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Pollution prevention methods in the surface coating industry

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Abstract

The surface coating industry is rapidly changing to meet environmental and economic pressures. Some of the changes include new formulations which meet environmental regulations, higher performance finishes with improved properties, continued development of solventless technologies such as powder coatings and radiation curable coatings, and new application methods with improved transfer efficiencies. These changes will be accelerated by the 1990 amendments to the U.S. Clean Air Act. These new environmental laws will require industry through the Environmental Protection Agency (EPA) and state and local agencies to further reduce emissions of volatile organic compounds (VOCs) which are contributors to ozone formation in the lower atmosphere. The focus of this paper will be to examine the paints and coatings industry and those pollution prevention methods that are being applied to meet these environmental pressures. It will review the life cycle of paints and coatings; from its inception in the manufacturing facility to its ultimate application and disposal. It will also review developing low VOC technologies that are being considered worldwide to comply with increasing VOC regulations.

Introduction

The manufacture of paints and coatings is big business with sales nearing $12 billion yearly [1]. In 1987, the U.S. consumed 1.047 billion gallons (3.9 10^9 L) of paints and coatings (See Fig. 1, based on information prepared by SRI International for the National Paint and Coatings Association in Washington D.C.) This figure shows 492 million gallons (47%) of architectural coatings, 387 million gallons (37%) of product coatings, and 168 million gallons (16%) of special purpose coatings. Most of the architectural coatings sold were water-based (73%). Most product and special purpose coatings are solvent-based (27%). In 1992, projected coating sales are expected to reach $13.5 billion yearly and coating shipments to reach 1.2 billion gallons in the U.S. The four largest coating companies account for over 30 percent of the total U.S. industry shipment. These companies are PPG, Sherwin Williams, Du Pont, and ICI Glidden [2].

Paints and coatings are utilized everywhere. Not only are paints essential

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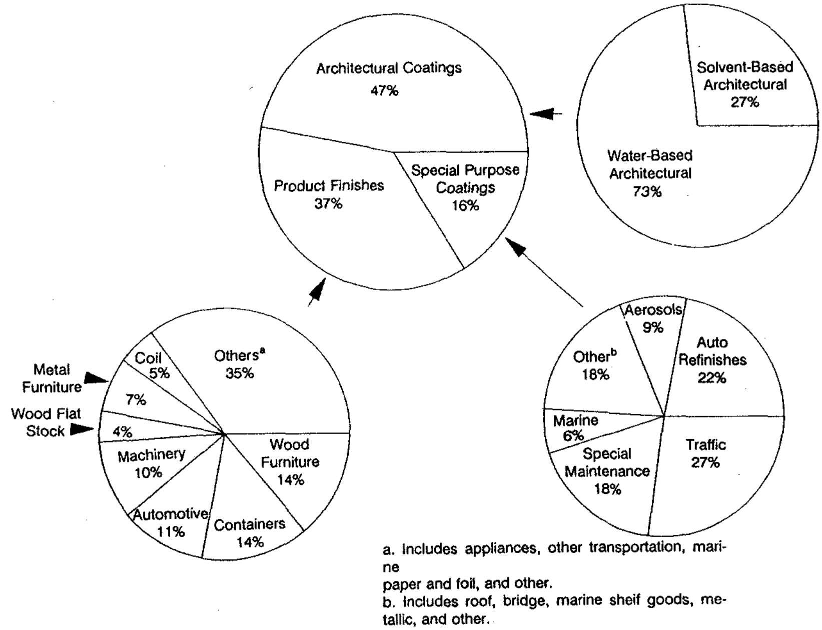

Fig. 1. U.S. Paints and coatings use in 1987. Total volume amounted to 1.047×10^9 gallons or 3.9×10^9 L. (Source: NPCA, Washington, DC.)

for the decoration and protection of surfaces of many industrial products, but also for the maintenance of existing structures and products such as homes, motor vehicles, machinery and equipment, buildings and factories. Paints are commonly called "surface coatings."

The main driving forces behind the changes in paints and coatings has been the environmental regulations and health concerns of the solvents used. Restrictions on volatile organic compounds (VOCs) and the reformulation process has been going on for many years. Paint and coating formulators as well as upstream raw material and resin suppliers are reevaluating all the components in their products and changing the constitutents and the performance of their coatings to meet the new environmental rules and comply with regulations. Paint producers look to technology leaders to meet reformulation needs. Coatings growth will be spurred by these new formulations to meet environmental regulations along with higher performance finishes and continued development on the solventless technologies; and as of yet no technology emerges as a clear leader from the ranks of alternative systems: waterborne, high-solids, radiation-cured and powder.

In response to the environmental and economic crisis, the surface coating industry is re-examining the production, application, and disposal of paints to reduce VOCs to meet environmental regulations and for coating manufacturers to optimize processes to reduce costs and increase profits. Pollution prevention, that is the reduction, elimination, or recycling of pollutant discharges to the air, water, or land is being applied in the production facilities and the applicators of the coatings. Corporate managers, production supervisors, and applicators realize that building big black boxes at the back of the coating and application facility to control pollutants is costly—hundreds of thousands or even millions of dollars. Pollution prevention holds the key to future gains in environmental protection and offers significant benefits that are not available through traditional pollution control approaches. Preventing or minimizing pollution at the source so that treatment at the end of the manufacturing process is not necessary is sensible. In addition, coating manufacturers are reformulating coatings so that when the product leaves the factory, there are no major problems in its application or in its final disposal.

