Table 3 also lists **References** to publications that will provide further information for each available technology. These references are given in full in Section 4.

The text further describes pollution prevention benefits, reported applications, operational and product benefits, and hazards and limitations for each available technology. Technologies in earlier stages of development are summarized to the extent possible in Section 3, Emerging Technologies.

Table 2. Available Clean Technologies fo[illegible]ganic Coating Replacements: Descriptive Aspects

Available Technology	Pollution Prevention Benefits	Reported Applications	Operational and Product Benefits	Hazards and Limitations
Powder Coatings	• 100% reactive solid • Eliminates solvent use and exposure of workers to solvents • Reduces need for disposal of solid paint waste • Reduces fire and explosion hazards	• Applied to general appliances, automotive, and general industrial finishing such as: – steel – aluminum – zinc and brass castings	• Can apply thick coatings in one application • Lack of volatile solvent means little air flow needed • Reduced energy use for heating makeup air • No mixing or stirring needed • Cleanup requires no solvent • Allows coating with polymers that are not amenable to solution coating techniques • Efficient material use (near 100% transfer efficiency)	• Requires handling of heated parts • For electrostatic application systems, – the part must be electrically conductive or be covered with an electrically conductive primer – parts with complex shapes are difficult to coat • Some difficulty in applying thin coatings • Difficult to incorporate metal flake pigments • Requires specialized equipment or extra effort to make color changes
High Solids Coatings	• Solvent-based with high resin concentration • Reduces solvent in the coating, but solvent still needed for cleanup	• Same as conventional coatings; resins available in formulations include: – saturated polyesters – alkyds – acrylics – polyurethane – epoxy • Used on zinc-coated steel doors, miscellaneous metal parts	• Reduced solvent concentrations in the coating, thus reducing the environmental, odor, and safety problems caused by solvents • Compatible with conventional and electrostatic application equipment and techniques • Lower solvent loadings allow reduced air flow in curing ovens and work spaces, thus decreasing energy needed for heating	• Solvent use not completely eliminated • Shorter pot life than conventional coatings
Water-Based Coatings	• Water-based with low solvent concentration • Eliminates or reduces solvent use • Water used for cleanup	• Wide range of application • Coating formulations include acrylics; colloids; amine-solubilized, carboxyl-terminated alkyds; and polyesters • Used for architectural trade finishes, wood furniture, and damp concrete surfaces	• Low odor levels • Easy to clean (uncured coating can be cleaned up with water) • Reduce solvent concentrations • Existing application equipment (nonelectrostatic) can be used with most water-based coatings • Reduced air flow in curing ovens and work spaces decreases energy needed for heating	• Coating flow properties and drying rates can change with humidity affecting coating application • Sensitive to humidity, and thus require humidity control in application and curing areas • High surface tension of water can cause poor coating flow characteristics • Special equipment needed to allow electrostatic application • Water in the formulation can cause corrosion of coating storage tanks and transfer piping, and "flash rusting" of metal substrates under the coating • Most require careful cleaning of the substrate to ensure oil and grease are removed • Resins in contact with water degrade, reducing shelf life • Susceptible to foaming due to surfactants
Ultraviolet (UV) Radiation-Cured Coatings	• 100% reactive liquid • Eliminates or reduces solvent in the coating, but solvent still needed for cleanup	• Wood • Some metal applications • Filler for chipboard • Used for 'wet look' finishes	• Efficient material use (near 100% transfer efficiency) • Lack of volatile solvent means little air flow needed • Low-temperature processing (reduced energy use for heating makeup air) • Rapid curing	• Styrene volatility • Yellow color • High capital cost of equipment • Limited to thin coatings, particularly with pigments present • Typically best applied to flat materials

Table 3. Available Clean Technologies for Organic Coating Replacements: Operational Aspects

Available Technology Type	Process Complexity	Required Skill Level	Waste Products and Emissions	Capital Cost	Energy Use	References
Powder Coatings	Medium	Medium	• Uncured powder can be collected for reuse	High	Low	Bowden, 1989 Crump, 1991 Fish, 1982 Hester and Nicholson, 1989 Ingleston, 1991 Maguire, 1988 Muhlenkamp, 1988 Robison, 1989
High Solids Coatings	Low	Medium	• Overspray loss similar to that of conventional coatings	Low	Medium	Dick, 1991 MP&C, 1988 Nelson, 1988 Paul, 1986 Pilcher, 1988 Smith, 1990
Water-Based Coatings	Medium	Medium	• Overspray loss similar to that of conventional coatings • Amenable to electrocoating, which gives very high resin use	Medium	Medium	Dick, 1991 MP&C, 1988 Paul, 1986 Pilcher, 1988 Product Finishing, 1986 Richardson, 1988 Scharfenberger, 1989 Swanberg, 1990
Ultraviolet (UV) Radiation-Cured Coatings	High	High	• Unreacted overspray can be collected for reuse	High	Low	Danneman, 1988 Dick, 1991 Keipert, 1990 Paul, 1986 Sun Chemical, 1991

POWDER COATINGS

Pollution Prevention Benefits

Powder coating uses 100% reactive resin in dry powdered form, thus eliminating the use of a volatile organic solvent and reducing solvent exposure to workers and fire and explosion hazards. High transfer efficiency and low coating waste reduce the amount of solid paint waste requiring treatment or disposal.

Powder coating has two attractive features from both a cost and pollution prevention standpoint:

- The total lack of solvent in the coating formulation
- The ability to apply essentially all of the coating to the substrate.

Material is applied to the surface as a dry powder and is then melted or reacted to form the coating. There is no need for a volatile solvent to provide a fluid medium. The powder is fluidized either by air flow up through a bed or by an electrostatic airspray gun. Because no solvent is needed to carry the coating, solvent evaporation is eliminated. Further, the coating equipment can be cleaned without the use of solvents.

For example, a conventional plant painting 12,000,000 ft^2/yr with a 1.2-mil-thick coat will produce about 38 tons per year of VOC emissions after a treatment system with a capture efficiency of 70%. A powder coating system using electrostatic application of polyester-urethane material will emit about 0.6 tons per year with no VOC control equipment in use (Hester and Nicholson, 1989).

How Does It Work?

In powder coating, a coating film is formed by applying a layer of dry powdered resin on the surface to be covered and then melting the powder. Either thermoplastic powders such as cellulose acetate butyrate, polyesters, polyamides, and polyolefins or thermosetting powders such as epoxy resins, acrylics, and polyesters can be applied. Thermoplastic powders are usually applied with a fluidized bed, whereas thermosetting powders are mainly applied by electrostatic spray.

A thermoplastic powder coating is one that melts and flows when heat is applied, but continues to have the same chemical composition once it cools and solidifies. Thermoplastic powders are based on high-molecular-weight polymers that exhibit excellent chemical resistance, toughness, and flexibility. These resins tend to be difficult to grind to the consistent fine particles needed for spray application, and they have a high melt viscosity. Consequently, they are used mostly in thicker film applications and are applied mainly by the fluidized bed application technique. Typical thermoplastic powder coatings include:

- Polyethylene powders
- Polypropylene powders
- Nylon powders
- Polyvinyl chloride powders
- Thermoplastic polyester powders.

Thermosetting powder coatings are based on lower molecular weight solid resins. These coatings melt when exposed to heat, flow into a uniform thin layer, and chemically cross-link within themselves or with other reactive components to form a higher molecular weight reaction product.

The final coating has a chemical structure different from that of the basic resin. These newly formed materials are heat stable and, after curing, do not soften back to liquid phase when heated. Resins used in thermosetting powders can be ground into very fine particles necessary for spray application and for applying thin, paint-like coatings. Because these systems can produce a surface coating that is comparable to, and competes with, liquid coatings, most of the technological advancements in recent years have been with thermosetting powders. Thermosetting powders are derived from three generic types of resins, i.e., epoxy, polyester, and acrylic. From these three basic resin types, five coating systems are derived. Epoxy resin-based systems are the most commonly used thermosetting powders and are available in a wide range of formulations (Hester and Nicholson, 1989).

Powder coating uses conventional equipment available from a wide variety of vendors.

Why Choose This Technology?

Applications

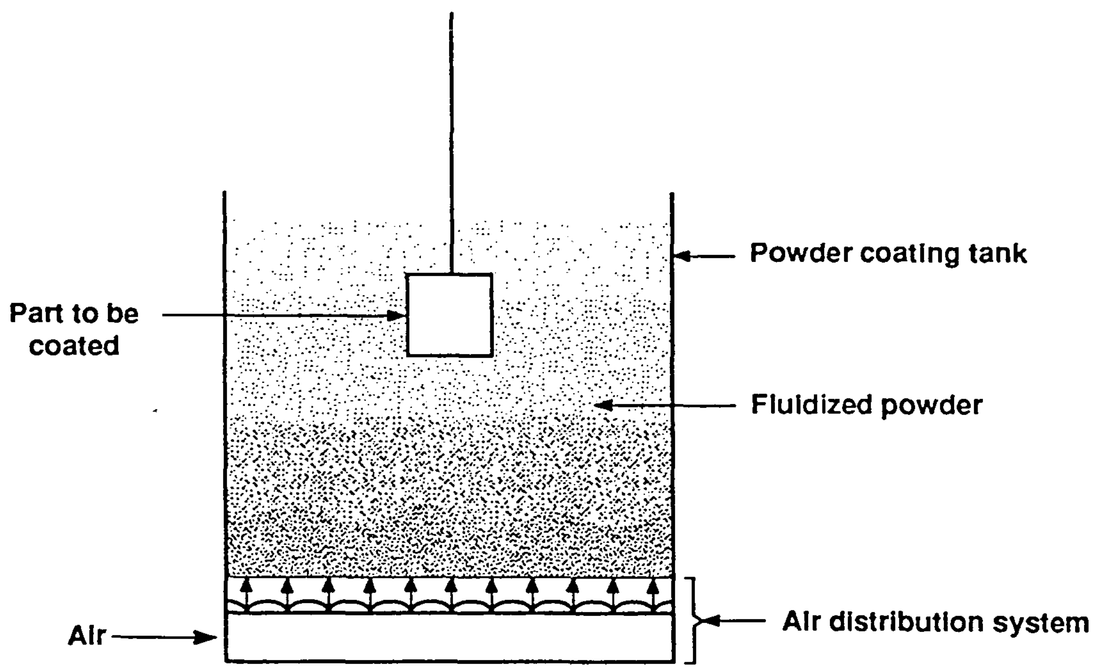
Powder coating is applied in thick coatings of thermoplastic materials or medium-thickness coatings of thermosetting materials to substrates in a single operation.

