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Barriers to the use of radiation-curable adhesives in the coated and laminated substrate manufacturing industry

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Abstract

The Air and Energy Engineering Research Laboratory (AEERL) of the US Environmental Protection Agency (EPA) is investigating the barriers to the use of radiation-cured technology in the coated and laminated substrate manufacturing industry. This paper presents information gathered from radiation-curable coating and equipment suppliers as well as technical publications. The focus of this project was to investigate the use of radiation-curable coatings as an alternative to conventional solvent-based coatings used in the coated and laminated substrate manufacturing industry. Data obtained included material inputs, equipment, output characteristics, emissions, and waste. Information was gathered to compare process and cost impacts to evaluate the technical, educational, and economic barriers to radiation-curable coatings for this industry. Pollution prevention/source reduction research opportunities were also identified.

Keywords: Pollution prevention; Adhesives; Radiation-curable coatings; Electron beam; Ultraviolet

1. Introduction

Section 4(b) of the Pollution Prevention Act of 1990 requires the EPA to 'review regulations of the Agency prior and subsequent to their proposal to determine their effect on source reduction' [1]. In support of the Pollution Prevention Act, EPA established the Source Reduction Review Project (SRRP) to focus this review on the regulations (and anticipated regulated industries) that will soon be mandated under the Clean Air Act Amendments of 1990 (CAAA), the Clean Water Act (CWA), or the Resource Conservation and Recovery Act (RCRA). One of the goals of SRRP tasks is to ensure that source reduction and multi-media issues are considered

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during the development of upcoming air, water, and hazardous waste standards. Seventeen industrial categories are affected by the SRRP [2].

One important set of regulations under the CAAA, a regulation of SRRP focus, is the standards for maximum achievable control technology (MACT) to reduce emissions of hazardous air pollutants (HAPs). Promulgation of these regulations began in 1992 and will continue throughout the decade and into the next century. The MACT standards offer EPA an excellent opportunity to use SRRP to incorporate pollution prevention measures into the upcoming standards for specific source categories. The Pollution Prevention Act of 1990 defines pollution prevention as source reduction, or 'any practice which reduces the amount of any hazardous substance, pollutant, or contaminant entering the waste stream or otherwise released to the environment (including fugitive emissions) prior to recycling, treatment, or disposal; and reduces the hazards to public health and the environment associated with the release of such substances, pollutants, or contaminants' [1]. Pollution prevention efforts offer economic and reduced health and ecological risk benefits to many sectors of society that are not available through traditional pollution control methods.

In support of the SRRP program, MACT standards development, and the Pollution Prevention Act, AEERL is investigating pollution prevention opportunities for products and materials that can be used to reduce waste. The specific objective of this project was to investigate the current industrial use and barriers to the extended use of radiation-curable coatings. Radiation-curable coatings have been demonstrated to reduce pollution in several specific end-use categories. The three Standard Industrial Classification (SIC) categories selected for initial investigation were Adhesive-Coated and Laminated Paper (SICs 2671 and 2672), Metal Cans (SIC 3411), and Commercial Printing – Not Elsewhere Classified (SIC 2759). All three of these industries face upcoming MACT standards. By initiating this project, EPA has begun a dialogue on pollution prevention with these industries. When the MACT standards are developed, EPA will have a better understanding of what coating technologies are feasible pollution prevention alternatives for these three industries.

This paper presents the results of a study to investigate and identify the technical, educational, and economic barriers to the use and implementation of radiation-curable coatings within the coated and laminated substrate manufacturing industry. This project involved preparing category analyses, identifying and classifying the use and implementation barriers, evaluating and assessing the environmental impacts, and identifying pollution prevention and source reduction research opportunities within the coated and laminated substrate manufacturing industry. In order to successfully accomplish these objectives, information was collected from several sources including literature searches, plant visits, pollution prevention experts, industry representatives, equipment and raw material vendors, and trade association personnel.

2. Industry description

Coated and laminated paper and plastic films have a wide variety of uses, including packaging, labelling, adhesive tapes, and decals. The industry spans two

4-digit SIC codes: 2671 (Paper and Plastic Films Coated and Laminated for Packaging), and 2672 (Paper and Plastic Films Coated and Laminated, Not Elsewhere Classified). Both of these SICs comprise the same industrial processes and consume many of the same materials. The primary differences are in the strict definition of the end uses of the products manufactured. Facilities within this industry tend to operate in one of two segments: one consists of large facilities operating coating lines dedicated to one type of product, such as label stock or masking tapes; and the other includes batch processors, or facilities that manufacture small batches of a wide variety of products (usually with a high value-added component).

3. Conventional process description

3.1. Raw materials and products

The raw materials used in the coated and laminated substrate manufacturing process consist of substrates, adhesives, and other coatings.

