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# SUBSTITUTION CASE STUDY:

# ALTERNATIVES TO SOLVENT-BASED PAINTS

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University of Massachusetts Lowell

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The Toxics Use Reduction Institute
University of Massachusetts Lowell


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TOXICS USE REDUCTION INSTITUTE



The Toxics Use Reduction Institute is a multi-disciplinary research, education, and policy center established by the Massachusetts Toxics Use Reduction Act of 1989. The Institute sponsors and conducts research, organizes education and training programs, and provides technical support to governments to promote the reduction in the use of toxic chemicals or the generation of toxic chemical byproducts in industry and commerce. Further information can be obtained by writing the Toxics Use Reduction Institute, University of Massachusetts Lowell, One University Avenue, Lowell, Massachusetts 01854.




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## PREFACE

As more companies search for and develop environmentally safer production processes the need for information on cleaner production processes is on the rise. To promote knowledge of the availability of technically and economically feasible alternatives to toxic chemicals and products in the workplace, the Toxics Use Reduction Institute sponsors "substitution" studies. A substitution study focuses on input substitutes or process changes that eliminate or reduce the use of the toxic chemical or product and replace it with a safer alternative. The need for substitution studies arise because input substitution in manufacturing is a complex process. Factors that make input substitution a complex process include changes to product quality, product profitability, environmental and human health, and roles of employees. All of these factors must be included in a substitution analysis to understand the effects of input substitution. The purpose of the substitution studies is to provide an understanding of safer chemistries, processes, and products that are on the market and the benefits and costs to a manufacturer of switching to one of these alternatives.

The substitution studies prepared for the Toxics Use Reduction Institute are designed to provide information to technical assistance programs, manufacturers, and government toxics use reduction and pollution prevention programs on technically and economically feasible safer alternatives to toxic inputs. This report was prepared by the Tellus Institute for the Toxics Use Reduction Institute. The opinions expressed in this report are those of the authors and not necessarily those of the Toxics Use Reduction Institute.

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## 1. Introduction

Paint is a generic term typically used to identify a wide range of surface coating products, including conventional solvent-based paints, varnishes (clear coatings formed by evaporation of the solvent and then by oxidation and polymerization of the resin), enamels (pigmented varnishes), lacquers (films formed by evaporation only) and latex paints (water-based system). All comprise a resin and/or pigment suspended in a liquid vehicle which facilitates application of the material to a substrate. Paint products, therefore, are a complex group of protective and decorative coating materials with industrial, commercial and home uses. The function of paints is not only to provide an aesthetically pleasing colored and/or glossy surface, but also to help coated materials withstand exposure to both their environment and every day use.

Conventional paint systems (solvent or aqueous) typically comprise four major components: 1) resins (or binders), the plastic-like film-formers which ultimately form the coating; 2) diluents or solvents, which keep the resins in solution, allow them to spread, and which then evaporate, leaving the resin behind to cure and form the coating; 3) pigments and fillers, which provide color and enhance the hiding ability and body of the paint; and 4) additives, such as surfactants, driers, flattening agents, preservatives, biocides, anti-skinning agents, anti-foam agents and many others.

Paint industry products are broadly categorized according to their *use* into three major groups: architectural coatings, product coatings, and special purpose coatings. Architectural paints can be defined as "all shelf goods and stock type coatings that are formulated for normal environmental conditions and general application on new and existing structures,"[1] and include interior and exterior house paints and stains, as well as undercoaters, sealers and primers. Product coatings are paints sold to and used by original equipment manufacturers (OEM). Paint consumers in this sector include producers of wood furniture and fixtures, metal containers, automobiles, machinery, metal furniture, metal coil, appliances and many others. Special purpose coatings are those used for automobile and machinery refinishing, high-performance maintenance, bridge maintenance, traffic paint, aerosols, and the like. In 1990, architectural coatings accounted for 52% of surface coating shipments, product coatings for 32%, and special purpose coatings for 16 percent.[2] In 1987 most of the architectural coatings sold were water-based (73%), while the overriding majority of product and special purpose coatings are still conventional solvent-based systems.[5]

This section focuses on the substitution issues surrounding the *use* of solvent-based coatings (as opposed to their production) and the coating alternatives available for these applications. Section 1.1 provides a description of the conventional solvent-based paint system and the environmental and health concerns they present. Section 1.2 provides general descriptions of the predominant substitute opportunities available to replace solvent-based paints, highlights some of the pros and cons of their use in general and, when available, in specific applications. Success or failure of a substitute technology is inextricably related to the substrate on which the coating is being used. That is, one alternative system may work for metal but pose serious difficulties when used on wood. As discussed in the "Substitution Methodology" section, because paints are a product and not a chemical, it is difficult using TURA data to identify Massachusetts users of solvent-based paints. For this reason it is difficult to address solvent-based paint substitute opportunities specific to Massachusetts. Instead, we highlight some generic issues surrounding applications to metal, wood, and plastic. Although architectural coatings is the largest paint use category, this application is not addressed in this study since most of the coatings used today are water-based. Even though they are not material substitution opportunities, Section 1.3 briefly describes coating application techniques which can reduce the amount of VOCs emitted to the atmosphere.

## 2. Conventional Solvent-Based Paints

Solvents allow coatings to be applied in liquid form. The primary function of the solvent is to disperse or dissolve the paint binder/resin to make the paint formulation less viscous and suitable for application. The solvent also helps to clean any residual grease or dirt from and to wet the surface, enhancing both adhesion of the film and penetration. Solvent characteristics also influence application properties such as consistency, setting rate, drying time and flow.[6]

The major components of solvent based paints are the vehicle (solvent and resin), fillers, and additives. The vehicle comprises the total liquid content of the paint and includes the binder (which may be a naturally occurring resin or oil, or a synthetic resin such as an alkyd, acrylic, or epoxides) and the solvent. The solvent portion of the vehicle evaporates after the coating has been applied, and the paint cures as the evaporation takes place.