Operating Features

The part being coated must be heated either before immersion in a fluid bed or in an oven after the powder is applied. As a result, the part must be of a size and shape to allow immersion coating or heating in a curing oven. In all cases, the part must be heated above the melting temperature of the resin and thus be able to withstand temperatures of 90°C and higher.

Basic Function. Fluidized bed systems are used to apply coatings of thermoplastic powders to thicknesses in the range of 10 to 30 mils. In fluidized bed application, a preheated solid substrate is immersed in a fluidized bed of thermoplastic powder.

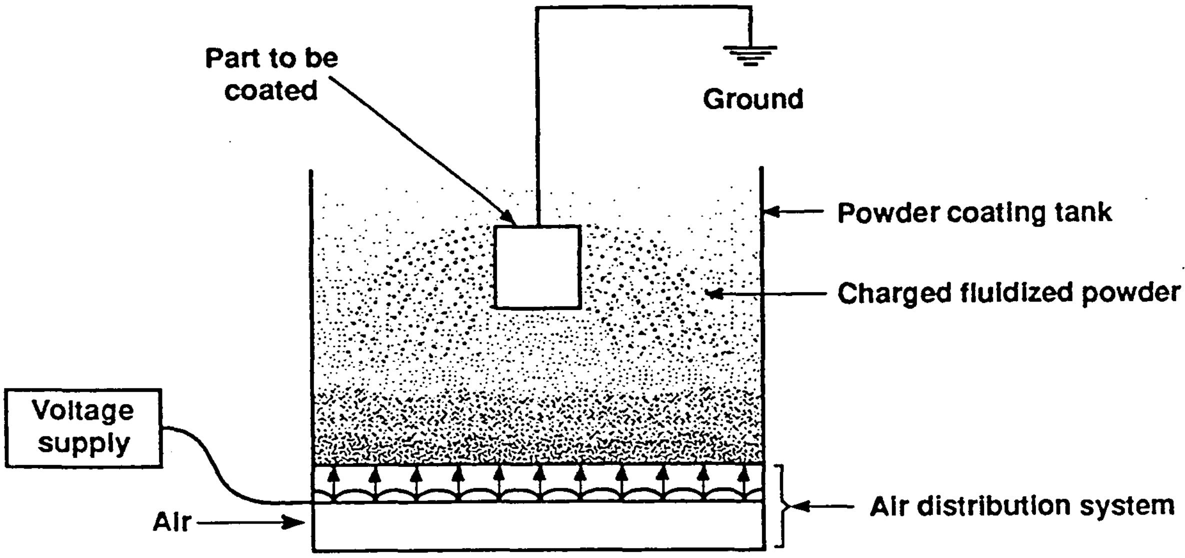
As indicated in the schematic diagram (Figure 1), air is introduced at the bottom of a bed of powder to fluidize the mass. The substrate temperature is adjusted to be higher than the melting point of the resin so, as particles strike the hot surface, they melt and coalesce to form a thin, continuous film on the substrate. As the part cools, the powder solidifies to form a coating. The fluidized bed method was the original method for applying powder coatings and is still favored for heavy functional coatings.



Source: Battelle

Figure 1. Powder Coating in a Fluidized Bed.

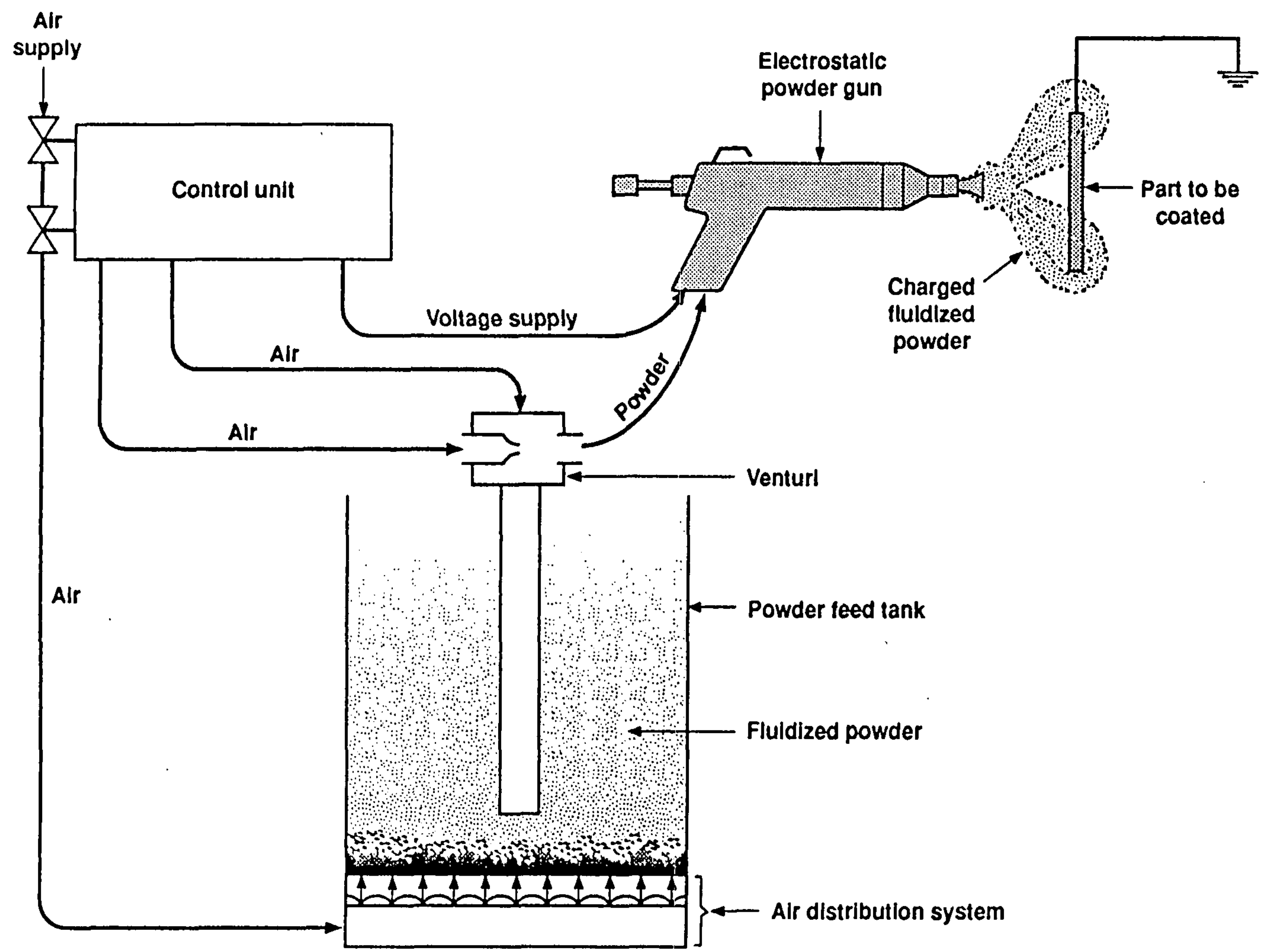
Electrostatic applications in either a fluidized bed (Figure 2) or by electrostatic spray (Figure 3) can achieve coatings thicknesses in the range of 1 to 3 mils with thermosetting resins. Electrostatic fluidized beds are limited to an effective depth of about 2 to 3 in so that they are best suited to coating two-dimensional parts (Muhlenkamp, 1988).



Source: Battelle

Figure 2. Powder Coating in an Electrostatic Fluidized Bed.

In electrostatic applications, the dry powder is applied to the unheated substrate as film of powder held in place by electrostatic forces. The substrate or a primer coat must be electrically conductive. The substrate, with powder coating, is then heated in an oven to melt and cure the coating. Additional polymerization and cross-linking occurs in the ~~thermoplastic~~ material during curing.
thermosetting



Source: Battelle

Figure 3. Schematic for Electrostatic Spray Gun for Powder Coating.

With spray systems, powder is supplied to the spray gun by the powder delivery system. This system consists of a powder storage container or feed hopper, a pumping device that transports a stream of powder into hoses or fed tubes. A compressed air supply is often used as a "pump" because it aids in separating the powder into individual particles for easier transport. The powder delivery system is usually capable of supplying powder to one or several guns, often located many feet from the powder supply. Delivery systems are available in many different sizes depending on the application, number of guns to be supplied, and volume of powder to be sprayed in a given time period. Recent improvements in powder delivery systems, coupled with better powder chemistries that reduce clumping of the powder, have made possible the delivery of a very consistent flow of particles to the spray gun. Agitating or fluidizing the powder in the feed hopper also helps prevent clogging or clumping of the powder prior to its entry into the transport lines.

Electrostatic powder guns function to shape and direct the flow of powder; control the pattern size, shape, and density of the powder as it is released from the gun; impart the electrostatic charge to the powder being sprayed; and control the deposition rate and location of powder on the target. All spray guns can be classified as either manual (hand-held) or automatic (mounted on a mechanical control arm) the basic principles of operation of most guns are the same; there is an almost limitless variety in the style, size, and shape of spray guns. The type of gun chosen for a given coating line can, thus, be matched to the performance characteristics needed for the products being coated.

Traditionally, the electrostatic charge was imparted to the powder particles by a charging electrode located at the front of the spray gun. These "corona charging" guns generate a high-voltage, low-amperage electrostatic field between the electrode and the product being coated. The charge on the electrode is usually negative and can be controlled by the operator. Powder particles, passing through the ionized electrostatic field at the tip of the electrode become charged and are thus directed by the electrostatic field. The particles follow the field lines and air currents to the target workpiece and are deposited on the grounded surface of the workpiece. One drawback to the use of this type of gun is the difficulty of coating irregularly shaped parts that have recessed areas of cavities (that may be affected by Faraday cages) into which the electrostatic field cannot reach. Because the powder particles are directed by the presence of the field, insufficient powder may be deposited on surfaces outside the reach of the field.

A relatively recent innovation in electrostatic spray guns is the triboelectric gun. The powder particles in a triboelectric gun receive an electrostatic charge as a result of friction which occurs when powder particles contact a solid insulator or conductor inside the delivery hose and gun. The resulting charge is accomplished through the exchange of ions, or electrons, between the powder and the material used for construction of the supply hose and gun barrel. Because there is no actual electrostatic field, the charged particles of powder migrate toward the grounded workpiece and are free to deposit in an even layer over the entire surface of the workplace. With the elimination of an electrostatic field, the Faraday cage effect can be prevented.

Other improvements that have been made to spray guns involve variations in the spray patterns to improve the coating transfer efficiency. Nozzles that resist clogging have been introduced. Spray guns with variable spray patterns are also available to allow the use of one gun on multiple parts of different configurations.