3.1.1. Substrates

A substrate (backing) is the material to which an adhesive is applied to make the desired product. Substrates are often in the form of large, continuous rolls called webs. Substrates provide strength, protection, and/or a colored surface for the adhesive. Substrate categories include paper, polymer film, fabric, foil, and foam. Paper and film are the two most frequently used backing materials [3, 4].

3.1.2. Coatings

The various coatings applied, along with the type of substrate, define the end-use of a coated and laminated product. Coatings typically consist of solvents, resins, and additives, with the composition varying depending on the desired characteristics. The fluid portion of the coating is referred to as the vehicle. Vehicles keep a coating in liquid form for easy application. Once a coating is applied to a substrate, the vehicle solvents should be evaporated completely. Vehicles transfer the solid portion of the coating to the substrate surface in a uniform layer and typically play no role in film formation. Some commonly used coatings include saturants, release coats, tie coats, and adhesives. Not all coated and laminated products incorporate all of these coatings. For example, saturants are used primarily with paper substrates, while tie coats are used mainly with film products. A brief discussion of each type of coating follows.

Saturants are mixtures applied to raw paper to improve the paper's internal strength and resistance to various environments. The backing of paper tape, for example, may contain as much as 50% saturant by weight [5]. Saturants reduce the number of loose fibers extending from the surface of a paper web. They also impart strength to the web once dried. The two types of saturants used are solvent-based and water-based. Solvent-based saturants orient all the fibers uniformly and provide better water resistance than the water-based coating; however, they do not strengthen the web as much as water-based saturants. Natural rubber and styrene-butadiene rubber (SBR) are the preferred polymers for solvent-based saturants. Other saturant raw materials include polyurethanes, toluene, polyether blends, and hydrocarbon resins. Although pollution problems and high costs of solvents make water-based saturants more attractive, solvents are considered necessary for the manufacture of electrical paper tapes because of the high performance characteristics currently offered only by solvent-based saturants [4].

Water-based saturants or latexes are used more often than solvent-based saturants for tape substrates. Water-based latexes are easier to use than solvent-based saturants, which must be broken down and compounded to dissolve the rubber. Several synthetic latexes used in the water-based saturants are SBR, acrylics, and carboxylated SBR. The most widely used latex saturants are acrylics. Acrylics provide excellent saturation, have a light color, and are heat and light stable. Other water-based coatings are available but not used as frequently due to performance issues.

Release coatings are applied to the side of the substrate backing opposite the adhesive. The release coat allows rolled adhesive products to be unwound, prevents tearing, and provides resistance to fluids infiltration [5]. A release coat or 'backsizing' contains release material, liquid resins, and solvents such as silicone solution, isopropyl alcohol, and toluene [4, 6]. The release coat should provide an adequate and consistent release, the release agent should not transfer to the adhesive surface, and aging should not affect the ability to unwind the tape. Waxes, silicones, and chained polymers are used in release coatings. Polymers are used to prevent the adhesive from penetrating the substrate. Waxes are added to polymer coatings to improve the slip, blocking resistance, and release of the coating. Silicones are added to improve the tack of the coating.

Tie coats or primers are coatings applied between natural rubber adhesives and film substrates to improve the bond between the adhesive and the film. Primers may be a mixture of creep rubber, diphenylmethane diisocyanate, and toluene or blends of SBR, with and without resins [4, 6].

Adhesive is applied to the saturated/backsized substrate. Adhesives may contain petroleum resins, solvents, natural and synthetic rubber, antioxidant, and filler [5]. Adhesives are required to have three main properties: peel adhesion, cohesive holding power, and surface tack. Natural rubber has a low tack and low adhesion to surfaces. Therefore, tackifying resins must be added to natural-rubber-based adhesives. Wood rosin and its derivatives, terpene resins, and petroleum-based resins are the main resins used with natural rubber. Other adhesive products include block copolymers; thermoplastic rubbers including polyethylene or polybutylene; butyl rubber, a copolymer of isobutylene with a minor amount of isoprene; polyisobutylene, a homopolymer; acrylic polymers; vinyl ether polymers; and silicon adhesive which is both a gum and a resin. Facilities have a wide variety of choices for raw material inputs for adhesive mixing.

3.2. Finished products and end-uses

The largest categories of products made by coated and laminated substrate manufacturers are tapes and labels. Classes of tape, identified by construction, include woven and nonwoven fabric tape, paper tape, film tape, foil tape, and foam tapes. Some of the web materials mentioned previously are used in combination with glass, rayon, nylon, polyester, or acetate fibers to produce reinforced substrates. Films such as polyethylene, polyester, or polypropylene are often combined with these fibers to produce tapes used in heavy-duty packing and bundling applications. The type and number of reinforcing strands per area, the thickness of the coating applied, and the type of film used differentiate the grades and types of film tape [4, 6]. Two-faced tapes are substrates with an adhesive coating applied on both sides of the substrate (usually foam or film). Two-faced tapes have both heavy-duty uses in carpet tapes and light-duty uses in business forms and nametag applications [4, 6, 7].