As traditional solvent-based coatings dry, organic solvents evaporate and are released into the air. Many of the volatile organic compounds commonly used in solvent-based coatings formulations are "ozone precursors", that is they are photochemically transformed to form ozone. Much of the attention focused on reducing the use of solvent-based coatings has come about largely in response to recent governmental regulations restricting the amount of volatile organic compound (VOC) in coating materials such as sealers, fillers, stains and paints. Federal limits on the VOC content of paints, dating to September 1987, require all flat and non-flat architectural paints to contain less than 250 grams VOC per liter of paint.[7] Proposed federal standards allow wood and plastic coaters to emit 50 tons of VOCs per year. If a facility produces more than 50 tons of VOC emissions, the state of Massachusetts places limits on the coatings that can be used, in terms of pounds of VOCs/gallon of solids applied. The limits vary widely within a substrate category depending upon the type of coating that is being applied, what is being painted, and whether or not pollution control devices are being used. For wood there are six different coating categories, and proposed limits range from 13 to 89.4 pounds VOCs/gallon solids applied. In the coating of miscellaneous plastics parts, proposed limits vary from 1.4 to 11.6 pounds VOCs/gallon solids applied. Federal regulations allow metal coaters to emit 10 tons of VOCs per year. For coaters emitting VOCs beyond that threshold, Massachusetts limits are 5.1 to 10.3 pounds VOCs/gallon solids for metal furniture coaters, and a similar limits for miscellaneous metal parts coaters.

Some common solvents used in solvent-based paints include toluene, xylene, methyl ethyl ketone (MEK), methyl isobutyl ketone (MIBK), acetone, and methylene chloride.[8]
In addition to the environmental compliance issues surrounding solvent-based paints, worker safety is a concern. Organic solvents render solvent-based paints as hazardous due to their flammability and/or toxicity. Table 1 summarizes the health hazards and exposure limits associated with these solvents.

## 3. Alternative Coating Systems

The main driving forces behind the development and improvement of alternatives to solvent-based coatings formulations has been the environmental regulations and health concerns of the solvents used in conventional systems. Because coaters have had to meet increasingly stringent air pollution regulations, coating producers have had to develop lower VOC coatings which allow the user to comply with federal and state standards.

The alternatives to conventional solvent-based paints fall into two categories: reduced VOC alternatives and nonvolatile alternatives. The reduced VOC content alternatives include water-based (latex) systems, high solids coatings and the supercritical fluid spray application, or UNICARB, technique. Water-based coating systems rely upon the evaporation of water instead of organic solvent, but a small amount of solvent is still used in the formulation. High solids coatings contain less solvent and more solids than conventional paints, while the UNICARB system replaces some of the solvent content with supercritical fluid carbon dioxide. Nonvolatile coatings such as powder, do not rely on the evaporation of solvent or water for their use.

### 3.1 Water-based Coatings

The composition of water-based paints is very similar to that of solvent based except that water rather than organic solvents is used as the liquid carrier, in which the resin is dissolved, dispersed or emulsified. Most aqueous paints still contain small amounts of solvents, such as glycol ethers, in order to facilitate the dispersion of the resin in the water. Water-based paints are typically composed of water, pigments, resins (usually an organic polymer such as an alkyd, polyester, vinyl acetate, acrylic or epoxide), extenders (to extend drying time), ammonia, dispersant, anti-foam additives, dispersant, anti-foam additives, polyvinyl alcohol emulsion, and a preservative.[9] Waterborne coatings have been successfully applied to metal, wood, and plastics.

TABLE 1. WORKER EXPOSURE LIMITS FOR VARIOUS PAINT SOLVENTS

| Chemical | Exposure Limits [1] OSHA [2] | NIOSH [3] | ACGIH [4] | Routes of Exposure | Health Hazards | Other Hazards | Source |
|---|---|---|---|---|---|---|---|
| Toluene | 200 ppm & 300 ppm; 500 ppm | 100 ppm & 200 ppm | 100 ppm & 150 ppm | Inhalation, Contact | May cause mutations; skin, eye & respiratory irritant; dermatitis; long term exposure may cause liver & kidney damage. | Flammable liquid; Fire hazard | 2 |
| Xylene | 100 ppm | 100 ppm & 200 ppm | 100 ppm & 150 ppm | Inhalation, Contact | May damage developing fetus; skin, eye & respiratory irritant; may cause head- aches, nausea & vomiting; long term exposure may cause bone marrow, liver & kidney damage. | Flammable liquid; Fire hazard | 1 |
| Methyl Ethyl Ketone | 200 ppm | 200 ppm | 200 ppm | Inhalation, Contact | Possible teratogen; skin, eye & respiratory irritant; can severely burn eyes & skin; can cause headaches, dizziness, nausea, blurred vision, dermatitis. | Flammable liquid | 1 |
| Methyl Isobutyl Ketone | 100 ppm | 50 ppm | 50 ppm | Inhalation, Contact, Ingestion | Skin, eye & respiratory irritant; may cause headaches, narcosis, unconciousness, dermatitis. | Flammable liquid | 3 |
| Acetone | 1,000 ppm | 250 ppm | 750 ppm & 1000 ppm | Inhalation, Contact | Skin, eye & respiratory irritant; may cause dizziness, unconsciousness; long term exposure may damage liver, kidneys & cause dermatitis. | Flammable liquid; Fire hazard | 1 |
| Methylene Chloride | 500 ppm; 1000 ppm; 2000 ppm | [5] lowest feasible concentration | 50 ppm | Inhalation, Contact, Ingestion | Potential carcinogen; skin, eye & respiratory irritant; may cause dizziness, headaches, unconsciousness; long term exposure may cause bronchitis, liver damage. | Flammable at high temps. | 2 |

Notes:

[1] Exposure limits are for air levels only.

[2] Legal airborne permissible exposure limit averaged over an 8-hour workshift and 40-hour work week & limit not to be exceeded during 15 min. period; max peak concentration (latter two if applicable).

[3] Recommended exposure limit averaged over an 10-hour workshift & limit not to be exceeded during 10 min. period; max peak concentration (latter two if applicable).

[4] Recommended exposure limit averaged over an 8-hour workshift and 40-hour workweek & short term exposure limit (STEL, if applicable).

[5] Methylene chloride OSHA limits: legal airborne exposure limit is 500 ppm; an exposure of 1000 ppm should not be exceeded at any time, with the exception that a peak exposure of 2000 ppm for a period of 5 minutes is allowed in any 2 hour period.