The focus of this paper will be mainly concerned with those pollution prevention approaches in the production and application of paints and coatings, its related paint products and the end use of these engineering materials. Pollution prevention approaches means source reduction and recycling/reuse methods with companies that manufacture these materials and the numerous application methods that are currently used. The paper will present an overview of the surface coating industries, the key ingredients used in the manufacture of coatings, the review of some of the processes to manufacture and apply coatings, identifying the wastes generated, and reducing and/or eliminating wastes into the environment.

Regulations

The primary driving force for the reduction of solvents in paints is the Federal Clean Air Act and state air emission regulations. Other minor forces in the equation contribute to operating costs and to profit (for without profit a business cannot operate). They are: energy savings, material savings, and time savings (that is the evaporation of solvent during the drying and curing operations. In the following, air pollution regulations are briefly discussed. The reader is referred to Reference [3] for a more comprehensive review of the air pollution regulations in the U.S. and in various European countries.

In the U.S., the original air pollution regulation was Rule 66 of the Los Angeles County Air Pollution Control District. The objective of Rule 66 was to control the emission level of photochemically reactive (meaning groups of chemical compounds in paints that react with certain components in air in the presence of ultraviolet light) solvents. Emphasis was given to aromatic compounds and to some ketones. However, that divided solvents into two categories: so-called exempt solvents and non-exempt solvents. It is known that harmless organic compounds can become irritants by reactions in the atmosphere induced by ultraviolet light. So the U.S. EPA enforced the concept of Volatile Organic Compounds (VOC) as its measure of emission control. All components in paint, not only solvents, are defined as volatile if the vapor pressure exceeds 13.3 Pa (0.1 mmHg) at 25°C; however, there are many exceptions to this rule. For example, two solvents, dichloromethane and 1,1,1-trichloroethane have been exempted from control. These two chlorinated solvents are considered to have negligible photochemical reactivity in the troposphere and no significant impact in the stratosphere. This has led to an increased use of these solvents in emerging technologies such as high solids and radiation-curing systems. However, this exemption may change in the future. According to the July 1989 California Air Resources Board technical support document on architectural coatings, manufacturers may elect to use exempt solvents such as 1,1,1-trichlorethane or other halogenated compounds to reduce VOC content of their coatings to meet standards. However, some of these substance (e.g. 1,1,1-trichloroethane) may be reviewed for possible identification as toxic air contaminants. Identification of a substance as a toxic air contaminant would, in addition, almost certainly lead to its removal from architectural coatings [4,5].

In general, the manufacturers of coatings are responsible for the compliance of their paints with the regulations of the areas in which they are sold. The user is responsible buying and using paints that the manufacturer stipulates are in compliance with local air pollution regulations. The user is also responsible for controlling the emission of solvent vapors at a rate not to exceed the maximum rate specified by the regulations. Presently, the EPA regulates only VOC emissions from paint coatings and has no regulations regarding solvents used or in cleanup. Federal VOC limits for paint are 420 g/L for paints that cure below 90°C and 360 g/L for paints that cure above 90°C [6]. Some state air pollution control agencies are setting strict VOC content limits for paint. For example, the South Coast Air Quality Management District in California has set a 350 g/L VOC limit for aircraft paints [7]. Since September 1987, all flat and nonflat architectural paints must contain less than 250 grams of VOCs per liter of paint [8]. In some cases, technical difficulties in formulating compliant products have resulted in delay in making these changes. For example, alkyd gloss architectural paints containing less than 380 g/L of VOCs have been plagued by yellowing problems and poor application and drying characteristics [9]. For more information, the reader is referred to the particular set of air pollution control regulations for his or her area of operation and country.

In Europe, many countries have differentiated the solvents according to their harmfulness. Germany is the forerunner in this respect with its Federal Emission Law of 1974. The volatile emissions are divided into three classes, with Class I compounds having extremely low emission limits. Most of the commonly used paint solvents belong to Classes II or III. The limits for each class have gradually been reduced since the law was issued and some solvents have been reclassified. Most West European countries have regulations or recommendations which basically follow either the U.S. or Germany. The situation is very complex, however, and many countries have regional air pollution regulations.

Paints manufacturing and processing

Industry information

According to the Standard Industrial Classification (SIC) 2851, the paints and allied products industry is primarily engaged in the manufacturing paints (in paste and ready mixed form), varnishes (clear coating), lacquers (films formed by evaporation only), enamels (pigmented varnishes) and shellacs, putties, wood fillers and sealers, paint and varnish removers, paint brush cleaners, and allied products. Information on businesses engaged in the manufacture of pigments (inorganic and organic), resins, printing inks, adhesives, and sealants, or artist materials are included in other SIC codes. This paper will primarily consider paints and allied products, SIC 2851.

Today, the number of U.S. paint producers is estimated at 900, a decline due to mergers and acquisitions. In 1967, 1459 companies produced paint; in 1982 there were 1170 paint producers, and now only 900. Reasons for the large number of mergers and acquisitions are: increase in paint ingredient costs, the costs of reformulating and relabeling to conform with local government regulations, the cost of complying with government regulations such as the Resource Conservation and Recovery Act (RCRA) and Occupational Safety and Health Act (OSHA), intense competition and increased globalization. In the future, this trend is expected to increase [5].