Label manufacturing is similar to pressure-sensitive tape manufacturing, with priority properties being printability, flatness, ease of die cutting, and release paper components. A label manufacturer may sell the product either in rolls or sheets as a final product, or as a raw product for a printing and die-cutting operation [6].

Other adhesive-coated and laminated product lines include adhesive-coated floor tiles, wall coverings, automotive and furniture woodgrain films, and decorative sheets for packaging.

3.3. Conventional process description

Both batch processing and dedicated-line facilities employ basically the same process flow. Incoming coating formulation raw materials are blended in mix tanks or drums with high- or variable-speed dispersers. The dedicated-line facilities typically formulate a coating from resins (e.g., natural or synthetic rubbers), solvents, and additives. Batch processors often mix purchased blends with performance-enhancing additives or use and apply coatings premixed by a supplier. Only a small percentage of the coatings used by a batch processor is mixed from scratch [6].

After the coatings have been mixed, they are pumped via a manifold system to the appropriate coating application system. Both industry segments use the same types of application equipment, including direct and reverse roll coaters and gravure cylinders. While a dedicated-line facility may have a cylinder library consisting of 10 gravure cylinders (one for each coating thickness), the batch processor might have a library consisting of several hundred gravure cylinders, each one dedicated to a certain coating thickness for a specific customer [6].

Similarly, a dedicated-line facility limits itself to a single type of substrate (e.g., film) with varying thicknesses, weights, and/or widths. A batch processor uses a variety of substrates, often including films, papers, foils, and foams. The substrate webs are loaded onto an unwinder. The substrate is guided by idling rolls to a coating application station where the appropriate coating is applied. Once the coating has been applied, it enters an oven (typically zoned) for drying. The dried substrate is then ready for the second coating, laminating, or winding. Following its final rewind, the coated, and possibly laminated, web is slit according to customer specifications (if necessary), packaged, and shipped [6].

3.4. Emissions and waste

In 1990, total air releases (fugitive and point emissions) by facilities operating under SIC 2671 were 10.5 million pounds (4.7 Mkg) [8]. SIC 2672 facilities emitted nearly 40.1 Mlb (18 Mkg) of reportable chemicals to the air [8]. Of the amounts reported by SICs 2671 and 2672, over 99% and 97% respectively, were volatile organic HAPs. Hazardous air pollutants are the 189 toxic chemicals listed in the CAAA under Section 112(b). Volatile organic HAPs are the organic chemicals from Section 112(b) which volatilize at or above 100 °F (37 °C). Chemicals which are VOCs are not necessarily HAPs, likewise chemicals which are HAPs may not be VOCs. Most coated and laminated substrate manufacturing facilities calculate these emissions based on raw material consumption. Therefore, total emissions reflect solvent losses occurring during raw material mixing, coating processing (including fugitive releases), equipment cleaning, and material storage.

The primary impacts of VOC reductions are dependent on the facility location. In heavily industrialized areas, the reduction of VOC emissions may produce a corresponding reduction in ambient hydrocarbon levels, and a corresponding reduction in ozone formation. In rural areas, lower VOC emissions will result in lower overall ambient hydrocarbon levels, helping to reduce the transport of ozone precursors to urban areas. In addition, the reduction of air toxics will lead to reduced environmental impacts on other media. For example, improperly handled chlorinated materials (e.g., methyl chloroform) often result in contaminated soil and groundwater. Reducing the quantities of these materials used for cleaning will reduce the number of contaminated aquifers, drinking water wells, and soils.

Emissions from the application of solvent-based coatings are often directed to a control device (e.g., carbon absorption, catalytic or thermal incinerators). While such control devices reduce VOC emissions, the use of incineration will actually increase ambient levels of nitrogen oxides (NO_x) in the area. A facility must consider that the reductions of a particular pollutant may cause increases in emissions of other pollutants associated with a particular control device.

Spent cleaning solvents are the largest liquid waste produced by coated and laminated substrate manufacturers. Many of these solvents are recoverable through distillation and can be incorporated in a future coating formulation; however, they may also be sent off-site for disposal. A second liquid waste stream consists of excess or off-specification coating.

Facilities are responsible for the environmental impacts that their water may have on a sewer or water system. A facility must always consider the effects of a new liquid waste stream on plant wastewater treatment (WWT) operations or on the publicly owned treatment works (POTW). Some coatings or cleaning compounds may reduce toxicity, hazardous waste, and air emissions, but may violate effluent limitations.