Sources:


1. "Hazardous Substance Fact Sheets," prepared by NJDOH, distributed by U.S. EPA Office of Toxic Substances, August 1985 - November 1986.
2. "Recommended Safe Practices Bulletin," MA DLI, Division of Occupational Hygiene, 1989.
3. "NIOSH Pocket Guide to Chemical Hazards," September 1985.

One advantage of working with waterborne coatings, in addition to reducing VOC emissions during curing and worker exposure to the solvents, is that the overspray resulting from spray application can easily be recovered with water, concentrated, and reused. Equipment can be cleaned with water instead of solvents, which further reduces VOC emissions and worker exposure. Using water-based paints reduces the combustibility/flammability hazard associated with solvent-based paints. In addition to reducing the risk of fire in application and storage areas, water-based coating users realize an associated drop in insurance costs. A key advantage to substituting solvent-based paints with aqueous coatings is that they can be applied with conventional spray equipment; no new investment in application equipment is necessary. Many other alternatives to solvent based coatings require special equipment to be used in the application and curing processes.

Waterborne coatings pose some challenges to those accustomed to using solvent-based paints. One problem is that they are difficult to apply under humid or inclement weather conditions. Application of aqueous paints can be difficult in colder temperatures since the viscosity of the paint increases as the temperature decreases. Often times, water-based paints have a longer drying time than solvent-based paints, which can decrease plant productivity or require investment in a drying oven. In addition it is important that the substrate being painted be very clean in order for the water-based paint to adhere to the surface. While the cleaning/degreasing ability of the solvents in solvent-based paints allows them to be successfully applied to substrates contaminated with residual grease or dirt, waterborne coatings require surfaces clean of any grease or dirt if the coating is to adhere properly. Therefore, while the use of waterborne coatings reduces VOC emissions in the coating stage, it may require the use of solvents in the cleaning process, which could negate the coating line VOC emission reductions. In terms of the final product quality, aqueous coatings are simply unable to provide the same gloss as solvent-based paints which may result in an "unacceptable" finish. Finally, water-based coatings typically cost significantly more than solvent based coatings. One industry source estimated solvent coatings at $12/gallon and aqueous coatings at $20/gallon, when bought in bulk.[10]

Not all of the resins used in water-based coatings are water-insoluble once the coating has cured. The resolubilization of an aqueous paint with water is referred to as water spotting or water sensitivity. Additives are blended with urethane resins to catalyze the crosslinking of the urethanes, which eliminates the potential for water spotting. Some industrial producers of water based coatings have expressed concern over the safety of the catalysts, such as polyfunctional aziridine, used with the crosslinking agents.[11] Although occupational exposure limits have not been established, the Material Safety Data Sheet for the aziridine indicates that it is slightly toxic by inhalation, absorption or ingestion. This component of some water-based paints illustrates the need for users to consider any new hazards that may be incurred in the switch from one coating process to another. Reduced impact resistance is a problem that has also been addressed in the formulation of water-based paints. Because water-based paints are usually composed of low molecular weight resins such as styrene, the coatings can be hard but brittle, which may lead to cracking and delamination of the coating. To increase the impact resistance of water-based paints, high molecular weight resins, such as acrylics, can be blended into the formulation. While the acrylics are safe to the paint user, creating them from monomers such as acrylonitrile exposes the producer to a probable carcinogen. Obviously this same hazard exists if a solvent-based acrylic resin is produced from acrylonitrile (see radiation-curable coatings section for a discussion of the hazards of acrylonitrile).

A Massachusetts producer of specialized metal tool cabinets has successfully switched from solvent-based to water-based paints in their coating operations. The painting process involves coating the metal drawers with a primer coat, and then spray painting the cabinets and drawer fronts with the color coat. Originally the components were spray-painted with solvent-based (xylene) paints for both the primer and color coats. In August 1981, the company switched over to a water-based first coat for the metal drawers, which is applied by electrodeposition in a fully automated process line. After the paint is applied, the drawer is low temperature baked at 250-275°F and conveyed to the spray booths for color coating. Although the reasons for implementing the electrodeposition tank were based on the fact that the process provided a better finish and increased production capacity, use of the electrodeposition tank also eliminated the waste produced from the spray paint application of the primer coat. The entire cost for the electrodeposition system was about $500,000 and included purchase and installation of the baking oven, the 2500 gallon tank and the control system.

Because of their desire to eliminate all solvent-based coatings, the company is currently converting their color coating spray line from solvent-based to water-based paints applied with a high volume-low pressure spray gun. As part of the water-based spray line system, they will be installing a filter to reclaim the overspray from the water that collects the paint from the spray booths so that the paint can be reused. This process has been used successfully by the corporation's parent company for a number of years. Switching to the water-based system reduces VOC emissions, reduces the fire hazard; the new recovery system eliminates the generation of waste paint.

Changing to a water-based spray system means incurring higher paint costs: current solvent-based paint costs $12 to $20/gallon and the water-based formulation will cost $25 to $30/gallon. The capital investment for the switch to water-based spray paints will be large, and includes purchasing and installing the new recovery system, disposing of the solvent contaminated clean-up water now circulating through the spray booths and purchasing the new spray guns. With the backing of the parent company, they can afford to make the switch, and expect to amortize costs within a "reasonable" (less than 5 years) period of time. Although figures for cost and payback period were unavailable, it was pointed out that companies of this size in Massachusetts would be unable to afford this type of recovery system.

The company considered powder coatings and high solids coatings (discussed below) as alternatives to the solvent-based spray painting line. In a market where customers expect a wide range of color options, they felt that the extensive clean-up and time associated with color switching in powder coating systems made it impractical. As well, they felt that the application technology for high solids painting is not proven, particularly if the painter is not experienced in working with high solids paints.

Another metal coater, Emerson Electric Company, has reported environmental and economic benefits from switching from solvent-based paints to a water-based electrostatic immersion painting system. Emerson, a producer of power tools, was concerned with the paint wastes generated at the facility. Replacing the solvent-based painting system with a water-based electrostatic immersion system has reduced waste solvent and waste paint solids generation by more than 95 percent. As well, the electrostatic painting system reduced paint costs by $600,000 per year. No capital investment data or per unit production data were available.[12]

The application of water-based coatings to wood products is technologically tricky because it involves applying water to a substrate that usually has been kiln dried in order to remove the water. Aqueous coatings have been used on wood products with mixed results.