Paint constitutents and their use

Liquid paint is a dispersion of a finely divided pigment in a liquid composed of a resin or binder and a volatile solvent. The liquid portion is known as the vehicle. Major raw materials used to manufacture paints are resins, solvents, pigments, extenders, and fillers. Based on the wide variety of paints used, no one type dominates the market and our outlined in Table 1. The function of pigments and fillers is not to provide simply a color surface, but to reflect much of the destructive wavelength of light and thus prolong the life of the paint. Extenders and fillers reduce the costs of manufacturing paints and frequently increase their durability.

As illustrated in Table 1, there is also a wide variety of synthetic resins used in coatings. Synthetic resins are generally defined as long-chain polymers or macromolecules of high molecular weight that are formed by the polymerization or polycondensation of organic intermediates or are chemically modified from such natural polymers as cellulose. The polymer chain may be linear, branched, or crosslinked or some combination of these forms depending on the functionality and reactivity of the monomers from which they are formed.

Resins are selected based on many factors. Alkyd and acrylic resins domi-

TABLE 1

U.S. Raw material consumption in 1987[a]

Material	Amount
Resin	2.57 billion pounds
Vinyl	436.9 million lbs/y
Other	462.6
Epoxy	205.6
Polyester	154.2
Urethane	128.5
Alkyd	668.2
Acrylic	514.0
Solvent	4.32 billion pounds
Toluene	648.0 million lbs/y
Other aromatics	172.8
Xylene	475.2
Aliphatic	950.4
Ketones and esters	1080
Alcohols	518.4
Others	475.2
Pigment consumption	3.1 billion pounds
TiO_2	930 million lbs/y
Other colors	279
other pigments	93
Talc Filler	310
$CaCO_3$ Filler	589
Silica Filler	186
Other Fillers	217
Clay Fillers	496

[a]Source: Chem. Week, Oct. 1989.

nate the market. Acrylic (predominately polymers and copolymers of esters of acrylic and methacrylic acid) resins, for example are an extremely versatile group that can be produced in either thermoplastic or thermosetting form. It is used as dispersions in latex paint as well as solutions in solvent-based coatings. Acrylic resins can be formulated into high gloss materials with outstanding clarity and color retention. They have excellent hardness, impact strength, and durability thus they dominate the market in automotive top coats. They have exceptional resistance to degradation by ultraviolet radiation, water, and chemicals.

Alkyds, on the other hand, are a group of resins that are called oil-modified polyester resins. They are polymers formed by the reaction of polybasic acids, polyhydric alcohols, and fatty monobasic acids. Alkyds have good adhesion and are used extensively in interior and exterior enamels and in coatings for metal and wood furniture, machinery and equipment, and general maintenance. To reduce VOCs, alkyd paints have become increasingly less important in architectural coatings. However, there may be new life in alkyd coating systems, as recent research into a natural reactive diluent derived from the seed of an African plant (*Vernonia galamensis*) promises to permit formulation of alkyd coatings that contribute virtually no VOCs as they cure [5].

Epoxies are made via condensation polymers of epichlorohydrin and bisphenol A or their derivatives. Epoxy resins are commercially available in emulsion form and are known for their adhesion, toughness, and chemical resistance.

Polyester resins are polymers formed by condensation reaction between acids and alcohols. They require curing by heat with cross-linking agents such as amino resins. They are produced in water-soluble form and have found intensive industrial use such as coil coatings.

Also, many vinyl polymers and copolymers (polyvinyl butyral, polyvinyl formal, polyvinylidene chloride) are known and used to varying degrees in surface coatings. Polyvinyl acetate and polyvinyl butyral resins are used extensively in emulsion paints particularly in interior paints since they have superior properties to styrene–butadiene and are less expensive than acrylics. These coatings are flexible and durable, adhere well, dry quickly, and generally do not discolor.

Polyurethanes are available in two-component systems, moisture curing systems, and air curing systems, where drying oil is added to the polymer. Important properties of polyurethanes include excellent corrosion resistance, high film strength, durability, and the ability to adhere to a variety of substrates. Uses of polyurethane range from floor coatings and wood and leather finishes to aircraft topcoats, coatings for buses and railway cars, marine and maintenance coatings and automotive topcoats.

Other resins are styrene monomers and its copolymers, polyethylenes. phenolics, polyamides, chlorinated polyethers, flurocarbons, and amino resins. Amino resins are not used by themselves in coatings, but are used to cross link alkyd resins, polyester resins, acrylic resins, epoxy resins, and so forth. Amino resins such as urea-formaldehyde and melamine formaldehyde types have excellent color and gloss retention and cure quickly.

The paint industry is the largest consumer of industrial solvents and utilizes a wide variety of different types in formulating coatings. The primary function of a solvent is to disperse or dissolve the paint binder and resin making the paint formulation less viscous and suitable for application. The solvent also helps to wet the surface, enhancing both adhesion of the film and penetration. It also influences application properties such as consistency, setting rate, drying time, and flow.

In architectural coatings and industrial finishes, solvent based paints have declined rapidly and now only comprise 27% of the architectural paint market (See Fig. 1). Air pollution regulations will continue to diminish their use except possibly in the specialty products area.