Innovations in the powder delivery system allow the powder supply reservoir to be easily switched to another color when necessary. However, if the overspray collection system is not also changed, the collected powder will be is a combination of all the colors applied between filter replacements or booth cleanings. For collected oversprayed powder to be of greatest value, it should be free of cross-contamination between colors. When a pellet of the wrong color adheres to the part being powder coated, it will not blend in with the color being used.

Numerous systems are now available that are designed to accomplish this segregation of colors and still allow several colors to be applied in the same booth. Most of these systems make use of a moveable dry filter panel or a cartridge filter that can be dedicated to one color and can be removed easily when another color is needed. Color changes can then be accomplished by disconnecting the powder delivery system and purging the lines, cleaning the booth with compressed air or a rubber squeegee, exchanging the filter used for the previous color with the filter for the next color, and connecting the powder delivery system for the new color.

Equipment manufacturers have made significant design improvements in spray booths that allow color changes to be made with a minimal downtime and allow the recovery of a high percentage of the overspray. As with spray guns, there are a large number of spray booth and powder recovery designs from which to choose, depending on the exact requirement of a given finishing system (Hester and Nicholson, 1989).

Material and Energy Requirements. The effectiveness of powder coating depends on obtaining a smooth, nonporous film. Formation of a good coating free of voids, pinholes, and orange peel depends on controlling the particle size distribution, glass transition temperature, melting point, melt viscosity, and electric properties of the powder.

A well-controlled size distribution is important to achieve good packing of the powder on the surface. Melting and melt flow properties are important to controlling the behavior of the powder as it melts to form the coating. The electric properties of the powder are important when the coating is applied by electrostatic spraying.

During fluid bed coating, powder is added to replace material carried out by the substrate. Because very little powder is lost or degraded during coating, material utilization is near 100%. With electrostatic spraying there is overspray of powder, much like overspray with liquid paint. However, unlike liquid paint overspray which cannot be recycled, powder coating overspray can be collected and reused. Figure 4 shows a schematic of a system for powder coating recycling. The high utilization of powder coating means waste paint solids disposal is reduced.

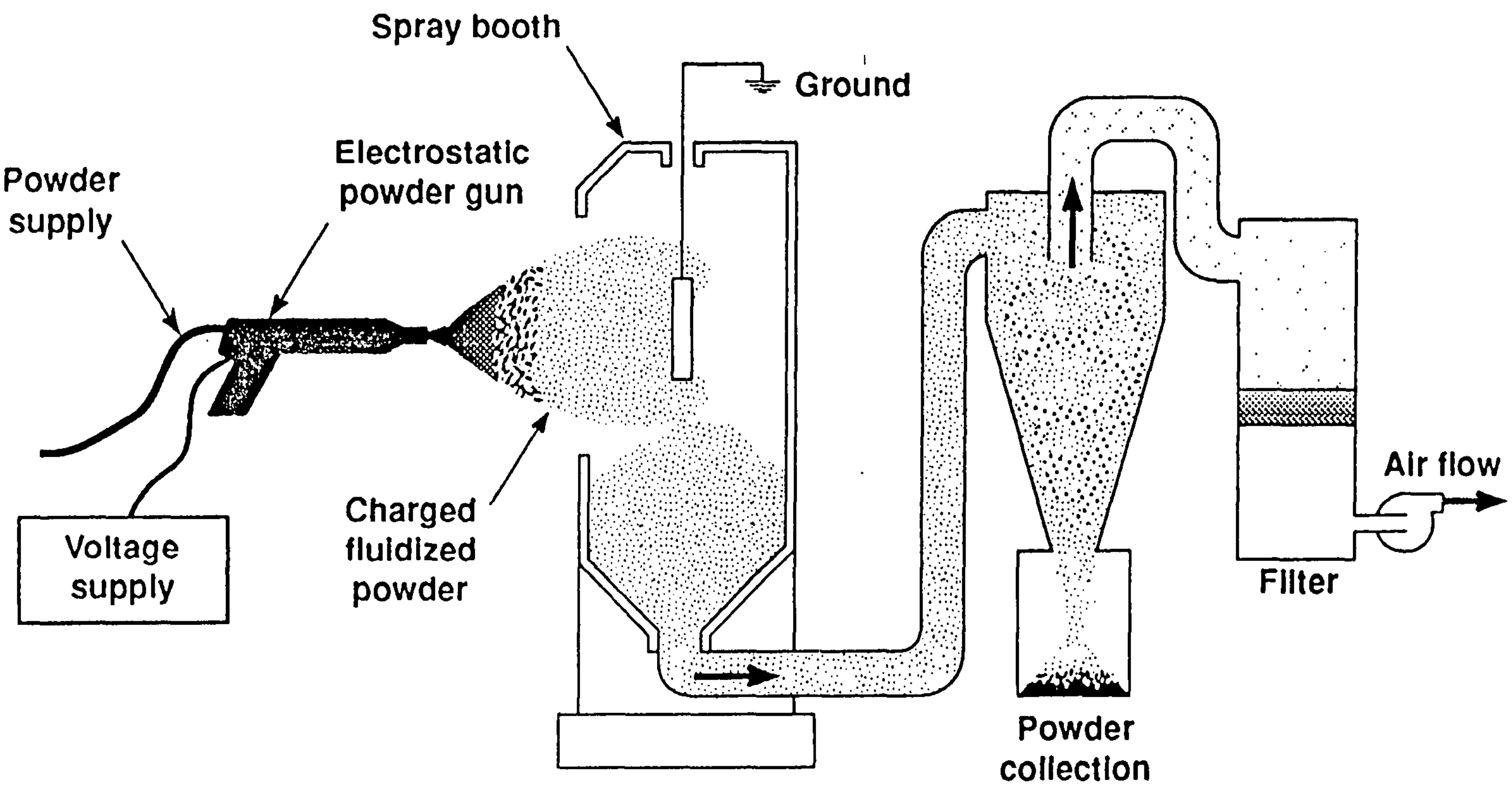
Required Skill Level

Powder coating uses equipment and techniques that are very similar to those for conventional dip coating or spray painting. The operator skill level is, therefore, similar to that for conventional electrostatic spray painting.

Cost

The capital cost for booths, electrostatic spray applicators, and curing ovens to apply powder coatings is typically somewhat higher than similar equipment for application of conventional fluid coatings. However, the conventional solvent-based coating application system may require equipment to control VOC emissions. VOC control equipment will significantly increase the capital cost for the conventional coating application system.

The powder coating material is more expensive than conventional coating material when compared on the basis of volume of reactive resin. However, the cost of the finished coating is lower for powder coating in many cases. The higher cost of the powder coating material is offset by the ability to effectively put essentially all of the



Source: Battelle

Figure 4. Powder Coating Recovery System.

reactive powder resin onto the substrate. Coating utilization efficiency for conventional coatings can be as low as 40% (Hester and Nicholson, 1989). The ability of powder coating to give a thick coating in one pass further improves the economics for powder coating for cases where a thick coating is needed.

For coating operations with a single color, maintenance and cleanup costs are low with powder coating. Because the powder coating is a dry material, no liquid mixing is needed prior to coating and no solvent is needed so cleanup can be done quickly. No waste solvent is generated and the waste coating material volume is low, reducing the cost of waste disposal.

For coating operations requiring frequent color changes, the operating costs of powder coating increase. To change colors, all of the powder in the coating system must be removed and replaced with the new color. The powder removal and handling time for color changes increases the operating cost. A cost comparison of powder, conventional, high solids, and water-based coatings is given in Hester and Nicholson (1989).

Reported Applications

Powder coating is a rapidly growing area due to both cost and pollution prevention benefits. The following five resins represent the bulk of the approximately 250,000 tonnes of powder coating material usage:

- Epoxy
- Epoxy/polyester mixture
- Polyester
- Polyurethane
- Acrylic (Ingleston, 1991).

Powder coating is used commercially for a wide range of small- to medium-sized metal parts, including lighting fixtures, equipment cabinets, automobile wheels, outdoor furniture, and hand carts and wagons. Some of the materials suitable for powder coatings include:

- Steel
- Aluminum
- Galvanize
- Zinc and brass castings (Robison, 1989; Bowden, 1989).

Fluidized bed or electrostatic spray systems may be used to apply chlorotrifluoroethylene fluoropolymer to metals. Electrostatic spraying is used for coating thicknesses in the range of five to

30 mils. A fluidized bed system is used if thicker coating is required. The curing temperature is about 500°F (Maguire, 1988).

Boeing is testing a powder coating material for application to both aluminum panels and epoxy fiberglass laminate panels. Several surface treatments and primers were tested. Powder is applied with an electrostatic spray gun and then oven-cured in a second step (Crump, 1991). Both corona discharge and tribo-friction charging systems were tested.

Operational and Product Benefits

Coating Operation:

- Powder coating can be applied in thick coatings in one pass, even over sharp edges.
- Because there is no volatile solvent, little air flow is needed through the coating application work areas or curing ovens. Reduced air flow requirements reduces energy use for heating makeup air.
- Basic resins that are not easily soluble in organic solvents can be used.

Preparation and Cleanup:

- Powder coating comes ready to use and therefore does not require mixing or stirring.
- No solvent is required for cleanup.

New Coating Types: Powder coating offers coating with polymers, such as polyethylene, nylon, or fluorocarbons, that are not amenable to solution coating techniques.

Operating Efficiency: The high material utilization, low reject rates, generally lower energy consumption, and lack of solvent waste reduces cost.

Hazards and Limitations

- The application of powder coating requires handling of heated parts because the parts must be subjected to elevated temperature.
- For electrostatic application systems, the part must be electrically conductive or be covered with an electrically conductive primer.
- For electrostatic application systems, parts with complex shapes can leave portions of the surface uncoated unless special application techniques are used.
- Application of thin coatings requires special techniques and equipment.

- It is difficult to incorporate the metal flake pigments that are popular for automotive finishes.
- Because powder coatings rely on large, fluidized bed reservoirs, it is difficult to make color changes.
- Color matching from batch to batch is difficult.

Tradeoffs

Powder coating can cover substrates without needing a volatile solvent to carry the film forming resins. In addition, because the powder remains dry until applied and cured on the surface, no solvent is required for equipment cleanup. In typical applications, nearly 95% of the powder coating material is applied to the substrate. These characteristics promote very clean operation with no loss of volatile organic compounds (VOCs) and minimal generation of coating waste.

Powder coating is good for applying a thick layer of thermosetting or thermoplastic material to a wide variety of substrates. If a medium thickness coating is needed, the part must be conductive and should have a simple geometry.

It is not possible to achieve thin coatings with present powder coating technology. Because curing is accomplished by heating, the substrate must be able to withstand high temperatures.

Summary of Unknowns

Powder coating is routinely used in industry but at the moment has a limited range of applications. The major area for expanding the use of powder coatings is development of methods to apply thinner coatings particularly to complex-shaped or nonconductive substrates.