Hoobert Toys started manufacturing wooden toys in Massachusetts approximately seven months ago. Prior to that, the company was a one-person operation in New York. From the outset, the Massachusetts owners were interested in using water-based paints (instead of the oil-based lacquer that had been used) in order to avoid the safety (combustibility and toxicity) and environmental issues linked to use of solvent-based paints. Although they may have been able to comply with current emission regulations while using the oil-based paint, the owners believe it is an investment in the future to start using the water-based coatings now. Reducing the use of oil-based paints also reduces the risk of fire, and the insurance costs associated with that risk. At the New York facility, toys were coated with oil-based paint with a soy-based resin and a VOC content of 4.5 to 5.0 pounds/gallon. The water-based acrylic paints currently being used contain 2.3 to 2.9 pounds VOC/gallon. The cost for both paints is approximately $25.00/gallon.

Although use of water-based paints has been fully implemented, some of the issues the toy producer and paint supplier are currently grappling with is the tendency of water-based paints to raise the grain of the wood and not provide the same filling ability that solvent-paints do. Solvent-based paints have the ability to fill in all the wood "dents and dings", giving the wood a very smooth appearance and texture. The same number of coats of water-based paints is unable to provide the same smooth, unblemished appearance. The filling ability of the water-based paints may be improved with the addition of some additives, and this route is currently being tested. Another shortcoming is that the water-based paint does not give the same high-gloss finish as the oil-based paint. The company is considering adding a coat of clear gloss over the water-based paints to brighten the finish.

On the benefits side, one of the unexpected advantages of water-based paints is that drying time for the toy components has decreased. The combination of water-based paint and a small, inexpensive drying tunnel allows the coating to dry much faster than the slow-dry oil based paint that had been used. This allows the spray painting line to operate continuously;

pieces do not have to be removed from the line, allowed to dry, and then returned for the next application of paint. As well, the acrylic resin used in the water-based paint is UV stable so the coating will not yellow with age, whereas the solvent resin is not UV stable and will cause the coating to yellow over time.

Earlier editions of Hoobert's Toys were coated with an oil-based paint, and provided plastic-looking finish. Although this is the look the Hoobert Toys still wishes to market, they believe the environmental and health benefits of working with water-based paints makes a compromise worthwhile. While the exact same finish may not be attainable, the owners feel that there is a very acceptable quality level that can be attained using the water-based paints.[13]

In a project conducted by the General Service Administration (GSA), in cooperation with the EPA and the U.S. Army, a low-VOC finishing system for the manufacture of wood furniture was evaluated and compared to an equivalent conventional solvent-based system. The low-VOC coating system included a waterborne toner/washcoat, a catalyzed sealer, and a catalyzed topcoat. The waterborne toner used contained only 43% VOC (by weight) as compared to conventional washcoat and toner which contained 92.1% and 99% VOC, respectively. The major disadvantage observed with the water-based toner was that the water in the formulation caused grain raising, creating a rough surface which required extra sanding. Grain-raising also allowed the stain to penetrate more deeply than in conventional solvent systems, producing a darker color. However, adding extra retarder to the filler and removing excess stain by wiping with naphtha helped to mitigate the problem. The material costs for the entire low-VOC system were less expensive than conventional systems ($4.59 versus $5.98/unit furniture), production rates were unchanged, and no equipment changes were necessary as the low-VOC coatings were applied with in-house equipment. Labor requirement were estimated to increase about 6% in the low-VOC system because of the need to sand and wipe the wood surface after application of the water-based toner.[14]

### 3.2 High Solids Coatings

High solids coatings contain the same basic ingredients as conventional solvent-based systems, but in different amounts. For example, the normal solids content for nitrocellulose resin coatings (typically used in the wood furniture industry) ranges from 8-30 percent. High solids coatings can achieve solids contents of 60-100 percent using acrylic and polymer binders.[15] High solids coating formulations tend to use low molecular weight resins with highly reactive functional groups to aid in polymerization; coatings being used and tested include polyurethanes cured by isocyanate, polyesters, polypropylene, and acrylics. High solids paints can be applied to wood, plastics or metal, but the best results have been attained on metal substrates.

Although it is possible to use the basic equipment, like the spray booth and curing ovens, with high solids formulations as with solvent paints, high solids require special spray equipment because of their high viscosity. One means of remedying this problem is to add an in-line heater to the application equipment which raises the temperature of the paint, effectively reducing the viscosity. It is important that spray painters be retrained when switching to high solids paints because the tendency is to apply too much paint. High solids coatings contain twice as much solid as conventional paint. In addition, because there is less solvent, the coating does not give the same wet look as conventional solvent paints when it is applied, so the sprayer is inclined to use more paint.

In the use of high solids coatings, surface preparation of the substrate is critical. Because there is less solvent in the high solids coating mixture, less solvent is available to clean/wet surfaces that are contaminated. While the solvent in solvent-based paints can "clean" a contaminated surface as it is applied, and at the same time deliver a smooth coating, high solids paints will not apply evenly to a contaminated surface. As with aqueous-based coatings, depending upon the cleaning operations used at a facility, the use of high solids paints may decrease VOC emissions associated with the painting process, but this could be offset by the use of additional cleaning solvents.

The switch from solvent-based to high solids paints has resulted in both environmental and economic improvements at the Freightliner Truck Manufacturing Plant in North Carolina. During 1989 high solids paints were substituted for conventional paint types, which increased paint transfer efficiency, reduced VOC emissions, and reduced paint wastes by 30 percent. The high solids paint substitution resulted in savings of $28,000 in paint purchases and paint disposal costs over the course of 1989.[16]

### 3.3 Powder Coatings

The use of powder coatings as an alternative to liquid, solvent-based coatings results in a significant reduction in VOC emissions. Powder coating has been characterized as the lowest VOC content coating among the options available to industrial finishers.[17] Powder coatings produce exceptionally tough coatings that do not drip or run during application. The use of higher molecular weight resins gives powder coatings extraordinarily high impact resistance. Powder coatings contain little or no solvents in their formulation, and are unique in that they are applied dry to the object to be coated. While conventional paints rely on solvents or water to facilitate application of the resinous binder over a surface, powder coating technology uses a dry paint which does not need a volatile carrier for the purposes of coverage or flow. Elimination of the volatile carrier allows VOC emissions to be eliminated in the coating process.