Solid wastes in the form of drums of coating and solvent waste from the manufacturing operations may be classified into three areas: cleaning waste, waste substrate, and solidified coating waste. Solid waste from cleaning includes items such as rags, floor coverings, machinery coverings, and coating filters. Waste substrate (from the edge of substrate rolls, at the beginning and ending of a run, and from cutting and packaging operations) disposal is dependent on local/state regulations but it can generally be disposed of as nonhazardous waste. The characteristics of the solvent remaining on the substrate also affect its classification as solid waste. Solidified coating waste is coating which has dried.

In addition, solid waste may be created by emissions control from equipment. Activated carbon from carbon adsorption systems must be replaced periodically, presenting a solid waste disposal difficulty. The remains of ash and sludge from incineration or ash, sludge, and spent catalyst from catalytic oxidation must be disposed of properly, usually as solid waste. Waste from incineration or oxidation may also have alternative uses.

4. Ultraviolet (UV) and electron beam (EB) process differentials

4.1. Raw materials

While the types of raw materials used in a radiation-curing process for coated and laminated substrates are generally the same as those used with conventional thermal systems (i.e., substrates, adhesives, and other coatings), the constituents of the raw materials may differ. The UV- and EB-curable adhesives have been applied to paper, film, and foil webs like their solvent-based adhesive counterparts. They have been used to laminate polyester, polycarbonate, polyethylene, and cellulose acetate films. At this time, the only web substrates to which UV- and EB-curable coatings have not been successfully applied are those that are porous, such as the fabric which may be used in medical tapes [9]. Because the substrates used in both radiation-curable and thermal coating and laminating systems are very similar, this section will focus on the coatings.

A coating must perform in a specific manner to meet customer demands. Whether these coatings are solvent-based or radiation-curable is irrelevant as long as customer specifications are met. Release coats manufactured for compatibility with EB- and UV-curable adhesives are often 100% solvent-free silicone acrylate. One manufacturer of EB-curable release coatings has received approval from the Food and Drug Administration (FDA) to use their coatings in food containers and other related applications. Specially formulated release coatings are critical in the EB-curing adhesive process because of the increase in tack associated with EB-curable adhesives. Currently available release coatings used with thermal systems may not perform properly with radiation-curable adhesives and may need to be reformulated or replaced.

Radiation-curable adhesives include both UV- and EB-curable varieties. UV-curable coatings consist of monomers, which reduce the coating's viscosity and provide application characteristics; oligomers, which give the coating its physical and performance characteristics; pigments; fillers; inhibitors, which improve shelf life; and photoinitiators, which speed the curing process. The UV-curable adhesives contain a photoinitiator which initiates the polymerization of the adhesive to the substrate when exposed to a UV light. EB-curable hot-melt pressure sensitive adhesives contain 100% solids with polymers, monomers, additives, but no photoinitiator. EB-curable low-melt adhesives which require less heating than hot melts and are developed to perform like solvent-based acrylic adhesives are currently being introduced in Europe. In the EB system, the electrons that are generated react directly with the monomers and polymers, eliminating the need for a photoinitiator [10].

4.2. Equipment

Radiation-cured coating and application equipment differs from conventional equipment in one area: the curing mechanism. Both thermal and radiation-curable systems operate unwind, coating, curing, and drying/rewind stations. In conventional adhesive curing, a thermal dryer is used to heat and dry or cure the coating. The thermal dryer system relies on electricity or natural gas to heat the air which then dries/cures the coating. In a radiation-curing system, energy beams are used to cure the coating. UV-curing equipment consists of a UV lamp suspended above the coated substrate, a light reflector, a radiation shield, and a cooling system. Mercury lamps are frequently used to provide the UV-curing mechanism. The substrate with the wet coating passes under the light and is exposed to the UV wavelengths which crosslink the polymers and monomers, creating a uniform adhesive layer.

EB-curing equipment consists of a control panel to regulate the amount of energy, a transformer to control line voltage, an electron accelerator to deliver the EB energy, and a nitrogen-inerting system to prevent ozone formation [11]. Production line speeds for EB-curing equipment can exceed 1600 feet per minute (fpm) (490 m/min), which is comparable to line speeds of equipment running solvent-based coatings. Operations in excess of 1600 fpm will need a specialized nitrogen-inerting system to prevent unacceptable ozone emissions [12]. The curing method for EB is similar to the UV process.

4.3. Physical processes

UV- and EB-curing represent the two most widely used radiation-curing methods. Each has process advantages and disadvantages which are discussed in detail below.

UV polymerization occurs when a specially formulated coating contacts a UV light source, primarily a mercury lamp. The characteristics of the coating and substrate affect the UV energy being absorbed by the photoinitiator. The curing of the coating is also dependent on both of these factors [11]. If the UV energy does not penetrate the coating effectively, much of the coating will not be cured. UV energy does not penetrate thick, dark, or colored coatings or substrates very well [12].