State of Development

Powder coating has a well-established niche in the coating industry. Both thermoplastic and thermosetting powdered resins and equipment for fluidized bed, electrostatic fluidized bed, or electrostatic spraying are available from standard vendors. Detailed information can be obtained from the Powder Coating Institute (see Table 6 in Section 4).

HIGH SOLIDS COATINGS

Pollution Prevention Benefits

High solids coatings are an evolutionary change from current coating formulations. The coating liquid formulation is very similar, but the resin systems are modified to allow a higher concentration of solids with a lower concentration of VOCs. Lower VOC levels mean less VOC loss during curing, thus lowering fugitive solvent sources. The lower solvent concentrations in the coating formulation thus result in less solvent vapor in the air in the operating areas. Reduced solvent concentration reduces health and safety problems such as worker exposure to solvent fumes and fire and explosion hazard. However, paint overspray still results in paint waste, and solvent is still needed for equipment cleanup.

For example, a conventional plant painting 12,000,000 ft^2/yr with a 1.2-mil-thick coat will release about 38 tons/yr of VOC emissions after a treatment system with a 70% capture efficiency. A high solids painting plant spray applying a similar coating will emit about 31 tons/yr with no VOC control equipment (Hester and Nicholson, 1989).

Some paints have been formulated with chlorinated solvents to replace the volatile organic ozone precursors. These coatings are sometimes referred to as "low VOC coatings," but they are not considered clean technologies because they use 1,1,1-trichloroethane or similar solvents. Low-VOC coatings formulated with chlorinated solvents, therefore, are not discussed in this guide.

How Does It Work?

High solids coatings are being actively developed to reduce the quantity of volatile organic solvent in coatings. Like conventional coatings, high solids coatings consist mainly of resins, coloring agents, extenders, and additives carried in a solvent. As the name implies, high solids coating liquids rely on increasing the concentration of resins in the coating formulation.

Conventional coatings typically use high-molecular-weight resins to obtain satisfactory cured-film properties. A direct increase of solids concentration with conventional resins would, therefore, result in an unacceptable increase in the viscosity of the coating fluid.

Thus, high solids coating formulations use reduced-molecular-weight resins in parallel with the increase of the solids concentration.

The resulting high solids formulation is applied in much the same way as conventional coatings using the same or similar equipment. Thus high solids coatings must:

- Have viscosity and physical properties similar to conventional coating materials
- Allow use of coloring additives giving the required colors and hiding power
- Have a reasonable curing rate
- Remain useful for an acceptable period after the coating is removed from the original container (pot life)
- Provide a quality coating.

Many vendors of conventional coating materials now have alternative high solids coatings, particularly urethanes, and they are developing new formulations. For more information, contact the trade associations described in Table 6 (Section 4).

Why Choose This Technology

Applications

Currently available high solids coatings are expressly developed to behave as much as possible like conventional coatings. Generic families of resins available in high solids coating formulations include:

- Saturated polyesters
- Alkyds
- Acrylics
- Polyurethane
- Epoxy (Paul, 1986; Pilcher, 1988)

Operating Features

Lower viscosity high solids coatings can be applied with conventional equipment such as air spray, airless spray, or electrostatic spray. The major problems with high solids coating materials occur during application when the viscosity makes it difficult to achieve acceptable curing times while maintaining an acceptable use time after preparing the paint and exposing it to the air (i.e., good pot life).

High solids coating formulations with higher viscosities can be applied with turbine bell or rotating disk atomization spray equipment. These new application technologies allow the use of high-viscosity formulations while maintaining coating quality.

Basic Function. High solids coatings require the formulation to contain lower molecular weight resins. Lower molecular weight resins allow high solids concentration while the viscosity remains acceptable for use in conventional application equipment. However, the lower molecular weight resins alone will give an unacceptable final dry film if normal curing time limits are applied. To overcome performance limitations caused by low-molecular-weight resins, additives are often used to increase crosslinking of the resins during curing.

In many formulations, e.g., alkyds, polyesters, and polyurethanes, the crosslinking additives decrease the stability of the coating fluid and, therefore, are shipped in a separate container. The additive is mixed into the coating formulation at the start of a painting session. The additives typically contribute to a shorter pot life for high solid coatings compared with conventional coatings.

In some formulations, a somewhat higher viscosity is accepted and new types of application equipment are used. These new equipment types, such as turbine atomizers, are able to effectively atomize the more viscous high solids coatings. Disk and bell turbine applicator systems are both used in finishing operations.

With disk or bell applicators, the coating liquid is fed into a rotating, insulated disk or bell, where it spreads to the outer edge by centrifugal force. To keep the paint from flying off the disk or bell in coarse droplets or strings, an ~100-kV electrostatic charge is applied to the insulated disk or bell charges the paint droplets. The charge also enables paint atomization to ensure uniformity of coating on all sides exposed to the painting operation. The turbine-powered bells have rotational speeds of up to 50,000 rpm; disks, up to 40,000 rpm to achieve atomization by centrifugal force. A high electrostatic charge slightly improves the atomization and significantly improves the transfer efficiency of the paint droplets. The article being coated typically continues through the disk or bell system on a continuous line into a curing oven.

A somewhat more conventional approach to high-efficiency application to reduce overspray loss involves high-volume, low-pressure (HVLP) application equipment. HVLP's low atomizing air pressure requirement of between 0.1 and 10.0 psig combines with turbine-generated high volumes of atomizing air. HVLP systems routinely accompany commercially available paint application equipment.

Airless Spray is another technique to improve transfer efficiency. It does not use compressed air to atomize the liquid coating. An airless system utilizes hydraulic pressure to atomize the liquid coating and deposit it on the work piece. Coating fluid under high pressure is released through an orifice in the spray nozzle. The high pressure separates coating fluid into small droplets, resulting in a fine atomized spray. Since air is not used to form the spray pattern, the term "airless" is used.

Air Assisted Airless is a combination of airless and conventional air spray which uses some air propellant to assist in atomizing the coating liquid to a smaller droplet.

The HVLP technology is being debated relative to other methods that also achieve high transfer efficiency, such as air-assisted airless spray. Rapid developments in these high-efficiency technologies will position some of them, such as HVLP, to dominate paint application system manufacturing (Dick, 1991).

Material and Energy Requirements. High solids coatings are applied in the same way as conventional coatings, so overspray losses and solvent use for equipment cleanup are similar. Paint loss with high solids coating can, however, be minimized because the high solvent coatings are compatible with conventional electrostatic application methods. High solids coatings typically contain 275 to 420 g VOC/l of liquid coating (2.3 to 3.5 lb/gallon) (Pilcher, 1988). Because of the lower quantity of solvent, VOC loss during preparation, use, and curing is reduced so air flow through curing ovens and in operating areas may be reduced. Lower air flow decreases energy use.

Required Skill Level

Viscosity changes in high solids coating fluids caused by solvent addition or evaporation are not as predictable as the viscosity behavior of conventional coating formulations. Many high solids coatings (and some conventional coatings) are shipped as two components. Two solutions must be mixed before the coating can be applied, requiring an additional handling and mixing step just prior to starting painting.

High solids coatings generally have a shorter pot life. Even though the application equipment is similar, the above factors lead to the need for more operator skill and attention when using high solids coatings.

Cost

High solids coatings use conventional application equipment so the capital cost for booths, electrostatic spray applicators, and curing ovens are the same as for equipment to apply conventional high-VOC coatings. In fact, many of the existing items of equipment in the coating system could be retained in a switch to high solids coating. High solids coatings contain up to 40% solvent, so some VOC control will still be required with many high solids formulations.

The high solids coating liquid is slightly more expensive than conventional coating liquid per unit of reactive resin. Coating fluid preparation, application, cleanup, and disposal costs are similar for high solids and conventional coating. A cost comparison of high solids, conventional, powder, and water-based coatings is given in Hester and Nicholson (1989).

Reported Applications

Steel door makers are using high speed turbine bell atomizers to apply high solid coating to zinc-coated steel doors. In addition to lower VOC emissions, the new high solids coating formulation allows lower curing temperatures required by the heat sensitive foam insulation cores now used in steel doors. The high solid coatings meet the highest adhesion rating in ASTM D 3359 and pass a 250-hr salt spray test per ASTM B 117 (Nelson, 1988).

A U.S. Department of Energy contractor was able to identify and qualify a low-VOC urethane material (420 g VOC/l (3.5 lb/gal)) to replace a conventional urethane material (520 g VOC/l (4.36 lb/gal) for coating miscellaneous metal parts (Smith, 1990).

High solids polyurethane materials are available meeting MIL-C-83285B for use on aircraft and ground support equipment. These high solids formulations contain 340 to 420 g VOC/l (2.8 to 3.5 lb/gal). The pot life is reported to be 6 hr. The materials are formulated for electrostatic application (MP&C, 1988).

Operational and Product Benefits

High solids coatings have the following benefits:

- They reduce solvent concentrations in the coating, thus reducing the environmental, odor, and safety problems caused by solvents.
- They are compatible with conventional and electrostatic application equipment and techniques.
- Lower solvent loadings allow reduced air flow in curing ovens and work spaces, which decreases energy needed for heating.

Hazards and Limitations

There are some disadvantages to using high solids coatings:

- Although they reduce the amount of organic solvents in the coating formulation, they do not completely eliminate solvent use.
- High solids coatings have shorter pot life than conventional coatings.

Tradeoffs

The main tradeoff involved in selecting the high solids coating option is the "comfort factor" versus less complete pollution prevention when compared to some of the other alternatives.

High solids coatings use technology that is similar to conventional solvent-based coatings. Many users will find that the transition to high solids coatings meets less resistance because it allows use of familiar equipment to apply a solvent-based coating. Both equipment operators and plant management tend to prefer evolutionary changes to radical departures in equipment and procedures.

Although high solids coatings are a valid clean technology offering a real reduction in VOC emissions, the potential reductions are not as great as with powder coating or 100% reactive liquid coatings.

Summary of Unknowns

High solids coatings are limited mainly by viscosity restrictions. The solution viscosity increases roughly linearly with the weight fraction of resin present in the coating formulation. Therefore, increasing the solids content increases coating liquid viscosity. The major unknown in high solids coating technology is what types of new formulations will provide good coating adhesion, flexibility, and impact resistance while maintaining coating flexibility. Methods to optimize pot life versus curing time are also needed.

State of Development

High solid content solvent-based coatings are compatible with electrostatic spraying techniques. Many of the formulations, particularly the two-component types, are compatible with conventional air spray equipment. As a result, changing to high solids coatings is less disruptive than changing to other technologies, such as 100% reactive liquid, water-based, or powder coating.