Powder coatings consist of a finely pulverized powder of thermoplastic or thermosetting resins mixed with pigments. These coatings are sprayed on dry, usually with electrostatic spray equipment. The coated part is then baked, causing the resin to melt and/or polymerize. Once cooled, the powder forms a tough, durable coating. Powder coatings are not really considered paint until the coated item emerges from the curing or fusion oven.

Because powder coatings are applied in a dry form, most resins used in these coatings are quite different from those used with liquid paints. While liquid paints require resins which are soluble or miscible with solvents or water, powder coatings require resins which are solid materials capable of melting sharply to low viscosities in order for them to flow into a continuous film when heated.

There are two major classes of powder coatings resins: thermosetting and thermoplastic. **Thermoset** resins are based on epoxy, polyester, polyurethane, and acrylic systems, which when heated in presence of a curing agent, fuse to a continuous film and then react chemically to form a higher molecular weight polymer. The thin film created by these resins demonstrates outstanding physical properties and corrosion resistance. **Thermoplastic** resins are high molecular weight polymers (nylon, polyvinyl chloride, fluoropolymers, and polyolefins) which, due to their high melt viscosity, are used mostly in thicker film applications.[18]

The User's Guide to Powder Coating describes two methods of powder coating application. In the fluidized bed method, the powder is placed in a "suitable container" and fluidized. The heated part is then "dipped" into the bed of fluidized powder and the powder, upon contact with the hot part, melts and adheres. In the more widely used electrostatic spray application method, the powder is dispersed in an airstream and each particle is given an electrical charge. The charged cloud is then directed to the part to be coated, which is grounded. The powder is held to this part by the electrostatic charge imparted to the powder during the spraying process. This attraction is sufficient to hold the powder on the surface during subsequent handling. In both of these methods, once the powder layer is in place the part is heated to completely convert the powder layer to the final desired coating.[19]

Current applications of powder coatings include linings on the inside of oil drilling pipes, reinforcing steel bars, truck primer/surfacer, automotive parts (wheels, bumpers, mirror frames, oil filters, battery trays and coil springs), major appliance parts (range housing, freezer cabinets, dryer drums, and microwave oven cavities), outdoor furniture, farm equipment, aluminum building products, bicycle frames, air conditioner housings, small appliances, and office furniture components. Film thicknesses range from 0.03 mm to 0.38 mm and can be produced in a variety of colors, textures and glosses.[20]

Although most of the powder coating industry is focused on the finishing of metal, a variety of other materials are being coated with powder, including plastics, glass, ceramics, metals and wood. That the substrate must be metallic in order for the charged powder to adhere, and that the substrate needs to withstand high oven temperatures for extended periods in the powder curing process, are common misconceptions concerning the limitations surrounding the use of powder coatings. Powder coatings are electrostatically applied to non-metal surfaces, sometimes aided by an electrostatic agent, sometimes with a preheat step, and sometimes with no special handling at all. Development of lower cure temperature resin systems and high intensity infrared radiation (IR) ovens have allowed powder coatings to be applied to wood and heat deformable plastics.

Much has been accomplished with powder coating applications to plastics, particularly with thermosetting fiber reinforced plastics (FRP). Powder coatings can be used in both pre-mold and post-mold coating processes. For example, in the pre-mold process, the powder coating is applied to the hot mold before the FRP. The powder melts almost instantaneously and reacts within seconds upon contact with the hot mold surface. However, the coating in contact with the atmosphere remains unreacted and does not begin to react until it is in contact with the plastic surface. Pre-mold coating applications include whirlpools, bathtubs, and motorcycle helmets. For post-mold applications, the cured thermoset part must be treated with an electrostatic agent (usually alcohol or aqueous dispersion of metal salt). Convection and high intensity IR ovens are used to cure the coating. Plastic parts cured out of the mold include automotive panels, and architectural pieces.

The economy of powder coating ceramic materials versus traditional glazing is extremely favorable due to lower oven temperatures, very high yields, and low defect rates. The substrate must be preheated for the powder to adhere properly. End products suitable for a decorative powder coat finish on ceramic substrate include flower pots, electric insulators, wall tiles, lamp bases, and a variety of other decorative ware. The application of powder to glass is the same as ceramic, but adhesion of powder to smooth surface can be difficult and requires the user to choose powder chemistry carefully. Current practical wood products for powder coating include furniture, shelving and door panels.[21]

A Massachusetts coating supplier suggests that powder coatings are good for large run, same size and color operations (such as painting horse shoes). Powder coating is most efficient if it is being used to paint the same type of object, the same color, repeatedly (such as metal shelving) because the facility needs a dedicated line for each color. Switching colors on a line is very time consuming, and carries the risk of old color that was not completely cleaned up being mixed in with new color application.[22]

However, the experience on a coating line at the Advanced Composite Structures facility in Canada has been that a color change can take place in less than an hour if the powder is heading for scrap. In their spray booths, air blows the majority of the powder off the walls and a dry squeegee is used to remove any remaining particles. If powder is reclaimed, more work is required and process may take an additional hour. Scrap powder (collected but not reused) is usually landfilled, but sometimes different colors are collected, mixed and sprayed on parts where color is not an issue but protection is.[23] Short color switching times have also been documented by Nepco of Canada, a division of Wiremold Canada Incorporated. Nepco manufactures products such as underfloor ducts and overhead wireways, and has installed a powder coating line on which color switching takes anywhere from ten minutes to half an hour.[24]

There are a number of environmental, worker safety and economic advantages to using powder instead of liquid solvent paints. Since powder coatings are 100% solids and contain no solvents, they are ready to use straight from the box. This eliminates worker exposure to solvents and environmental releases of VOCs associated with the mixing and thinning of solvent-based paints. Because solvents are eliminated from mixing, application or clean-up, venting, filtering and solvent recovery systems required to control VOCs are unnecessary, resulting in significant reductions in energy costs. Fire hazards generally associated with solvent paints are eliminated. Up to 99% of overspray resulting from powder coating applications can be recovered and reused, which helps reduce raw material and waste disposal costs. Because powders are 100% solids and almost all are classified as nonhazardous, their use eliminates or minimizes the problems and cost associated with hazardous waste storage and disposal. When waste is an issue, it can usually be treated as a non-water soluble solid.