EB-curing occurs when a specially formulated coating is exposed to electrons. The proper curing of an EB adhesive is dependent on the mixture of raw materials and the level of energy used to power the electrons. One advantage that EB has over UV is that the electrons can cure the layers of 100% solid adhesives. This ability allows EB-curing to be used on a variety of substrates [11]. However, if the ratio of energy to raw materials is not properly determined, a substrate can be damaged (e.g., paper can become brittle) [12]. EB-curing is similar to UV-curing with one notable exception: the UV-curing requires a photoinitiator to generate the free radicals. Both systems cure the coating in approximately 1 s [11].

The use of radiation-curable adhesives has allowed the coating of substrates which have previously been unusable. Substrates such as plastics can now be coated with EB- and UV-curable adhesives which provide high bond strengths at low adhesive weights. Although no EB-curable adhesive lines are in commercial operation in the United States, tests have been conducted to evaluate and compare the performance of EB-laminating adhesives with those of solvent and standard hot-melt adhesives. Laboratory tests were conducted comparing peel and shear properties of radiation-curable, solvent-based, hot-melt, and silicone-based adhesives [11].

4.4. Emissions and wastes

In general, UV- and EB-curable coatings do not contain solvents. The absence of solvents completely alleviates VOC and volatile organic HAP emissions to the air from the application and curing process. The EB systems use nitrogen (N_2) to inert the curing area and prevent ozone emissions. In addition, the EB- and UV-curing processes do not create any hazardous waste.

Both UV- and EB-curable coatings are considered solid waste before and after curing since the ingredients are 100% solids. Due to the size of the UV and EB machinery, less solid waste is created since less makeready substrate, used to thread through the lines prior to beginning the coating process, is needed. Also, both UV and EB systems can coat the substrate to the edge, thus creating less slitter waste from the edges. Recycled paper substrates can also be used in the radiation-curing process but not in traditional solvent systems.

Another source of emissions and wastes is equipment cleaning. Solvent-based coating spills are usually cleaned with a solvent-type cleaner. Radiation-cured coatings can be removed with less polluting methods. Spills and overflows of the radiation-curable coatings from the dam can be cleaned with a dry rag, industrial strength soap, or isopropyl alcohol (IPA), a non-toxic solvent. The solvents used in the coating and cleanup of conventional solvent-based adhesives present a toxicity threat which the radiation-curing process does not pose [11]. The radiation-curable coatings do have the potential to cause skin irritation, which can be prevented by wearing the proper protection.

5. Cost factors

One of the many aspects of investigating alternative technologies is the cost difference between the conventional and alternative technologies. Four primary cost centers were evaluated as part of this study; materials, equipment, operation and maintenance, and energy. The information provided was received from several sources and, thus, should be used only as a guide.

5.1. Materials

In order to compare the raw material costs for both solvent-based and radiation-curable processes, several factors must remain constant. The substrate (i.e., paper, foil, film) purchase cost remains the same because no new substrates are required to be developed. Line speeds and required coating thickness (i.e., a 1 mil (25.4 μm) thick coating after curing) also must be considered constant for this comparison. The cost for the coatings applied to the substrate is the variable examined. All pressure sensitive adhesive products have both a release and adhesive coating. The solids content in pressure-sensitive release coatings for the three (i.e., UV-curable, EB-curable, and solvent-based) types of coatings vary. Solvent-based release coatings (30–50% solid, 50–70% solvent) and adhesives (30–60% solid, 40–70% solvent) were reported to sell for approximately $1.50–1.90 per wet pound ($3.30–4.20/kg) [13]. Liquid UV-curable release coatings and adhesives (100% solids) were reported to sell for approximately $3.00–5.00/lb and $4.00–6.00/lb ($6.60–11.00/kg and $8.80–13.20/kg), respectively. Of the $3.00–5.00, it was estimated that approximately 25–50% of the UV-curable adhesive costs are for the photoinitiator [13]. The EB-curable release and adhesive (100% solids) coatings were reported to sell for approximately $10.00/lb and $1.50–2.00/lb ($22.00/kg and $3.30–4.40/kg), respectively [9, 13, 14]. In addition, water-based release coatings and adhesive coatings were reported to sell for $0.75–1.50 and $1.00–2.00 per dry pound ($1.65–3.30/kg and $2.20–4.40/kg), respectively [15]. Hot-melt release coatings are predominantly waterbased, while the hot-melt adhesives cost approximately $3.75–4.75 per dry pound ($8.25–10.50/kg) [13]. Dry pound refers to the 100% solids or preheated state of the coatings. Wet or liquid pound refers to the ready-mixed coating's form. Fig. 1 is a graphical representation of release coating costs, while Fig. 2 shows adhesive coating costs.