Compatibility makes high solids coatings attractive as near-term replacements for conventional solvent-based coatings. Development of urethane formulations is the most advanced, but paints based on other resin types are also becoming available.

WATER-BASED COATINGS

Pollution Prevention Benefits

Water-based coatings are a diverse group of liquid coating materials in which water supplements or replaces the organic solvent. Water, alone or in conjunction with solvent, acts as the carrying medium for film-forming resins, coloring agents, and other elements of the coating formulation.

Water-based coatings have little or no solvent in the coating formulation, and the uncured coating can be cleaned up with water. As a result there is less solvent vapor in the air in the operating areas and less bulk solvent storage. Reduced solvent use reduces health and safety problems such as worker exposure to solvent fumes or liquids and potential fire or explosion hazard.

For example, a conventional plant painting 12,000,000 ft^2/yr with a 1.2-mil thick coating will release about 38 tons of VOC, even with a treatment system running at 70% capture efficiency. A water-based painting plant spraying a similar coating and running no VOC control equipment will emit only about 26 tons/yr (Hester and Nicholson, 1989).

Reduced solvent concentration in the coating thus results in lower VOC emissions during curing and can make a significant contribution to lowering fugitive solvent releases. However, paint overspray still results in paint waste. New HVLP application equipment can reduce overspray loss.

Water-based coatings are not directly compatible with current generation electrostatic application equipment. Cleanup of equipment covered with uncured water-based coatings can be done with water, which also helps reduce solvent use.

How Does It Work?

Water-based coatings use solvents, resins, coloring agents, extenders, and additives either dissolved or dispersed in water. A wide range of technologies are used to achieve good coating performance with water-based coatings. There are three main classes:

- Water-soluble or water-reducible coatings
- Colloidal or water-solubilized dispersion coatings
- Emulsion coatings.

These three vary significantly in physical and mechanical properties. For example the handling characteristics and performance parameters for a solubilized polyester (water-soluble) with molecular weight of 2,500 will be different from those of an acrylic latex (emulsion) with a molecular weight of more than 1 million.

Water-soluble coatings are generally easier to apply than emulsion coatings because they exhibit better flow, substrate wetting, and leveling; less foaming; and easier cleanup. The emulsion coatings, although more difficult to formulate and apply, tend to have greater durability and resistance to chemicals (Paul, 1986).

In addition to conventional application methods, water-based coatings are amenable to electrodeposition. Electrodeposition of coating resembles electroplating in that the substrate is submerged in an aqueous bath. The ionized organic coating material is deposited on the substrate by means of the direct current flow.

Water-based latex acrylics and epoxies are available and are routinely used. New formulations are being developed for other applications. Many of the vendors of conventional coating materials have alternative water-based coatings. For more specific information, contact the trade associations listed in Table 6 (Section 4).

Why Choose This Technology?

Applications

The great diversity of water-based coating technology is a potential strength but presents a challenge when first encountered. Because a wide range of characteristics are available with water-based coating technology, formulations can be prepared to fit many specific applications. However, the coating formulation will typically require more care in application and have a more limited range of potential uses than similar conventional solvent-based coatings. Thus, it is difficult to characterize or classify water-based coatings into a few simple groups having wide ranges of application.

Two-part acrylics; colloids; amine-solubilized, carboxyl-terminated alkyds; and polyesters are examples of some of the coating formulations generally considered as water-based technologies. Each of these groups has different properties creating challenges both for users in defining their needs and for coating manufacturers in providing the optimum coating to fill user needs (Pilcher, 1988). However, the diversity of water-based coating technology allows flexibility in tailoring the performance of the coating.

Water-soluble resins are normally prepared by one of three methods. The most common approach is to convert the polymer backbone to anion or cation forms by neutralizing the carboxylic or amino groups. Other possible approaches include adding nonionic groups such as polyols or polyesters to the resin to allow water solubility, or using water-soluble zwitterion (organic ion with both a positive and negative charge) copolymers.

Water-soluble formulations can include water-soluble oils, polybutadiene adducts, alkyds, polyesters, and acrylics. Water-soluble coatings tend to have simpler formulations and are easier to apply than emulsions but have lower durability and resistance to solvents.

Colloidal dispersions lie between water-soluble and emulsion coatings with respect to both application behavior and physical characteristics. The colloidal coatings consist of a dispersion of very fine, partially water-soluble polymer droplets in water. Colloidal dispersions are used mainly to coat porous materials such as paper or leather.

Emulsion formulations (also called latex) are currently the most commonly used of the water-based coatings. Emulsion coatings are dispersions of polymer droplets in water. The polymer droplets are stabilized in the aqueous medium by emulsifiers and thickeners. Most emulsion coatings use acrylic or acrylic copolymer resins. Emulsion coatings have lower gloss, film buildup, and pigment loading than water-soluble coatings.

Operating Features

Water-based paints are liquid products that can be applied with either conventional nonelectrostatic atomizers or modified electrostatic atomizers. In many cases, two-component formulations are used. Although two-component formulations slightly increase the complexity of coating liquid preparation, many conventional coatings are also shipped as two separate components.

Emulsion formulations are thixotropic and may, therefore, not be compatible with existing pumps and piping. Uncured water-based coatings can be removed with water, so solvent use is reduced both in the formulation itself and in secondary uses associated with cleanup at the end of the coating operation.

Basic Function. Water-based coatings are one- or two-component liquids that are applied in essential the same manner as conventional solvent coatings. The thixotropic viscosity behavior of emulsion coatings may require the use of special pumping and application equipment.

Also, the electrical conductivity of aqueous solutions means that special equipment and techniques are needed for electrostatic application of water-based coatings. Electrostatic coating application is widely used to reduce overspray losses. Cutting the amount of coating that does not reach the substrate helps prevent pollution and reduce costs.

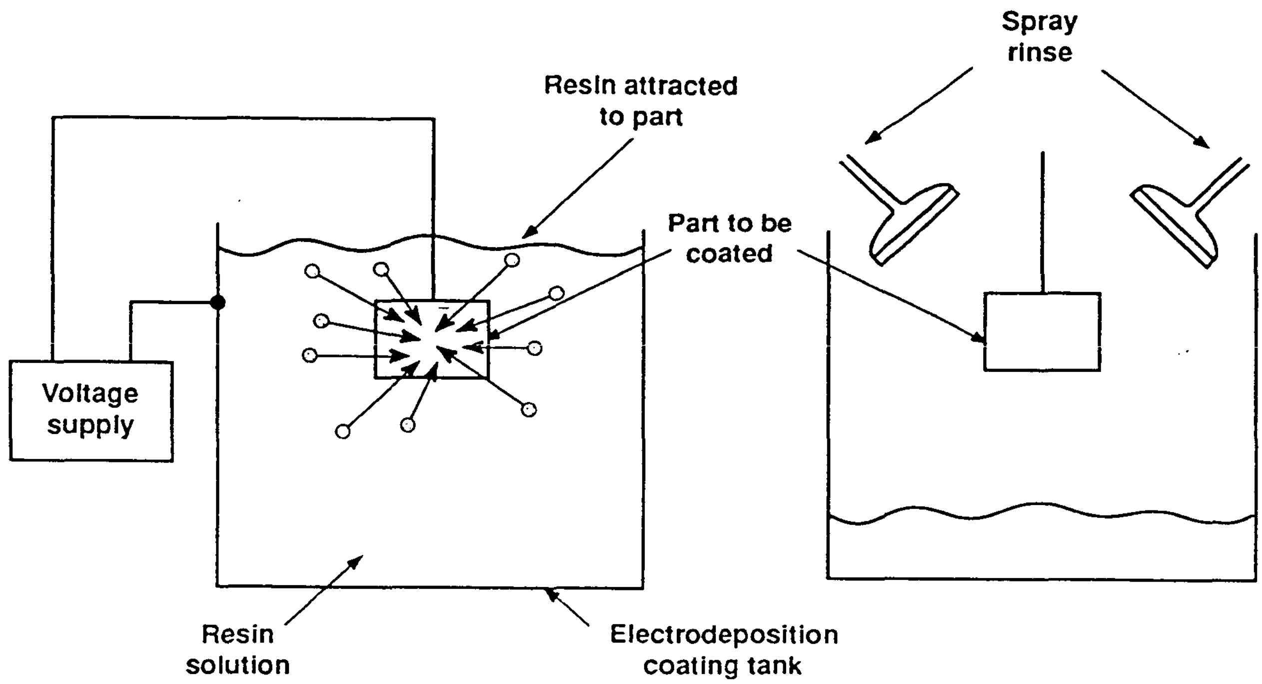
There is also a clean technology advantage to electrostatic application because reduced overspray cuts solvent releases and coating waste production. However, aqueous solutions have higher electrical conductivity than organic solvent solutions, so it is more difficult to maintain voltage in an electrostatic application system using water-based coatings. Four options exist for electrostatic application with water-based coatings:

- Isolate the coating liquid storage and supply system from any electrical ground to prevent current leakage from the application atomizer to ground through the coating supply system.
- Use an external charging system attached to but electrically isolated from the application atomizer.
- Electrically isolate the coating liquid storage and supply system from the application atomizer to prevent current leakage through the coating supply system.
- Place the electrostatic charge on the substrate and ground the application atomizer (Scharfenberger, 1989).

Although the electrical conductivity of water-based coating solutions presents problems for conventional electrostatic spray application, it opens up the possibility of a new application approach. Coating resins can be applied to electrically conductive substrates by electrodeposition. In electrodeposition, ionized resins are attracted to the substrate by electrical charge as shown in Figure 5.

Film-forming cations can be obtained as organic substituted ammonium macro-ions such as RNH_3^+ or R_3NH^+. When an appropriate film-forming resin, R, is used, an adherent deposit will form on the substrate held at cathodic potential. Anodic film-forming resins can be prepared from coating resins that have carboxylic groups. Resins with molecular weights in the range of 2,000 to 20,000 typically are used for electrodeposition from water-based coating solutions.

Electrodeposition is used most in applying automotive primers because of its high ability to provide protection from corrosion with very thin, evenly spread films. Electrodeposition gives remarkably uniform films no matter what the surface. Recesses, tapped holes, and sharp edges exhibit uniform coating. By "forcing" a dense film against the substrate during coating, electrodeposition provides excellent adhesion and resistance to corrosion. The fully automated systems that are available give higher than 95% deposition efficiency. Because electrocoatings use water as the main solvent, fire hazards and air pollution are minimized.



Source: Battelle

Figure 5. Electrodeposition Coating.