Manufacturing process

In the production of paints, the various operations needed are wholly physical, that is, there are no chemical reactions or conversions of the raw materials to other products and byproducts. These paint operations are shown in Fig. 2, a simplified block diagram for paint manufacturing [10]. Typical paint makers produce both solvent based and water based paints via similar processes, although the components vary. Water based paints are typically composed of water, ammonia, dispersant, pigments, extenders (to extend drying time), resins, preservatives, antifoam agents, and polyvinyl acetate emulsions. Solvent based paints are typically composed of resins, pigments, extenders, solvents, plasticizers, tints, and thinners.

Procedures

There are at least five (5) operations common to all paint factories: premixing, dispersion, thin-down and adjustments, filtration, and packaging. The following illustrates a typical paint manufacturing run for solvent based pigmented paints. The manufacture of clear (non-pigmented) lacquers will normally not include dispersion.

First, the pigments, and a portion of the resins and solvents are weighed and/or measured into a tank and pre-mixed by the use of a Cowles-type high speed mixer to ensure homogeneity. This mixture is then dispersed in one of several types of mill, depending on the type of pigment. Dispersion consists of

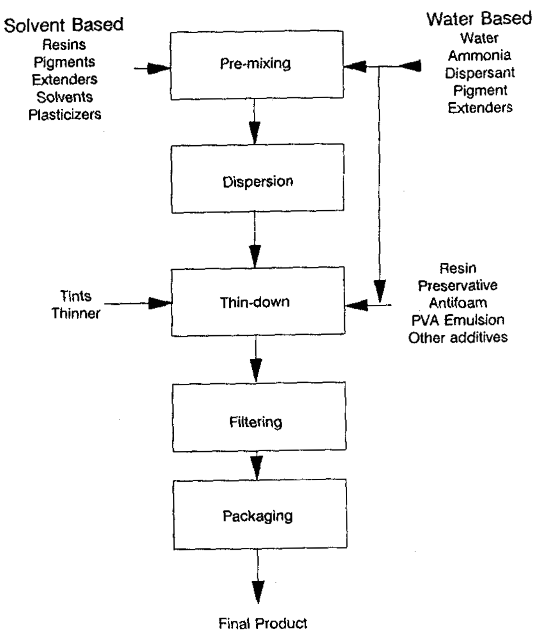

Fig. 2. Block diagram of paint manufacture.

breaking up and wetting the agglomerated pigment particles into their individual particle size. The maximum fineness (smallest size) of the particles in the final mix is that of the premicronized pigments used. Common types of mills used include vertical mills, both open and closed head; horizontal bead mills, attritors, and pebble or ball mills.

Ball mills offer an older but still effective method for dispersion. In this type of mill, the initial charge of materials are loaded directly into the ball or pebble mill without pre-mixing, and are dispersed under the rotating action of the mill and its grinding media, usually spherical steel or ceramic balls. This type of mill may be used to actually reduce the maximum particle size of the pigments.

The resulting pastes from the above milling processes are then transferred to another larger vessel where they are "thinned" with additional solvents and additives, and tinted to final color to meet the performance specifications for the finished product. After final quality control, the paint is then filtered through various media ranging from cheese cloth to 10 μm cartridge filters as may be required.

The filtered paint is then "filled off" or packaged for shipment to the customer. The package sizes may vary from an ounce in the case of fingernail or other specialty paints up to as much as a tank truck load. After filling and labeling, the product may either be warehoused or shipped immediately to a customer.

For latex and other water based paints, the operation begins by mixing water, ammonia, and dispersant together in a mixing tank, perhaps a pony mixer followed by pigments premixed and ground in a ball mill. The pigments and extenders most used are water dispersible grades of titanium dioxide, zinc sulfate, lithopone, and regular grades of barium sulfate, mica, diatomaceous earth, clay, and magnesium silicate. After mixing is complete, the material is ground in a mill and transferred to another agitated mix tank. In the agitated mix tank, film formers such as resins and plasticizers are added to the mixture along with a preservative solution (usually chlorinated phenol) and an antifoam (sulfonated tallow or pine oil). The polyvinyl acetate or acrylic emulsion is stirred in slowly followed by water as thinner to reach the desired viscosity. The paint is mixed, screened, and mixed again before packaging. Latex paints require the addition of thickeners to allow the paint to spread satisfactorily. Other additives are needed for specific purposes such as antibacterial and antimildew agents, freeze–thaw stabilizers, surfactants, defoamers, and pH adjusters [10–12].

Paint manufacturing process wastes

The major wastes from paint manufacturing facilities are shown in Table 2. Paint industries handle the wastes by either on-site recycling, off-site recycling or treatment/disposal. On-site recycling involves the reuse of raw materials or wash materials for producing other batches of paints. This reduces the operating costs for the plant and reduces their waste management costs. On-site recycling of solvents is performed by distillation, usually only by large paint companies (those that produce more than 35,000 gallons of solvents waste each year). Small companies send their wastes to an off-site recycler. Treatment/ disposal involves incineration or land disposal [10].

Of these wastes, equipment cleaning wastes are by far the largest, accounting for over 80% of the industry's wastes [13]. Process equipment is routinely cleaned to prevent product contamination and/or restore operational efficiency. Equipment that may need cleaning include high speed dispersion mixers, sand mills, colloid mills, rotary batch mixers and blenders, drum mixers and rollers, grinding equipment, mixing vessels, pumps and motors, filters and strainers, filling and capping equipment and packaging equipment.

In light of increasing costs and compliance requirements, paint manufacturers are taking a more active role in waste management in order to control costs, improve productivity and quality, and protect the environment. More paint companies are turning to pollution prevention methods such as source reduction and recycling.