Another study provided a comparison of costs for thermal and EB-curable adhesives in Europe. Some European companies are currently using EB technology in commercial adhesives applications. The study compared a 60% solids, 40% solvent adhesive to a 100% solids hot-melt and 100% solids low-melt EB-curable adhesive. During the manufacture of the coated product, a 0.008 lb/ft^2 wet [0.04 kilogram per square meter (kg/m^2)] coating of the 60/40 adhesive was applied to obtain a 0.005 lb/ft^2 (0.02 kg/m^2) dry coating. The adhesive costs approximately $1.50/lb ($3.30/kg). The study estimated the cost to be approximately $0.13/$yd^2$ ($0.15/$m^2$) to use the 60/40 solvent-based adhesive. The 100% solids EB-curable rubber hot-melt adhesive costs approximately $2.30/lb ($5.00/kg). This corresponds to a cost of $0.12/$yd^2$ ($0.14/$m^2$) with a 0.005 lb/ft^2 (0.02 kg/m^2) coating. The EB-curable low-

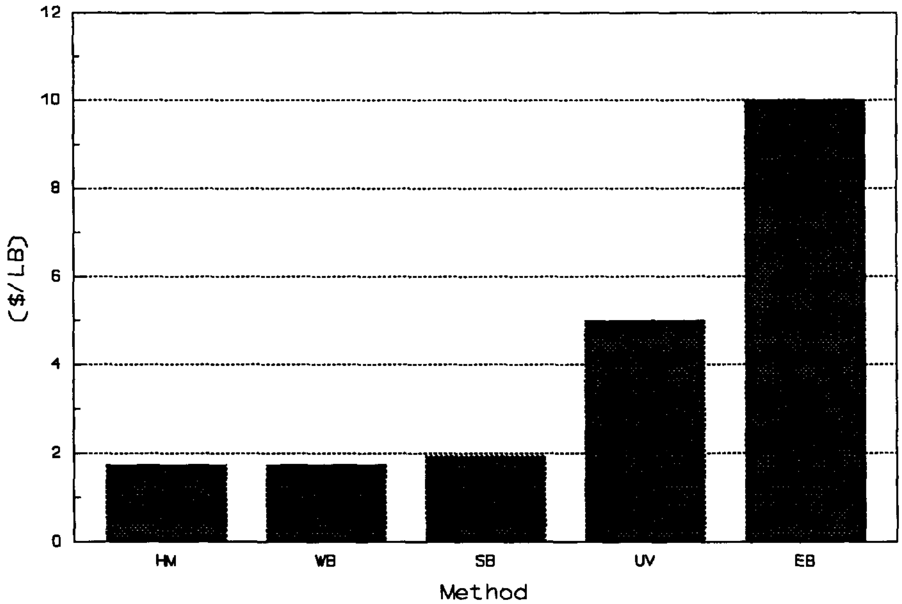

Fig. 1. Release coating costs: HM – hot melt (dry); WB – water-based (dry); SB – solvent-based (wet); UV – ultraviolet (wet); and EB – electron beam (dry).

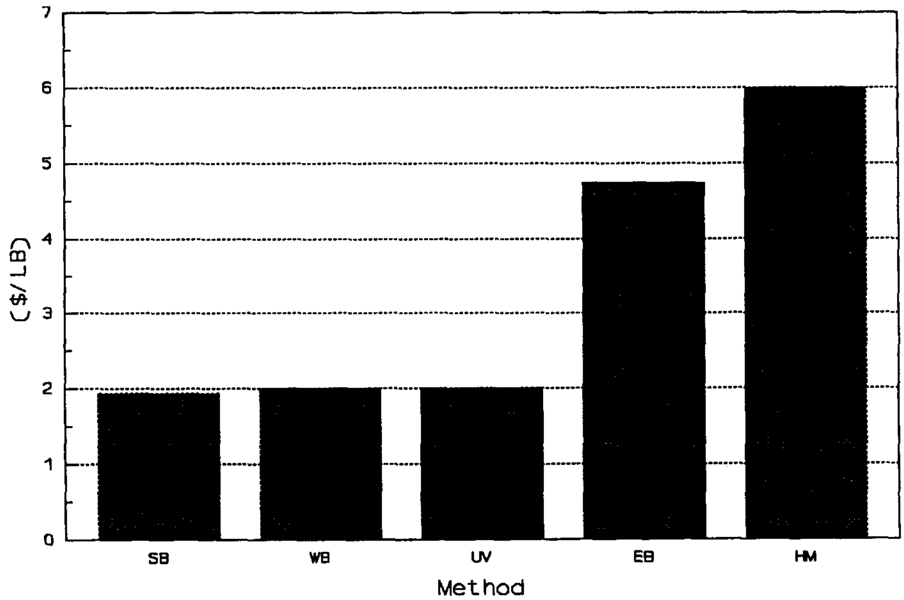

Fig. 2. Adhesive coating costs: SB – solvent-based (wet); WB – water-based (dry); UV – ultraviolet (wet); EB – electron beam (dry); and HM – hot melt (dry).