The electrodeposition technology does, however, require special equipment and procedures resulting in high installation and other costs. Electrodeposition requires new coating tanks, extra-clean application and curing areas, and infrared radiation to speed up the final setting of the coating surface. Operators must learn to formulate and precisely control the coatings. Electrodeposited coatings are highly sensitive to contaminants. To produce a high gloss finish, the first coating must include a conductive pigment. The surface of metal substrates can dissolve into the coating and cause discoloration. Thus, only very large numbers of similar parts justify the costs of installing electrodeposition equipment and providing the required training (Dick, 1991).

Material and Energy Requirements. Water-based coating formulations contain fewer VOCs than conventional coatings, and uncured coating waste can be cleaned up with water. Because of the lower solvent use, the VOC loss during coating preparation, use, curing, and cleanup is reduced so that the air flow through curing ovens and in operating areas may be lower. Lower air flow decreases energy use.

Required Skill Level

Special equipment and procedures are needed for electrostatic application of water-based coatings. Some water-based coatings (and some conventional coatings) are shipped as two components. Two solutions must be mixed before the coating can be applied, requiring an additional handling and mixing step just prior to starting painting.

Water-based coatings typically require more care in surface cleaning and preparation than do conventional coatings. Even though the application equipment is similar, the above factors lead to the need for more operator skill and attention for application of water-based coatings.

Cost

The capital cost for electrostatic spray applicators for water-based coatings will typically be higher than similar equipment for application of conventional fluid coatings because of the electrical conductivity of water-based coatings. Water-based coatings typically contain some solvent but are less likely to require VOC control equipment. If VOC control is needed, the lower concentration of solvent in the coating should reduce the volume of carbon absorber needed, thus reducing capital and operating cost.

The water-based coating liquid is more expensive than conventional coating liquid per unit of reactive resin. Coating fluid preparation, application, cleanup, and disposal costs are similar for water-based and conventional coating. A cost comparison of conventional, powder, high solids, and water-based coatings is given in Hester and Nicholson (1989).

Reported Applications

Water-based coatings are primarily used as architectural coatings and industrial finish coatings. Because water-based paints are easy to apply, adhere to damp surfaces, dry rapidly, are easy to clean with soap and water, and lack solvent odor, more than 70% of architectural coatings are water-based paints. Coatings include:

- Wall primers, sealants
- Interior flat/semigloss wall paints
- Interior and exterior trim finishes
- Exterior house paints

Water-based coatings have not been so readily accepted in the industrial sector. But tightening regulations are making compliance more economical through use of these coatings, and they are gaining a foothold in both primer and topcoat industrial finish applications where these attributes count:

- Can be used with existing solvent-based coatings application equipment
- Can be thinned using only water
- Have low flammability
- Offer minimized toxicity, environmental pollutants, and odor
- Application equipment can be cleaned using only water (Dick, 1991).

Resins include:

- Acrylics
- Epoxy esters
- Alkyds
- Polyesters.

About 10% of U.S. coil lines, which have aluminum as the primary substrate use acrylic-based, waterborne coatings because of the flexible and adhesive properties of these coatings. Acrylics also offer exterior durability and resistance to yellowing. Epoxy esters also reliably adhere to the substrate and are resistant to corrosion and detergents. Polyesters, on the other hand, lack detergent resistance but provide good exterior durability. Alkyds balance lower performance with a lower cost (Dick, 1991).

Water-based epoxy coatings are particularly useful for application on green or damp concrete. The water-based formulations provide excellent adhesion to the concrete substrate. Water-based epoxy coatings give low odor levels during curing, and the cured coating surface is easy to clean. These characteristics make water-based epoxy coatings suitable for areas requiring a high level of hygiene, such as hospitals or food processing plants (Richardson, 1988).

A low-VOC water-based flexible epoxy primer is available as a two-component formulation. Unlike most water-based formulations, no water is present in either of the two components as shipped. The components, which are supplied in a 3 to 1 volume ratio, are mixed just before application to prepare a catalyzed resin mixture.

Water is added to the mixture to reduce the viscosity to allow application. At application, the formulation contains about 340 g VOC/l (2.8 lb/gal) (MP&C, 1988).

An aerospace company compared a series of water-reducible coatings to current aerospace topcoats. The base case coatings selected were a conventional solvent-based, two-component polyurethane meeting Military Specification MIL-C-83286 and a high solid polyurethane meeting MIL-C-85285. The VOC concentrations of the conventional and high solids coatings were 600 g/l (5 lb/gal) and 420 g/l (3.5 lb/gal), respectively.

Both polyurethane and polyester resin formulations were tested with and without crosslinking agents. The crosslinkers tested were carbodiimide, polyaziridine, di-functional amine, or tertiary amino alkylylamine. The VOC concentration in the water-based formulations ranged from 65 g/l to 345 g/l (0.54 lb/gal to 2.9 lb/gal).

Skydrol resistance testing by ASTM D 1308 showed severe softening for all the water-based formulations and the high solids base case. However, the overall performance of the cross-linked water-based coatings was found to be nearly as good as the high solids solvent-based polyurethane (Swanberg, 1990).

Application methods for water-based coatings include:

- Dip coating
- Flow coating
- Air spray
- Airless spray
- Electrostatic spray (Dick, 1991).

Operational and Product Benefits

There are several operational and environmental benefits of water-based coatings:

- Because water-based coatings reduce the solvent concentrations in the coating, they reduce the environmental, odor, and safety problems caused by solvents.
- Existing application equipment (nonelectrostatic) can be used with most water-based coatings.
- Reduced air flow in curing ovens and work spaces decreases energy needed for heating.

Hazards and Limitations

Water-based coatings have several drawbacks:

- They are sensitive to humidity, so effective application normally requires humidity control in the application and curing areas.
- The high surface tension of water can cause poor coating flow characteristics.
- Special equipment is needed to allow electrostatic application.
- Water in the formulation can cause corrosion of the coating storage tanks and transfer piping.
- Water in the formulation can cause "flash rusting" of metal substrates under the coating.
- Most waterborne coatings require careful cleaning of the substrate to ensure oil and grease are removed.
- Resins in contact with water degrade, reducing shelf life for water-based coating formulations.
- Water-based emulsion coatings are susceptible to foaming due to surfactants used to stabilize the emulsion.

Tradeoffs

Water-based coatings offer a tradeoff of "comfort factor" versus pollution prevention similar to high solids coatings. However, the factors involved are different. The "comfort factor" with water-based coatings is lower because they do not use the familiar solvent technology and are not compatible with existing electrostatic application equipment. However, the potential for solvent reduction is higher. At least some of the water-based coatings eliminate solvent from the formulation. Also, cleanup of uncured water-based coatings can be done with water, which eliminates solvent use in cleanup. Thus the solvent reduction potential is higher with water-based coatings compared to high solids coatings.

Summary of Unknowns

Water-based coatings have proven compatible with porous surfaces such as concrete, paper, and leather. Compatibility with metal surfaces is less well established. Unless the pH of the coating formulation is high or a corrosion inhibitor is included in the formulation, the water can corrode the substrate. Also, water-based coatings typically require a cleaner surface than solvent-based coatings. Future work is needed to develop low-cost cleaning methods.

State of Development

Many of the water-based formulations are compatible with conventional nonelectrostatic spray equipment but require special provisions for electrostatic application. As a result, a change to water-based coatings can be somewhat less disruptive to existing coating operations than a change to other technologies such as powder coating. Compatibility gives water-based coatings the potential to replace conventional solvent-based coatings. But the high cost of clean application areas, environmental control, and infrared flashoff may limit the use of water-based coatings in small industrial finish coating shops.

ULTRAVIOLET (UV) RADIATION-CURED COATINGS

Pollution Prevention Benefits

UV-cured coatings allow the use of 100% reactive liquids, eliminating solvent use, and near 100% transfer efficiency, reducing paint waste. UV curing provides an alternative in cases where baking has been used to remove the solvent component from conventionally processed organic coatings.

How Does It Work?

UV curing uses high-intensity UV light to initiate the free radical crosslinking of acrylate oligomers and prepolymers. Of the available chemistries, this is the most frequently used. The UV light changes the ink or coating from wet to dry product. This fast, relatively cool process enables inks and coatings to be cured on heat-sensitive substrates. The crosslinking of the inks and coatings, when properly cured, yields high chemical and physical resistance (Sun Chemical, 1991).

UV-cured coatings consist of:

- ♦ An oligomer or a prepolymer containing double-bond unsaturation
- ♦ A reactive solvent, e.g., monomers with varying degrees of unsaturation
- ♦ A sensitizer to absorb the UV radiation-initiating polymerization
- ♦ Coloring agents (Sun Chemical, 1991).

UV-cured coatings are available from a variety of commercial vendors. For more specific information, contact the trade associations listed in Table 6 (Section 4).

Why Choose This Technology?

Applications

UV curing is most used in these industrial finishing areas:

- ♦ Wood finishing
- ♦ Metal decorative coatings
- ♦ Automotive coatings
- ♦ Wire coatings
- ♦ Packaging coatings
- ♦ Floor finishing.

UV curing often replaces conventional thermal treatments for coating flat wood surfaces because of its low cost and ease of application. Because the UV radiation must reach the entire coated surface, UV curing systems are most easily used with flat material. However, curing systems are being modified to allow three-dimensional coating, or coating of all surfaces, at one time. UV curing has been investigated for the U.S. metal-can industry and often replaces thermally cured coatings for aluminum and galvanized steel tubing because of its hardness and salt spray resistance lasting 200 to 500 hr. The technology offers a low-cost, high-throughput alternative for finishing automotive hubcaps and wheel rims. Used on both bare and insulated wire, UV-cured coatings provide highly cross-linked, strong, yet flexible 10-mil-thick films.

Liquid acrylic and liquid polyurethane-acrylic UV-cured coatings surpass press varnish and water-based coatings in quality and resemble film laminations. Likewise, tough UV-cured coatings have found a market niche in high-gloss vinyl floor coverings. They surpass the conventional urethane polymers in ease of application and in abrasion, solvent, and stain resistance (Dick, 1991).