Methods to reduce paint manufacturing wastes

Pollution prevention, or the method of preventing pollution through source reduction and recycling, is becoming a cornerstone of most progressive waste management programs. Reducing wastes to remain competitive has been an important ingredient for successful business in the past and it will be absolutely essential in the future. In the paint industry, continued merger and acquisition activity is anticipated due to factors such as higher capital cost, increased customer sophistication, growing governmental regulation, changing

TABLE 2

Paint manufacturing process wastes

Raw material packages bags, containers	Unloading of materials into mixing vessels
Pigment dusts from control devices	Unloading of pigments into mixing vessels
Solvent emissions	Storage tanks, leaks, and open process equipment
Off-spec paints	Color matching problems or customer returns
Spills	Accidental discharge
Rinsewater	Equipment cleaning using water or caustic solutions
Paint sludge	Equipment cleaning
Filter cartridges	Undispersed pigment, spent paint, resins

channels of distribution and the development of global paint markets. These factors will make it increasingly difficult for small coating manufacturers to effectively compete with their larger counterparts [2]. So controlling and optimizing all parts of the process is critical to reduce costs and continue to be competitive and profitable.

Pollution prevention approaches can be broken down into the following two categories:

- Source reduction—good manufacturing practices (GMP), production process changes, and input material changes.
- Recycling—use and reuse of wastes, reclamation (on-site, off-site recovery).

A low capital method which can be applied is good manufacturing practices. It generally means better procedural or institutional policies and practices and can include waste segregation, personnel practices, procedural measures, loss prevention practices, and accounting practices. Personnel practices can include upper management initiatives, employee training, or employee incentives. Careful attention to production and maintenance operations is important to reduce spills and minimize off-specification product. Making employees more aware of the impact of wastes on the company's costs as well as the impact on the environment and their health is important. Procedural measures can include better documentation, better material handling and storage, material tracking and inventory control and better production scheduling techniques. For example, since thousands of different paint formulations require special production runs, more effective planning and production scheduling may be needed. Paint production, although a vital phase, must intermesh smoothly with purchasing, formulation, sales, accounting, inventory, and personnel management to make it profitable. Production planning and scheduling may consist of a scheduling board listing the batches to be run on each piece of equipment and the expected starting and finishing times. It aids maintaining adequate inventory of active raw materials without overstocking and permits attainment of delivery of committments to customers. Also, if practiced effectively, it helps level peaks and slumps in production during surges of short delivery orders or establish "downtime" of each piece of equipment keeping check of overall efficiency and ensuring maximum equipment utilization.

In loss prevention practices, better awareness of spill prevention and inhouse preventive maintenance programs may be required. Accounting practices should incorporate a better apportionment of waste management costs to the departments that generate wastes.

Most off-specification paint is generated by small shops that produce specialty paints. Since the production costs for specialty paints are typically high, most "off-spec" paints are reworked into marketable products. However, the costs of reworking off-spec paints are avoided if better trained and supervised operators and quality control are reinforced so that the generation of off-spec paints is avoided.

Obsolete paint products and customer returns can be blended into new batches of paint. Obsolete products result from changes in customer demands, new superior products, and expired shelf life. Careful production planning and inventory control can reduce obsolescence resulting from expired shelf life. Also marketing policies such as discounting older paints can help reduce the amount of obsolete products [14].

There are many other ways of applying good manufacturing and operating practices. For example, soliciting employee suggestions may uncover methods to make changes especially since the operators understand the paint process operations. Quality improvement teams make significant improvements to improve the quality of the product, optimize the process, improve efficiency and productivity, and reduce the wastes in the process. In addition, incentives, rewards, and bonuses can be used to support pollution prevention programs and reduce paint wastes.

Process production changes

Improving the efficiency of a production process can significantly reduce wastes generation. Available techniques range from eliminating leaks from process equipment to installing state of the art production equipment. This pollution prevention category include improved operation and maintenance, procedural changes, and equipment modifications.

Table 3 illustrates the major wastes and methods to reduce the wastes in the paint manufacturing industry. Equipment cleaning wastes represents the largest source of waste in a plant. Methods that reduce the need or frequency of tank cleaning or allow for reuse of the cleaning solutions are the most effective.

The use of mechanical techniques such as rubber wipers reduces the amount of paint left on the tank walls of a mix tank. Wipers are used to scrape the sides of a cylindrical mix tank (flat or conical). Equipment cleaning is usually a manual operation so this change may be justified based on reduced labor costs as well as reduced usage of cleaning solution (another savings). High pressure spray heads and limiting wash/rinse time systems can be used in place of regular hoses to clean water-based paint tanks. Studies show that high pressure wash systems can reduce water use by 80 to 90% [15].

Teflon-lined tanks are sometimes used to reduce wall adhesion and improve drainage. Teflon-lined tanks are expensive and can rust easily if scratched. This method is usually applicable to only small batch tanks. A plastic or foam "pig" is used to clean pipes. The pig device is forced through the pipe from the mixing tanks to the filling maching hopper, using an inert gas such as N_2 to propel the pig.