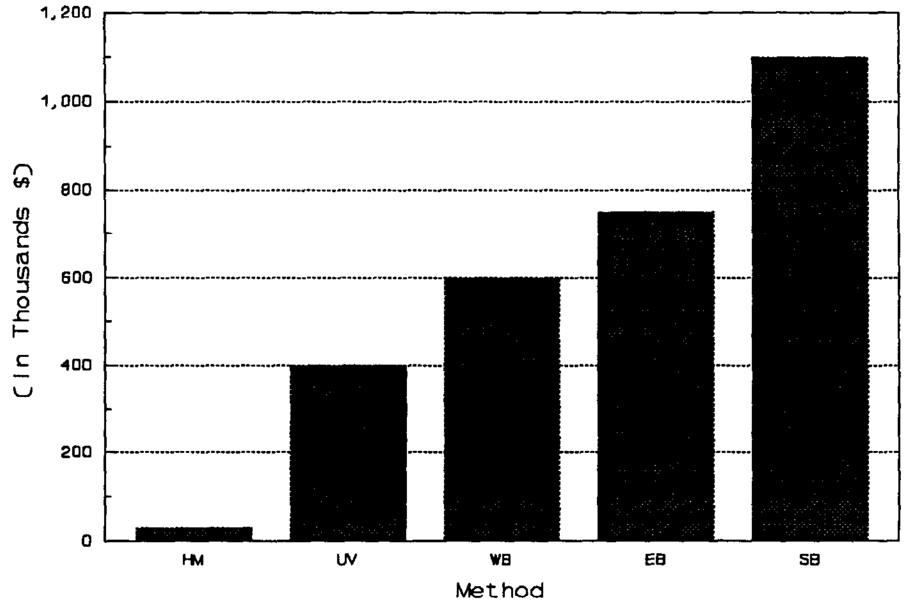

Fig. 3. Capital cost for adhesive cure mechanisms: HM – hot melt; UV – ultraviolet; WB – water-based; EB – electron beam; and SB – solvent-based.

melt costs approximately \$3.00/lb (\$6.60/kg), making a square yard of product cost approximately \$0.22 ($0.26/m^2$) to produce at 0.005 lb/ft^2 (0.02 kg/m^2) [15].

5.2. Equipment

Pressure-sensitive coating application equipment can range in performance, price, and size. The equipment costs discussed below represent a comarison between the types of coated and laminated adhesive curing mechanisms. These figures compared systems which cure a 60 in (152.4 cm) wide substrate at line speeds of 600 fpm (182.9 m/min). A solvent-based thermal adhesive dryer was estimated to cost approximately \$1.1 million while an EB adhesive curing 'turn-key' system was quoted at \$750 000 [12]. Water-based adhesive system dryer costs were estimated at \$600 000 while a hot-melt chill roller with the chiller system costs approximately \$30 000 [13, 16]. Fig. 3 is a graphical representation of a manufacturer's capital costs for various adhesive cure mechanisms.

5.3. Operation and maintenance

Operating and maintenance (O and M) costs occur for all types of coating lines. The thermal system's maintenance cost was estimated to be approximately \$2500/yr for approximately 6000 h of operation. For the thermal lines, dryer conveyors and heating mechanisms are the primary O and M cost items. EB and UV systems were estimated to cost approximately \$2000 and \$6000–8000 a year, respectively, for similar operating times and maintenance. EB machinery maintenance primarily involves replacing the windows which expose the substrate to electrons. The UV system's maintenance costs consist of replacing the lamp system. These estimates are based on the opinions of EB-curing, UV-curing, and thermal equipment manufacturers [12]. A printing study showed amortized (i.e., 7 yr, 6000 h of operation per year) maintenance costs for thermal, EB-curing, and UV-curing of $0.16, $0.45, and $7.00/h, respectively [17].

5.4. Energy

At this writing, no coated and laminated substrate manufacturers were willing to provide information on energy costs for a production line, considering that information proprietary. In lieu of a coated and laminated substrate manufacturing line, the results of a printing study will be used as a comparison of energy costs for thermal, EB, and UV operations. In addition, hot-melt energy costs are examined in a separate study of coating substrates [13].