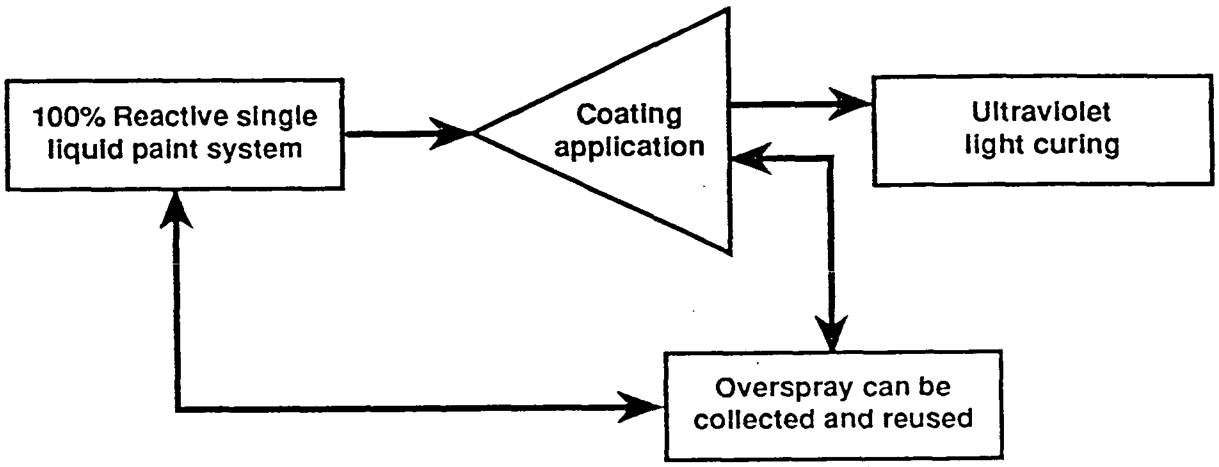
Operating Features

UV curing actually takes place in two instantaneous steps using first the UV light energy and then the UV thermal energy. First, the photoinitiator absorbs the UV light energy and converts it to free radicals through several chemical mechanisms. Then the UV lamps provide thermal energy to make the free radicals attack the acrylic double bonds and make the ink or coating polymerize. Because curing takes place so quickly, it is advised to allow time between application and curing to allow the ink or coating to level out and to achieve maximum gloss.

Some radicals "live on" in the film after exposure to high-intensity UV light, causing postcuring if the crosslink conversion is weak. Postcuring cannot achieve the desired properties if the initial curing has been inadequate.

Ink color and opacity to UV light affect the curing rate of inks. Darker and more opaque inks block the light and require longer exposure time for adequate curing. Likewise, thicker films and multiple films cure more slowly than thin or single films of inks and coatings (Sun Chemical, 1991).

Solvent is not needed in most UV curing uses, although some dilution may be needed for spray applications. Solvent is used for the cleanup of uncured coating. The coating is applied as a fluid and exposed to the UV light, which initiates formation of a cross-linked polymer coating (see Figure 6).



Source: Battelle

Figure 6. 100% Solids Ultraviolet-Light-Curable Liquid Paint System.

Reported Applications

UV coating formulated from polyester resin in styrene has seen commercial application as filler for chipboard. The polyester-styrene system has not been widely applied because of styrene's volatility, the yellow color of the coating, and the high capital cost of UV coating equipment.

UV-cured coatings are being developed based on acrylate-modified resins such as polyesters, epoxides, and urethanes. UV-cured coatings are typically limited to wood substrates, but application to metals has been studied (Paul, 1986). UV coating techniques are used to coat flat sheet stock and to apply "wet look' finishes to assembled furniture.

A variety of Dual Cure™ urethane/acrylate and epoxy/acrylate UV-cured coating systems are being developed (Keipert, 1990).

Operational and Product Benefits

UV-cured coatings have a number of operational, cost, and environmental benefits:

- Eliminates or reduces solvent use
- High transfer efficiency
- Low-temperature processing
- Rapid curing
- Equipment requires less space than curing ovens.

Hazards and Limitations

UV technology has several drawbacks:

- It requires new equipment with high capital cost.
- The presence of pigments limits penetration of UV.

Tradeoffs

UV curing offers good pollution prevention potential but requires new operating procedures and expensive new equipment.

Unknowns and Future Developments

More widespread future use depends on the development of the following:

- More highly developed UV equipment
- New products/markets for radiation processing technologies
- New 100% reactive monomers and oligomers that are nontoxic and of low viscosity
- New monomers, oligomers, and polymers that adhere to metal substrates
- New electronic and optronic resist materials
- Lower costs for materials
- Further study of coating service life (Dick, 1991).

SECTION 3

EMERGING TECHNOLOGIES

How to Use the Summary Tables

Six emerging coating replacement materials are evaluated in this section, namely

- Electron beam (EB)-cured coatings
- Radiation-induced thermally cured coatings
- Two-component reactive liquid coatings
- Water-based temporary protective coatings
- Vapor permeation- or injection-cured coatings
- Supercritical carbon dioxide as solvent.

Tables 4 and 5 summarize descriptive and operational aspects of these technologies. They contain evaluations or annotations describing each emerging clean technology and give a compact indication of the range of technologies covered to allow preliminary identification of those that may be applicable to specific situations. Readers are invited to refer to the summary tables throughout this discussion to compare and contrast technologies.

Descriptive Aspects

Table 4 describes each emerging technology. It lists the **Pollution Prevention Benefits**, **Reported Applications**, **Operational and Product Benefits**, and **Hazards and Limitations** of each.

Operational Aspects

Table 5 shows the key operating characteristics for the emerging technologies. These characteristics serve to qualitatively rank the clean technologies relative to each other. The rankings are estimated from descriptions and data in the literature.

Process Complexity is qualitatively ranked as "high," "medium," or "low" based on such factors as the number of process steps involved and the number of material transfers needed. **Process Complexity** is an indication of how easily the new technology can be integrated into existing plant operations. A large number of process steps or input chemicals, or multiple operations with complex sequencing, are examples of characteristics that would lead to a high complexity rating.

Table 4. Emerging Clean Technologies for Organic Coating Replacements: Descriptive Aspects

Technology Type	Pollution Prevention Benefits	Reported Applications	Operational and Product Benefits	Hazards and Limitations
Electron Beam (EB)-Cured Coatings	• 100% reactive liquid • Eliminates or reduces solvent in the coating, but solvent still needed for cleanup	• Used on – paper – wood – plastic	• Efficient material use (near 100% transfer efficiency) • Lack of volatile solvent means little air flow needed • Low-temperature processing (reduced energy use for heating makeup air) • Rapid curing	• Typically best applied to flat material
Radiation-Induced Thermally Cured Coatings	• 100% reactive liquid • Eliminates or reduces solvent in the coating • May be water-reducible for application and cleanup depending on coating	• Pilot testing for curing powder or waterborne coatings	• Low-temperature processing	• Best when used with robotic system • Typically best applied to flat material
Two-Component Reactive Liquid Coatings	• 100% reactive liquid • Eliminates or reduces solvent in the coating, but solvent still needed for cleanup	• Undergoing initial feasibility testing	• Low-temperature processing	• Uncured resin may be harmful
Water-Based Temporary Protective Coatings	• Water-based formulation eliminates or reduces solvent use • Water used for cleanup	• Automobiles in shipment • Machined metal during shipping or between manufacturing steps • Metal masking during milling and etching	• Produces tough, transparent film • Safe, quick removal	• Coating is temporary
Vapor-Permeation or Injection-Cured Coatings	• 100% reactive liquid • Eliminates or reduces solvent in the coating, but solvent still needed for cleanup	• Pilot testing of permeation curing by amine vapor	• Low-temperature processing	• Further testing required
Supercritical CO_2 as Solvent	• Reduces solvent in coating formulation	• Replacement for conventional spraying systems	• Compatible with conventional and electrostatic application equipment and techniques • Lower solvent loadings allow reduced air flow in curing ovens and work spaces, thus decreasing energy needed for heating	• Solvent use not completely eliminated • Requires new CO_2 handling equipment

Table 5. Emerging Clean Technologies for Organic Coating Replacements: Operational Aspects

Technology Type	Process Complexity	Required Skill Level	Waste Products and Emissions	Capital Cost	Energy Use	References
Electron Beam (EB)-Cured Coatings	High	High	• Unreacted overspray can be collected for reuse	Very high	Low	Dick, 1991 Paul, 1986 Sun Chemical, 1991
Radiation-Induced Thermally Cured Coatings	High	High	• Unreacted overspray can be collected for reuse when used with powder coatings	High	Low	Paul, 1986 Poullos, 1991
Two-Component Reactive Liquid Coatings	High	High	• Overspray loss similar to that of conventional coating	High	Low	No data available
Water-Based Temporary Protective Coatings	Medium	Medium	• Overspray loss similar to that of conventional coating	Medium	Medium	Product Finishing, 1986 Toepke, 1991
Vapor-Permeation or Injection-Cured Coatings	High	High	• Unreacted overspray can be collected for reuse	High	Low	Pilcher, 1988
Supercritical CO_2 as Solvent	Medium	Medium	• Overspray loss similar to that of conventional coating	High	Medium	Nordson, 1991

The **Required Skill Level** of equipment operators also is ranked as "high," "medium," or "low." **Required Skill Level** is an indication of the level of sophistication and training required by staff to operate the new technology. A technology that requires the operator to adjust critical parameters would be rated as having a high skill requirement. In some cases, the operator may be insulated from the process by complex control equipment. In such cases, the operator skill level is low but the maintenance skill level is high.

Table 5 also lists the **Waste Products and Emissions** from the emerging clean technologies. It indicates tradeoffs in potential pollutants, the waste reduction potential of each, and compatibility with existing waste recycling or treatment operations at the plant.

The **Capital Cost** column provides a preliminary measure of process economics. It is a qualitative estimate of the initial cost impact of the engineering, procurement, and installation of the process and support equipment. Due to the diversity of cost data and the wide variation in plant needs and conditions, it is not possible to give specific cost comparisons. Cost analysis must be plant-specific to adequately address factors such as the type and age of existing equipment, space availability, throughput, product type, customer specifications, and cost of capital. Where possible, sources of cost data are referenced in the discussions of each clean coating material.

The **Energy Use** column provides data on energy conversion equipment required for a specific purpose. In addition, some general information on energy requirements is provided.

The last column in Table 5 lists **References** to publications that will provide further information for each emerging coating material. These references are given in full in Section 4.

The text further describes the operating pollution prevention benefits, reported applications, operational and product benefits, and hazards and limitations. Technologies in later stages of development are discussed in Section 2, Available Technologies.

ELECTRON BEAM (EB)-CURED COATINGS

In a process similar to that of UV curing, EB curing uses the high energy of accelerated electron to directly cause the crosslinking of inks and coatings. Also as with UV curing, acrylate oligomers and prepolymers are used, although other chemistries are available for EB curing.

The high energy of EB curing gives the highest margin of safety for applications where extractables or low odors are essential. This high energy ensures adequate conversion from oligomer to polymer. Thus, unlike UV curing, very thick films and laminating adhesives can be EB-cured. Furthermore, the EB process is not sensitive to either ink color or the opacity of the film or paper.

EB curing is a cold curing process. Thus, heat-sensitive substrates can be printed and cured without causing deformation.

The curing chamber must be inerted, i.e., pressurized or filled with nitrogen or carbon dioxide, during EB curing. Air, i.e., oxygen, significantly retards EB curing.