A comparative economics study published by Powder Coating Institute in 1990 revealed that the total annual operating costs of a powder coating system resulted in yearly cost savings of $76,000 over high solids, $225,000 over waterborne, and $214,000 over a conventional solvent system.[25] Bocchi reports that for metal finishing, powder coating advantages are even greater, citing the annual savings realized by a Canadian furniture manufacturer when they switched from a "wet" system to powder coating: $432,000 in labor, due to less labor for pre-application mixing (powder is ready-to-use), maintenance and clean-up, and because powder allowed for increased automation of the coating line; $173,000 in coatings; $61,000 in waste treatment; $69,000 in energy; and $18,000 in other areas.[26] Although hard numbers were not provided, the *User's Guide to Powder Coatings* suggests that the capital costs associated with the installation of a powder coating system are becoming more competitive with those expended when installing a liquid coating system, and less expensive than the installation of an electrocoating tank system. Many finishers "are experiencing a one year or less payback period upon installing the powder coating system."[27]

Powder coatings are dispersions of various ingredients (curing agents, catalysts, pigments, etc., all dispersed in resin) that have little or no solubility in water, therefore the most likely routes of exposure are through skin contact or inhalation of dust. Pigments, curing agents, polymers and fillers all present potential health hazards if permitted to escape the spray containment area, because of improper ventilation or because of improper handling or use of the powder. While most powder coating ingredients are inert or of a low degree of hazard, some ingredients may be hazardous, therefore threshold limit values vary somewhat with coating composition. Experience with powder coating materials has determined that most should be classified as nuisance dusts with a threshold limit value of 10 mg/m3 (the OSHA regulation for a nuisance dust). Because powder coating materials may form explosive mixtures with air (as is the case with any finely divided organic material), care must be taken to keep the concentration of the powder in the air well below the lower explosive limit (the lowest concentration of powder dispersed in air which will explode when ignited). Carefully designed application and recovery equipment, as well as fire detection systems help to minimize the potential for an explosion.[28]

To reduce potential health hazards associated with powder coating materials, the *User's Guide to Powder Coatings* lists the following basic suggestions:

- Wearing gloves and masks when transferring the powder into other containers, during maintenance of equipment, or disposing of empty containers because exposure to the skin for extended periods may cause drying of the skin.

- Washing skin exposed to powder materials with soap and water.

- Avoiding exposure to respiratory inhalation. If powder contamination is in the air, respirators or masks should be worn.

Caution must be used in operating the electrostatic powder coating spray system; guidelines for proper safe operating procedures are provided by the National Fire Protection Association.

### 3.4 Radiation-cured Coatings

Radiation-cured coatings, like powder, have little or no solvents in their formulation. These coatings are cured almost instantly upon exposure to ultraviolet light (UV-cured), infrared light (IR), high-energy electron beams (EB-cured), or microwave radiation which causes the coating to polymerize and harden. Although only UV and EB curing appear to be of commercial importance for paints and coatings today, IR curing is being used on a large scale in some paper coating operations.[29] Because of the absence (or near absence) of solvent, radiation-curable coatings offer another means of eliminating or reducing emissions of VOCs. These coatings cure rapidly; they do not require high temperatures to cure the coatings and, therefore, are especially useful on heat-sensitive materials such as paper, wood, and plastics.

UV-cured coatings are the most common of radiation cured systems, and are composed of a low molecular resin containing olefinic bonds (liquid reactive monomers or oligomers), a very small amount of reactive solvent which also contains unreacted bonds, and a photoinitiator. The coatings may also contain pigment and additives such as antioxidizing agents and optical brighteners. The photons generated by UV light initiate the curing process in these formulations.

Radiation-curable coatings are currently being applied to, in order of decreasing use, plastics, wood, paper, and metal. Some major uses include flat-stock fillers in particle board and hardwood floors, as well as glossy coatings for cans, no-wax floor tiles, and wood finishes. Because UV and EB curing is initiated by exposure to a radiation source, many users think of radiation-curable coatings as suited only for production line coatings of flat-stock products. Although flat materials cure best, coating of three-dimensional objects is possible; carefully designed equipment allows all parts of a products to be exposed to the light.[30]

In the past, UV systems were unable to cure pigmented systems because the lamps used only produced UV light at the lower end of the spectrum. Lamp systems have improved, and they are capable of curing pigmented coatings. Previous to this development, only electron beam systems could cure pigmented coatings. This is an important development, as the cost of UV cured systems is much lower than EB curing systems. One industry source is cited as saying that start-up costs for UV curing systems range from $4200 to $200,000 for the largest system. Electron beam systems require a significantly larger capital investment, ranging from $750,000 to $1 million. Note however, that heavily pigmented, thick coatings still will not cure well under UV light, and still require an electron beam curing system.[31]

The cost of radiation-curable coatings ranges from $15 to $100 per gallon, which means that coating costs can be competitive with other paint systems. Because the coatings cure almost instantaneously upon exposure to the light source, radiation cured coating systems dramatically decrease the "drying" time required in other systems. This means that subsequent production steps, such as furniture assembly, or packaging can take place shortly after coating application. UV/EB curing also offers considerable reductions in energy requirements as compared to the thermal drying process; although EB curing is five to ten times more energy efficient than UV curing, UV systems are 50 to 100 times more energy efficient than oven curing. Unlike the aqueous alternatives to solvent based paints, radiation curable coatings give the same finish regardless of environmental conditions.

Almost all radiation curable coatings are made with acrylate materials. Therefore, worker safety concerns associated with the use of radiation-curable coatings focus primarily on the acrylate materials used in the coatings. The problem lies in exposure to the UV resins while they are still in the unreacted form, and is an issue for both the users and producers of radiation-curable coatings. Acrylate materials such as acrylonitrile are known skin and eye irritants, and are probable carcinogens. Acrylonitrile can affect workers through either inhalation or exposure to the skin. High exposure to acrylonitrile can cause collapse and death. Low exposure may cause weakness, headache, confusion and vomiting. Vapors may irritate the eyes, nose, throat and lungs, whereas skin contact can cause irritation and severe blistering.