Manufacturing procedures may be improved. For example, a paint facility's wash solvent from each solvent-based paint batch is separately collected and stored. When the same type of paint is to be made, waste solvent from the previous batch is recycled and used in place of virgin solvent. Also, in some

TABLE 3

Pollution prevention methods for the paint manufacturing industry

Wastes	Methods
Equipment cleaning wastes	Use high pressure wash systems
	Install teflon lines on mix tanks
	Use foam/plastic pigs to clean lines
	Reuse equipment cleaning wastes
	Schedule production to minimize need for cleaning
	Clean equipment immediately
	Use countercurrent rinse methods
	Use alternative cleaning agents
	Use mechanical devices on mix tanks
Spills and off-spec paint	Increase use of automation
	Use appropriate cleanup methods
	Recycle back into process
Leftover inorganic pigment in bags and packages	Use water soluble bags and liners
	Use recyclable/lined/dedicated containers
Air emission	Modify bulk storage tanks
	Use paste pigments
	Install baghouse systems
Filter cartridges	Improve pigment dispersion
	Use bag or metal mesh filters
Obsolete products/returns	Blend into new products

cases, cleaning sludge can be recycled. It has been reported that sludge is recycled from alkaline cleaning of the water-based paint mix tanks into a marketable product [10].

Countercurrent rinsing processes can be applied to those plants with sufficient tank space. This technique is used to recycle "dirty" solutions initially to clean tanks and then is followed by a "clean" solution to complete the rinse cycle. The level of contamination builds up more slowly with the clean solution than the dirty reused solution thus extending cleaning solution life.

Sometimes, alternative cleaning solutions can be used. For example, some facilities use caustic washing to clean their tanks. When the buildup of solids and organic reaches a certain concentration, the solution must be diposed of and replaced. It has been reported that proprietary alkaline cleaning solutions are used to cut solution replacement frequency and reduce volume of cleaning solution disposed of [10].

Spills are due to accidental or inadvertent discharges usually occurring during transfer operations or equipment failures. For example, during a loading operation, a spill may occur from a leaking fill hose or fill line connection or leaking valves, piping, and pumps. Sometimes spills occur from overfilling of tanks or due to improper or malfunctioning overflow alarms. Usually improved regular inspection and training programs may prevent these spills from occurring. Also improved instrumentation and automation and efficient cleanup methods if spills do occur.

After emptying inorganic pigments from bags, a small amount remains, thus classifying the bags as hazardous waste unless cleaned. Cleaning and drying bags allow them to be disposed as nonhazardous wastes. Also, ordering pigments in slurry or paste form eliminate problems of disposing of waste bags or packages. Empty containers of liquid raw materials that contain hazardous compounds are typically cleaned or recycled back to the original raw materials manufactures or to a local drum recycler. This avoids the costs of disposing of the containers [14].

In regard to air emissions, there are two major types of sources in paint manufacturing plants: VOCs and pigment dusts. Volatile organic compounds may be emitted from the conservation vents on top of the bulk storage tanks of resins and solvents and from the use of open processing equipment such as agitated mix tanks. Since most process equipment is of open design, reducing VOCs from equipment could require substantial capital expenditure in retrofit costs. There are few cost effective methods to reduce VOCs from open vessels. Closed vessels with overhead refrigerated condensers will require considerable capital investments which most paint manufacturers cannot afford. In fixed roof design, maintained conservation vents, conversion to floating roof, use of nitrogen blanketing to suppress emissions or the use of refrigerated condensers. Implementing these options can result in cost savings to the plant and reduced raw material losses.

Dusts generated during handling, grinding, and mixing of pigments are hazardous and therfore dust collection equipment such as hoods, exhaust fans, and baghouses are used. Use of pigments in paste form instead of dry powder will reduce or eliminate dust generated from pigments and also the drums can be recycled.

Also, a major advance in paint manufacturing is the growing use of electronic control devices and batch automation. The intent is to avoid operational accidents, improve quality, and production efficiency, and the overall accuracy and repeatability of the batch. The effect should be less waste generated in much the same way as good manufacturing practices. Computers are increasing by being used for materials allocation, match and formula costing, and inventory control. They are also being used in preventive maintenance and tracking. As the costs of plant automation equipment decrease, the use of automation in paint manufacturing facilities will increase.

Paint application

The previous section indicated methods to reduce wastes generated in the formulating and production of coatings. The remainder of this paper will discuss preparation of surfaces, the methods of applying paints to surfaces, the waste generated by these processes, and the approaches to reduce these wastes.

The painting process

Figure 3 is a simplified block diagram of the painting process. Paints are applied to surfaces of parts. Components are assembled products for corrosion protection, surface protection, identification, and decorative purposes. Paint application wastes are also summarized in Table 4. Painting operation and wastes will be discussed next.

Surface preparation

Usually before coatings are applied, the surface of the substrate is prepared. Surface preparation is important for coatings to develop good adhesion to the surface, especially one contaminated with soil, grease, or other foreign materials. There is a variety of methods of surface preparation for metals that include abrasives, alkalines, acids, solvents, and other mechanical and chemical treatment methods for removing rust and mill scale and for passivating the surface against corrosion. The importance of removing surface contamination is fairly well recognized for coatings, for no matter how carefully a coating is formulated and produced, it will not have the anticipated properties if the sur-

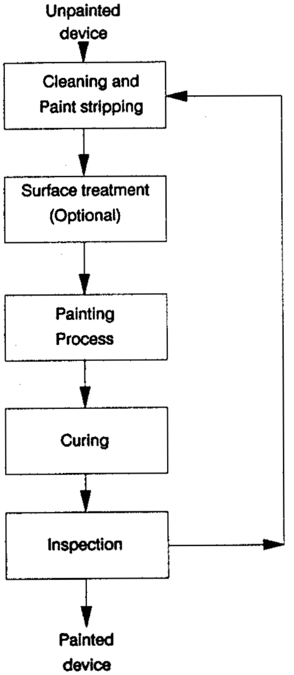

Fig. 3. Paint application processing steps.