EB curing takes place instantaneously. Thus, as with UV curing for high gloss applications, time should be allotted between coating and curing to let the coating or ink flow out and level. If this is not possible, other precautions and equipment should be considered to achieve the desired gloss level (Sun Chemical, 1991).

EB coatings are used mainly for paper, wood, and plastic substrates. They often replace conventional thermal treatments for coating flat surfaces. At least one company in Japan used EB curing for metal coil stock. EB has seen limited use in high-volume printing operations. A more frequent use is to finish automotive hubcaps and wheel rims (Dick, 1991). The high capital cost of EB curing equipment has limited the acceptance of EB-cured coatings (Paul, 1986).

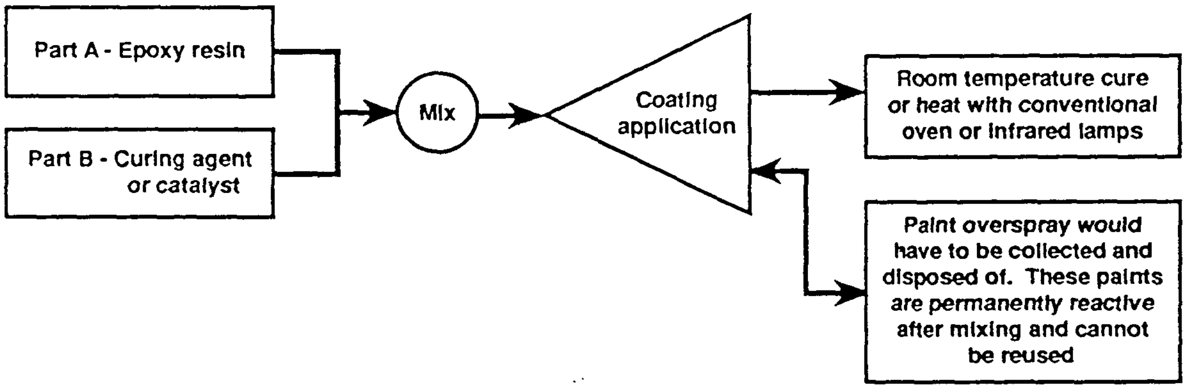
RADIATION-INDUCED THERMALLY CURED COATINGS

Laser heating, particularly when applied by a robotic system, allows accurate heat input to rapidly cure thermoplastic or water-based coatings. The laser fusion system was originally designed to cure fluorocarbon thermoplastics such as polytetrafluoroethylene. The curing of other powder and water-based coatings is being tested.

Infrared, microwave, laser, or radio-frequency radiation can be used to heat a fluid coating to induce curing by thermal mechanisms. The curing reaction is essentially similar to conventional curing in a convection oven, except that heat is supplied by the incident radiation (Paul, 1986; Poullos, 1991).

TWO-COMPONENT REACTIVE LIQUID COATINGS

In a two-component reactive liquid coating system, two low-viscosity liquids are mixed just before entering the application system as shown in Figure 7. One liquid contains reactive resins, and the other contains an activator or catalyst that promotes polymerization of the resins. Conventional, airless, or electrostatic spray equipment can be modified to accommodate new coating materials such as two-component epoxies, polyurethanes, and polyesters. The two components are fed into the spray gun through separate metering devices. Flow control valves and cleaning valves are built into the spray unit to prevent the two reactive components from coming in contact with each other until just before spray release. Two-component application allows coating without the use of a volatile organic solvent in the coating formulation. Some solvent may be used to clean up any unreacted liquids.



Source: Battelle

Figure 7. 100% Solids Chemical Cure Two-Component Liquid Paint System.

WATER-BASED TEMPORARY PROTECTIVE COATINGS

Consumer products, particularly automobiles, are shipped from factory to consumer through an uncontrolled and potentially harsh environment. A protective coating helps to maintain the quality of the factory finish. Temporary coatings are also applied to protect machined metal surfaces from corrosion during shipping or between manufacturing steps.

The normal practice is to apply a solvent-based coating. Solvent in the coating evaporates into the atmosphere as the coating cures. Solvent may also be needed for removal of the temporary coating when the product arrives at the point of sale or use.

Temporary coating materials using a water-based acrylic copolymer system are available to produce a tough transparent film. The film can protect the paint for up to 1 year but can be removed by washing with an aqueous alkali solution.

The reported removal time for the water-based temporary protective coating is 10 minutes for an automobile compared to 20 minutes for removal of a wax coating (Product Finishing, 1986).

Water-based coatings have also been tested as masking layers to protect areas of metal substrate during chemical milling and etching (Toepke, 1991).

VAPOR PERMEATION- OR INJECTION-CURED COATINGS

Solvent use is avoided in vapor cure coating formulations by applying a reactive resin as a liquid and then inducing curing by exposing the liquid to a vapor containing a compound that initiates polymerization. Some solvent may be used to clean up unreacted resin. One example is polyol-isocyanate coatings cured by tertiary amine vapor injection (Pilcher, 1988).

SUPERCRITICAL CARBON DIOXIDE AS SOLVENT

Supercritical CO_2 fluid can be used to replace organic solvent in conventional coating formulations. This new technology can substitute up to 80% of the organic solvent required in many spray applications. The CO_2 solvent is compatible with classical high-molecular-weight resins and existing painting facilities and procedures. Thus, it enables finishers to continue to use their existing resin formulations while substantially reducing VOC emissions. Application of supercritical solvent coatings requires investment in new paint mixing, handling, and spraying equipment.

Supercritical CO_2 proportioning and supply units are available from at least one commercial supplier. The unit mixes coating concentrates and CO_2 to give a coating fluid with the required viscosity. The supercritical CO_2 solvent is mixed with coating concentrate and supplied to a specially designed spray gun. The coating/solvent mix is applied in the same way as conventional paint. The CO_2 operating pressure ranges from 1200 to 2000 psi, and the airspray supply pressure is about 70 psi (Nordson, 1991).

SECTION 4

INFORMATION SOURCES

References

Bowden, Champ. 1989. "The Future is Clear." *Products Finishing.* 53(10), July.

Crump, David L. 1991. "Powder Coating Technology at Boeing." In: *Sixth Annual Aerospace Hazardous Waste Minimization Conference.* Boeing Company, Seattle, Washington, June 25-27.

Danneman, Jeffrey. 1988. "UV Process Provides Rapid Cure for Compliant Wood Finishes." *Modern Paint and Coatings.* 78(2): 28-29. February.

Dick, Richard J. 1991. Personal Communication. Battelle, Columbus, Ohio, December 5.

Fish, John G. 1982. "Organic Polymer Coatings." In: Rointan F. Bushah (ed.), *Deposition Technologies for Films and Coatings.* Noyes Publications, Park Ridge, New Jersey. pp. 490-511.

Hester, Charles I. and Rebecca L. Nicholson, 1989. "Powder Coating Technology Update." EPA-45/3-89-33. October.

Ingleston, Roy. 1991. "Powder Coatings: Current Trends, Future Developments." *Product Finishing.* 6-7. August.

Keipert, Steven. 1990. "Dual Cure Photocatalyst Systems." In: *First Annual International Workshop on Solvent Substitution*, pp. 245-249, Phoenix, Arizona, December 4-7.

Maguire, George. 1988. "Fluoropolymer Powder Coatings on the Move." *Products Finishing.* 53(1), October.

MP&C (Modern Paint and Coatings). 1988. "Low-VOC Coatings Applications for Military Usage Present Major Formulation Challenge." *Modern Paint and Coatings.* 78(9): 35. September.

Muhlenkamp, Mack. 1988. "The Technology of Powder." *Modern Paint and Coatings.* 78(1): 52-68. November.

Nelson, Larry. 1988. "Door Market Opens to Low-VOC Coatings." *Products Finishing.* 53(3): 48-53. December.

Nordson. 1991. UNICARB™ System Supply Units. Amherst, Ohio.

Paul, Swaraj. 1986. *Surface Coatings Science and Technology.* John Wiley & Sons, New York, New York.

Pilcher, Paul. 1988. "Chemical Coatings in the Eighties: Trials, Tribulations, and Triumphs." *Modern Paint and Coatings.* 78(6): 34-36. June.

Poullos, Mark. 1991. "Laser Curing of Finishing Systems." *Pigment and Resin Technology.* 20(3): 4-6. March.

Product Finishing. 1986. "ICI Wins Pollution Abatement Award for Low Solvent Emission Paints." *Product Finishing.* 39(5): 23. May.

Richardson, Frank B. 1988. "Water-Borne Epoxy Coatings: Past, Present and Future." *Modern Paint and Coatings.* 78(4): 84-88. April.

Robison, G. Thomas. 1989. "Custom Coating for Over a Half Century." *Products Finishing.* 53(7), April.

Scharfenberger, Jim. 1989. "Spraying Water-Borne Coating Electrostatically." *Products Finishing.* 53(4): 48-56. January.

Smith, Mark D. 1990. "Low VOC Coating Alternatives." In: *First Annual International Workshop on Solvent Substitution*, pp. 237-244. Phoenix, Arizona, December 4-7.

Sun Chemical. 1991. *Suncure.* Northlake, Illinois.

Swanberg, David. 1990. "Water-Reducible Polyurethane Enamels: Candidate Low VOC Aerospace Topcoat Formulations." In: *First Annual International Workshop on Solvent Substitution*, pp. 229-235. Phoenix, Arizona, December 4-7.

Toepke, Sheldon. 1991. "Water Base Chemical Mill Maskant." In: *Sixth Annual Aerospace Hazardous Waste Minimization Conference.* Boeing Company, Seattle, Washington, June 25-27.

Trade Associations

Table 6 shows the trade associations and the technology areas they cover. Readers are invited to contact these trade associations and request their assistance in identifying one or more companies that could provide the desired technological capabilities.

Table 6. Trade Associations and Technology Areas

Trade Association	Technology Areas Covered	Contact
Association for Finishing Processes of the Society of Manufacturing Engineers	Industrial finishing operations	P.O. Box 930 One SME Dr. Dearborn, MI 48121 tel. (313) 271-1500
Federated Societies for Coating Technology	Decorative and protective coatings	492 Norristown Road Bluebell, PA 19422 tel. (215) 940-0777
National Paint & Coatings Association	Paints and chemical coatings, related raw materials, and equipment	1500 Rhode Island Ave. N.W. Washington, DC 20005 tel. (202) 462-6272
Powder Coating Institute	Powder coating materials and equipment	1800 Diagonal Rd., Suite 370 Alexandria, VA 22314 tel. (703) 684-1770
Radtech International -	Radiation-curable coatings	60 Revere Drive Suite 500 Northbrook, IL 60062 tel. (708) 480-9576