Acrylonitrile is classified as a probable cancer-causing agent. The OSHA permissible exposure limit is 2 ppm averaged over an 8-hour work shift and 40-hour work week, and 10 ppm, not to be exceeded during any 15-minute work period. The NIOSH recommended airborne exposure limit is 1 ppm over an 8-hour workshift and 10 ppm, not to be exceeded during any 15-minute period.[32] In 1987, the suppliers and users teamed up to form Specialty Acrylates/Methacrylates Panel (SAMP) to test the toxicity of the acrylates. Testing to date is incomplete.

As with all toxic materials, proper ventilation and handling can help minimize any potential problems; it is recommended that all those working with acrylate materials wear safety glasses or goggles and impervious gloves to avoid all skin and eye contact. At least one producer of radiation curable materials has developed a family of materials, vinyl ethers, that can be used in place acrylates and have low-toxicity (not non-toxic) profiles.[33] No information on the performance of these acrylate alternatives was available.

### 3.5 Supercritical Fluid Spray Application (UNICARB)

The basic concept behind Union Carbide's UNICARB system is to replace conventional solvents in spray applied paint and coatings formulations with supercritical carbon dioxide, thereby reducing VOC emissions. Carbon dioxide can replace up to two thirds of the organic solvent concentration in conventional coatings, and reduce VOC emission by 30 to 70 percent and is applicable to metal, wood and plastic substrates. While conventional coatings may contain 4.0 pounds of VOCs/gallon paint, replacing solvent with carbon dioxide reduces the VOC content to 2.8 pounds/gallon. The system allows for a reduction in VOCs while still using high molecular weight polymers (has been demonstrated using acrylics, polyesters, cellulosics, alkyds, and commercial paints and lacquers in clear, pigmented and metallic systems). Aside from reducing VOC emissions, the UNICARB system offers other advantages associated with decreasing solvent use: reduces worker exposure to solvents and reduces fire hazards. However, care must be taken when working with this high pressure gas, as typical pressures in the airless spray operation range from 1200 to 2200 psig, and the operating temperature may range from 100 to 150°F.

The UNICARB system does not create carbon dioxide, but instead uses by-product carbon dioxide from other industrial processes such as ammonia and natural gas production, and fermentation. Carbon dioxide is an inexpensive, non-toxic and non-flammable gas. Although investment cost were unavailable, the system can be easily retrofitted into existing facilities.[34]

## 4. Alternative Application Techniques

In the industrial setting, one means of reducing both environmental emissions of and worker exposure to volatile organic compounds is to reduce the amount of paint used per unit operation. This requires increasing the transfer efficiency, that is, the ratio of the amount of coating solids deposited onto the surface of the coated part to the total amount of coating solids used[35] in the application process. For most industrial processes, the standard method of paint application is the air spray gun, which presents hazards due to overspray and rebound. Transfer efficiencies typically range from 20% to 40%.[36] This means that 60% to 80% of the paint used in a process is never applied to the substrate, paint that is ultimately wasted. Increased transfer efficiency also means less worker exposure to overspray, and less need for the solvents typically used during clean-up.

Some application alternatives which result in a greater than 40% transfer efficiency are: high volume, low pressure (HVLP) turbine, air-atomized electrostatic, and airless electrostatic. HVLP uses high volumes of air at low pressures (pressure limit is 10 psi) and is a form of air atomization. The lower pressure reduces overspray and improves transfer efficiency. The cost of HVLP equipment varies significantly, beginning at about $1,000 for a basic one-gun system to almost $20,000 for a complete, multi-gun system.[37] Electrostatic spraying involves using an electrical transformer capable of delivering up to 60,000+ volts to create an electrical potential between the paint particles and the surface being coated. These charged paint particles are thus electrically attracted to the object. Electrostatic guns capable of working with conventional solvent-based paints, paints with highly conductive resins, and water-based paints as well as powder have been developed. As with powder coatings, the hazards of working with an electric potential must be addressed. A wood furniture producer reported a 20% drop in finishing material costs when they replaced the conventional spray finishing line with an electrostatic finishing system.[38] The drop in finishing costs occurred because less coating was being used per piece of furniture, which can be translated into fewer VOCs per unit of furniture.

## 5. Conclusions

Historically, solvent-based paints have provided high quality, lasting finishes for almost all coating processes. Environmental regulations to reduce emissions of volatile organic compounds, which are ozone precursors, and concerns about worker exposure to organic solvents have heightened concern about the use of solvent-based paints. These issues, particularly regulatory pressures, have pressed coatings producers to provide low VOC alternatives to conventional solvent-based paints. Table 2 summarizes the positive and negative aspects associated with the solvent-based paint alternatives examined in this report.

Waterborne, high solids, powder and radiation-curable coatings all offer viable alternatives to conventional solvent-based paints. None of these options allow coatings users to simply switch from solvent-based paints and end up with exactly the same coating results. The coater may encounter additional costs for equipment and/or coating materials, a change in the appearance of the coating, and a need to retrain workers. All options, however, allow coaters to reduce VOC emission and worker exposure to toxic solvents, as well as reduce the fire hazard associated with solvent-based paints.

Water-based paints have been successfully applied to plastic, metal and wood. The major advantage in switching to water-based systems as opposed to other alternatives is that they require no new equipment for application. However, longer drying times usually associated with waterborne coatings may decrease plant production, or require investment in a drying oven. There also is concern over worker exposure to the crosslinkers often used in water-based paints. High solids coatings seem particularly suited for wood and metal applications. Because the composition of high solids paints is often very similar to solvent-based paints but contain less solvent and more solids, coaters can achieve coating colors and results very similar to those of solvent-based coatings. Application of high solids paints can be difficult and may require new equipment, such as a heater to reduce the viscosity of the paint just prior to application, and retraining of workers using the paint. Powder coatings have had their greatest success as metal coatings, but they are not limited to this substrate, and provide a coating that is often superior to solvent-based coatings. Radiation-cured coatings, because they do not require heat for curing, are especially useful for materials like paper, wood and plastic. Ultraviolet and electron beam coatings cure almost instantly, making it possible to dramatically increase productivity. The substantial capital investment in new equipment, and concerns about worker exposure to acrylates and methacrylates, may cause some coaters to reject this alternative.