TABLE 4

Paint Application wastes

Wastes	Origin
Leftover paint in metal cans	Raw materials
Spent solvent	Cold cleaning and/or vapor degreasing
Spent alkaline cleaners	Removal of organic soils, descaling
Spent acid cleaners	Removal of scale, dirt
Rinse water	Removal of previous cleaning solutions
Paint overspray	Overspray from paint application
Water and/or solvent	Cleaning of application equipment

face on which it is applied is not prepared properly and if the coating is not applied correctly.

Surfaces to be painted must be clean and dry to insure proper paint adhesion. The usual ways include smoothing (grinding, filing, sanding or grit blasting) and cleaning (mechanical, solvent or chemical methods). Cleaning methods depend on the substrate to be painted. Grinding methods generate paint wastes that contain aluminum oxide or silicon carbide. Blasting abrasives can be glass, metal shot, or walnut hulls. Abrasives quickly become contaminated and are disposed of when the operation is complete. Most parts are cleaned by simply dissolving the contaminants in a suitable solvent. Vapor degreasing methods are widely used with common solvents such as trichloroethylene and perchloroethylene, 1,1,1-trichloroethane, or in certain cases, Freon. During the degreasing operation, some solvent is lost to the air. Small heat exchangers with chilled water may knock back and collect and recycle these losses. With use the tank solution accumulates grease, oil, and other contaminants. The cleaning solvent can be reclaimed by distillation. Chemical methods are usually alkaline washing or acid etching. In addition, extensive use of water is required to rinse parts of cleaning solution so that the residual cleaner does not contribute to a contamination problem [13].

Once the part is cleaned, a surface treatment such as phosphate coating can be applied if needed. The purpose of surface treatment is to condition the surface so that the paint forms a better adhesion bond with the metal surface.

Correct preparation of the surface on which the coating is to be applied and also the proper application of the coating are important factors in its performance. After the item has been cleaned and treated, paint can be applied.

Painting application and wastes

Most painting is performed by conventional liquid spray technology. Spray technology was principally developed for the automobile assembly line. In spray painting, the paint is mixed with a carrier, usually an organic solvent, and is applied to the surface with an air-pressurized sprayer. Spray painting is usually done in a horizontal or downdraft paint spray booth. During painting processes, two significant sources of hazardous wastes are generated: paint sludges and waste solvents.

The first and largest volume involves air emissions that create paint sludges. During typical spray painting, 50% of the paint is deposited on the surface being painted and 50% called overspray is sprayed into the air. The second significant source is the use of solvents to clean painting equipment. Most paints are still conventional solvent based and require solvents for cleanup. As the paint dries, the solvent evaporates into the air. The type of solvent varies with the paint but some common ones are methyl ethyl ketone (MEK), xylene, 1,1,1-trichloroethane, toluene, butyl acetate, ethylene glycol, ethyl acetate, and other alcohols. The air from a spray booth is often exhausted through a water scrubber that separates the paint from the air. The scrubber water is usually recycled and paint solids are removed from the scrubber sump. When the sump fills with paint sludge, it is removed and put into drums for hazardous waste disposal [16,17].

Specialty paint applicators use small cans and containers (less than 5 gallons or 19 L) for use in spray gun equipment. These small quantities of paint and often a large variety of color are discarded as wastes after the paint is empties out of the can. Facilities can strive to recycle the cans to the paint formulators as much as possible. Purchasing the paint in bulk can often reduce the amount of wastes thrown away in cans. Also, paint formulators may accept returned bulk containers to clean and reuse. When the purchase in bulk is impractical, personnel should be aware of minimizing paint residual and be sensitive to reduce waste disposal costs.

As mentioned, most significant wastes generated are primarily due to overspray or the failure of the paint to reach its target. One way to reduce these wastes is to improve the efficiency of the paint application process. Reduced use of paint results in less solvent to evaporate in leaving the final product film. Also, reduced overspray means less paint sludge to be removed from a water-wall scrubber or less paint to be stripped off the walls or floor of a spray

TABLE 5

Expected transfer efficiency of various painting methods

Painting method	Transfer efficiency range (%)
Air atomized, conventional	30–60
Powder coating	90–99
Air atomized, electrostatic	65–85
Pressure-atomized, conventional	65–70
Centrifugally atomized, electrostatic	85–95

paint booth. Table 5 describes the expected transfer efficiencies of various painting spray systems. Transfer efficiency is defined as the ratio of the quantity of paint sprayed from a paint gun to the amount adhering to the product surface. As transfer efficiency increases, the quantity of VOC pollution decreases due to a decrease in paint overspray. So, improvements in the transfer efficiencies will reduce paint wastes. For example, Flexsteel Industies in Dubuque, Iowa, changed from conventional spray to electrostatic systems and reduced the amount of overspray by 40% [18]. This saved the company $15,000 a year in paint costs and repaid the investment within two years.