Although alternatives to solvent-based paints do reduce worker exposure to toxic solvents, they by no means eliminate hazardous materials from the workplace. Some worker health concerns are similar for several different coatings. For example, acrylic resins can be used in any of the coating systems. However, concerns about their use are increased because both the coater, as well as the resin producers, are exposed to acrylic monomers such as acrylonitrile, a probable carcinogen. Some of the other hazards associated with the alternatives include exposure to crosslinking agents and working with an electric potential in electrostatic applications. Coaters considering alternatives to solvent-based coatings must carefully consider any new hazards that they may be introducing into the workplace environment.

Successful substitutions for solvent-based paints have been made when the users and suppliers work closely with each other to determine the option best suited to the substrate being painted, the coating process and purpose. Sometimes, the coater must decide exactly what constitutes an acceptable finish, and be willing to compromise the look of the finish to which they were accustomed, but not necessarily the actual quality of the finish, in order to make the facility more environmentally and worker-friendly.

TABLE 2. SUMMARY OF ALTERNATIVE PAINT COATINGS

| Alternative Coating System | Attributes of the Coating System | Coating Substrate | Technical Advantages | Technical Disadvantages | Capital Costs | Operating Costs | Product Quality | Environment/ Safety |
|---|---|---|---|---|---|---|---|---|
| Water-Based Coatings | Water is used as the liquid carrier instead of solvents. Small amounts of solvents are typically used to facilitate dispersion of the resin. | Metals | Overspray can be easily recovered and reused. Equipment can be cleaned with water instead of solvents. | Difficult to apply under humid or cold weather conditions. Often have a longer drying time. Substrate must be very clean. May lead to reduced impact resistance. | Sometimes, no new investment in application equipment is necessary. Although purchase of a drying oven, recovery system, and new spray guns may be needed. | Higher costs per gallon of paint. Reduced insurance costs (reduced fire hazard) and hazardous waste disposal costs. | Reduced "gloss" quality. | Reduced VOC emissions and worker exposure in spraying. Reduced combustibility and flammability hazards. Reductions, however, may be offset by the use of solvents in cleaning the substrate. |
| | | Wood | Drying time may be lessened when using a drying oven. Problem with "yellowing" over time is lessened. | Raises the grain of the wood and lessens the "filling ability" as compared to solvent-based paints. | Sometimes, no new investment in application equipment is necessary. Although purchase of a drying oven may be needed. | Shorter dryer time increases production speed. Higher costs per gallon of paint. Reduced insurance costs (reduced fire hazard) and hazardous waste disposal costs. | Reduced "gloss" quality, but acceptable product quality is achieved. | Reduced VOC emissions and worker exposure in spraying. Reductions, however, may be offset by the use of solvents in cleaning the substrate. |
| High Solids Coatings | Contain same basic ingredients as solvent-based coatings but in different concentrations: more solids less solvent. | Can be applied to wood, plastics, and metals, but the best results are attained with metals. | Can increase paint transfer efficiency, thereby reducing paint wastes and purchases. | Surface preparation of the substrate is critical. | Require special spray equipment because of high viscosity. | Lower operating costs due to reduce paint wastes and purchases. Workers need to be retrained. | Similar quality. | Reduced VOC emissions and exposure in spraying. Reductions, however, may be offset by the use of solvents in cleaning the substrate. |

| Alternative Coating System | Attributes of the Coating System | Coating Substrate | Technical Advantages | Technical Disadvantages | Capital Costs | Operating Costs | Product Quality | Environment/ Safety |
|---|---|---|---|---|---|---|---|---|
| Powder Coatings | Coatings are applied in dry form. Resins must be capable of melting sharply to low viscosities. | Mostly metals, although plastics, glass, ceramics, and wood can be powder coated. | Produce coatings with high impact resistance that do not drip or run. | In some cases the facility will need a dedicated line for each color, because changing colors can be time-consuming and carries the risk of contamination to new products. | Depends on method used, "fluidized bed method" or "electrostatic spray method". Fluidized bed method requires a "bed", oven to heat products, and equipment for moving products from oven to bed. Electrostatic static requires different spray equipment and "hardening" (baking) ovens. | Operating costs may decline due to lower labor costs (less pre-application mixing and more automation), expenditures on coatings, waste treatment, and energy. | Similar product quality. | Eliminates VOC emissions and exposure in spraying. Exposures to pigments, curing agents, polymers, and fillers may increase in poorly ventilated workspaces and through inadequate protective clothing (gloves and masks). Powder coatings can form explosive mixtures with air, therefore the concentration of the powder in the air needs to be well below the lower explosive limit. |
| Radiation-Cured Coatings | Coatings contain no or little solvents. Coatings are cured by exposure to ultraviolet light, high-energy electron beams, and infrared light. UV-cured coatings are the most prominent. | Used to coat plastics, wood, paper, and metal. | The coatings cure rapidly, requiring little to no drying time. Since high temperatures are not required for curing, they are especially useful on heat-sensitive substrates such as paper, wood and plastics. Less energy use in drying. | UV systems have difficulty curing pigmented coatings and coating three-dimensional products. | UV systems are much cheaper than EB systems. The cost range for UV systems is \$4,200 - \$200,000 and for EB systems from \$750,000 - \$1,000,000. | Costs per gallon of paint are competitive with other paint systems. | Similar product quality, although UV systems have difficulties coating three dimensional products and curing pigmented coatings. | Little to no solvents used. Potentially less energy use due to decreased drying needs. Exposure to acrylate materials must be controlled. Acrylates can contain acrylonitrile, a known skin and eye irritant, and probable carcinogen. |
| Supercritical Fluid Spray Application | Solvents are replaced with supercritical carbon dioxide. | Used to coat metal, wood and plastic substrates. | | | | | | Reduces solvent use and VOC emissions, and worker exposure to solvents. However, care must be taken in using supercritical $CO_2$, which is a high pressure gas used at temperatures ranging from 100 to 150°F. |

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