Developing technologies

Alternatives to conventional solvent based spray painting can reduce hazardous wastes. These alternatives require an integrated approach in which painting techniques are improved and process optimized to reduce or eliminate hazardous wastes. Among options already discussed are improvements in the application of paints. Coating technologies that have been in existence since the 1970's but are being refined are high solids, waterborne, powder and radiation curable. These methods are unique and these coating technologies are briefly described in the next sections. Also, the UNICARB® process, a new low VOC spray application technology by Union Carbide is reviewed.

High solids coatings

High solids coatings contain 25% to 60% solids by volume and compared to solvent based coatings, use lower molecular weight paint resins with highly reactive sites to aid in coating polymerization. The finished coat is comparable to typical solvent-base coatings.

High solids solvent based coatings are slowly replacing regular solvent base coatings. The major advantage will be the ability to comply with the more stringent VOC limitations while using the same paint, equipment, and application techniques. High solids require special spray equipment for application because of their high viscosity. Because less solvent is used, less is available to wet metallic surfaces that are contaminated with oils; therefore, surface preparation for removal of oils is more critical. Also, spray application can be wasteful because there is a tendency to apply too much coating to achieve a wet appearance similar to that obtained with normal solvent coatings.

Waterborne coatings

In their simplest form, paints consist of pigments, binders, and volatiles. In a waterborne system, the pigments are similar to those used in a solvent system in most respects. The binder is usually an organic polymer. For example, polymers used include alkyd, polyester, vinyl acetate, acrylic, and epoxies, and can be dissolved, dispersed, or emulsified. One major advantage is that no major equipment changes are necessary to apply waterborne coatings with conventional equipment. The major pollution prevention advantage lies in the ease of recovering paint overspray. Overspray can be collected with water in the spray booth. The solution may be concentrated and reused again. Waterborne coatings have been increasingly been used in industry as an alternative to solvent systems. For example, Emerson Electric Company reported environmental and economic benefits in a waterborne electrostatic paint system [19]. The changes included: improved quality of application, decreased downtime from 3% to 1%, reduction in the generation of aromatic waste solvent by 95%, reduction of paint sludge by 97%, and the increase in efficiency with up to 95% recovery and reuse of the paint. The new system also reduced hazardous waste disposal costs and decreased personnel and maintenance costs by 40%.

Radiation curable coatings

Radiation curable coatings comprise ultraviolet (UV), electron beam (EB), infrared (IR), and microwave cured systems. Only UV and EB curing appear to be of commercial importance for paints and coatings today; however, IR curing is being used on a large scale in a related paper coating process.

Ultraviolet curing is the most common of the radiation processes. The main components are a low-molecular resin containing olefinic bonds, a reactive solvent, also containing unsaturated groups, and a photoinitiator. A reduction of solvent use up to 100% is feasable with UV curing.

Powder coatings

Powder coatings are unique among all present day compliance coatings in that they are dry solid coating materials, as opposed to the liquid materials of high solids, waterborne, and radiation curable coatings. Powder coatings are finely pulverized pigmented resin particles that are electrostatically sprayed onto a metal part to be coated. The charged particles adhere to the surface and the part is conveyed to a curing oven where the powder melts under heat to form a uniform, durable high quality finish.

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. Table 6 presents a VOC reduction comparison of the four coating systems [20].

Most of the drawbacks to the use of powders that existed a few years ago have been eliminated. New resin systems allow powders to meet the coating specifications for almost any product.

Supercritical fluid spray application technology

Union Carbide's UNICARB® System enables VOC emissions to be reduced by 30 to 70% in applying high quality coatings by using supercritical carbon

TABLE 6

VOC reduction comparison

	Conventional solvent	Water-borne	Higher solids	Powder
Volume solids at spray viscosity, %	33	35	60	99
Volume VOC content, %	67	16	40	1
Actual coverage, SF/gal (SF/lb for powder)	233	272	570	96
VOC emissions, tons/y	38	26	31	0.6

dioxide to replace the volatile organic solvent fraction that is used to obtain atomization viscosity. This enables applicators to reduce the VOC emissions while continuing to use high molecular weight polymer systems. Supercritical carbon dioxide can produce vigorous atomization that remedies the deficiencies of the airless spray process so that high quality coatings can be applied. The technology is applicable to most spray applied coatings and has been demonstrated using acrylics, polyesters, cellulosics, alkyds, and commercial paints and lacquers in clear, pigmented, and metallic systems. The technology can be retrofitted into existing coatings operations to utilize existing investment [21].

Conclusions

The paints and coatings industry will continue to see changing technologies for an environmental era. Manufacturers of architectural coatings under increasing environmental regulations will continue to reduce the VOCs contained in their coatings by displacing oil based products with water based coatings. In particular, the paint industry will center its research upon reformulations and increasing the efficiency of coating applications and meeting stricter environmental regulations via water based paints, powder coatings, high-solids enamels, reactive diluents, and radiation curable coatings.

Pollution prevention methods are making significant contributions to the effort to reduce the VOCs and paint wastes and sludges through source reduction methods such as process/production techniques, good manufacturing practices, and material substitutions. The coating industry's comprehensive efforts by utilizing source reduction and recycling techniques will be important towards the foal of reducing these pollutants. Reauthorization of the Clean Air Act will continue these efforts to cut emissions farther and faster. The future will encompass technological advances with low cure powders, faster curing processes, improved application systems, and ultimately cutting emissions levels to reduce its contribution to ozone formation in the lower atmosphere.

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