The printing study compared thermal, EB- and UV-curing systems. Each line was evaluated for 6000 h of operation per year. Conditions during operation were for full operating time, standby, and warm-up. The thermal line's energy costs for electricity and natural gas were $25.40 and $18.20, respectively, for a total cost of $43.50 h. The thermal line operating parameters were 5500 h full operating time, 300 h standby, and 200 h warm-up. The EB-curing system's energy costs for

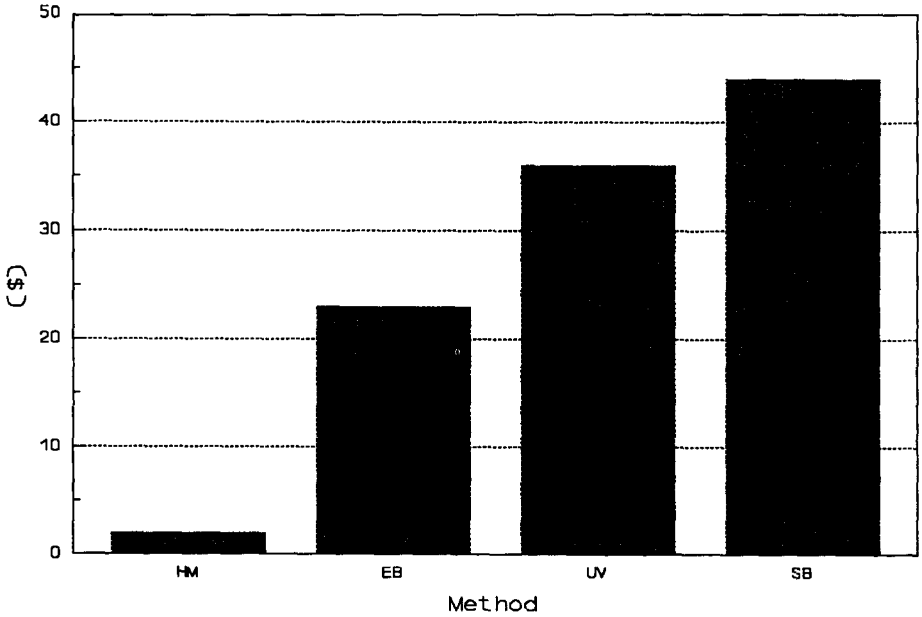

Fig. 4. Energy costs for coating lines (per hour): HM – hot melt; EB – electron beam; UV – ultraviolet; and SB – solvent-based.

electricity and nitrogen were \$6.50 and \$15.20, respectively, for a total cost of \$21.70 h. The EB-curing system's operating parameters were 4000 h full operating time, 500 h standby, and 1500 h of non-operation. The curing mechanisms for both EB and UV can be started and shut down in a matter of minutes; therefore, less hours of full operation and none for warm-up are needed, resulting in the 1500 h of non-operation. The UV-curing system's energy cost for electricity was \$36.80 h. The UV-curing system's operating parameters were 4000 h full operating time, 500 h standby, and 1500 h of non-operation [17]. Fig. 4 graphically summarizes the energy costs per hour for cure systems.

Another study compared a solvent-based to a hot-melt curing system. The solvent-based curing system required 83 000 Btu per thousand square feet (942 j per thousand square meters) of substrate with a 1.5 mil (38.1 μm) coating thickness of a 40% solids adhesive. The hot-melt systemrequired only 2000 Btu per thousand square feet (23 j per thousand square meters) of substrate to a 1.5 mil (38.1 μm) coating thickness. The solvent-based system's energy costs were \$23 0000 per year (\$38/h for 6000 h of operation). The hot melt system's energy costs were \$5500 per year (\$0.92/h for 6000 h of operation) [18]. It should be noted that the hot-melt system's energy costs are for cooling, thereby curing the adhesive. No costs were available for heating the hot-melt adhesive to the application temperature.

6. Technical barriers

Reviewing alternative technologies for the coated and laminated substrate manufacturing industry reveals several technical barriers, the greatest of which is the lack of available practical, commercial production experience in using UV- or EB-curing systems. Currently, tape and label manufacturers using radiation-curing for production purposes are unwilling to share proprietary information on these lines. This has made it increasingly difficult to completely identify all technical barriers to radiation-curing in the coated and laminated substrate manufacturing industry. However, in discussions with equipment and raw material vendors, some general technical barriers have been identified. These technical barriers can be categorized as: equipment suitability, materials availability, product and adhesive performance characteristics, and health and safety issues. Each of these barrier categories will be discussed in this section.

6.1. Equipment suitability

For the purposes of this discussion, the important equipment for the coated and laminated substrate manufacturing industry can be broken down into two segments: coating application equipment and curing equipment. All other auxiliary equipment, such as the wind and unwind stations, remain the same regardless of the type of application and curing equipment used.

The application equipment for liquid UV-curable adhesives should be the same as for a solvent-based coating system. UV-curable adhesives can be applied by a reverse roll coater, a metering rod coater, or gravure roll coater [19]. Therefore, most tape and label manufacturers would not need to retrofit or replace existing equipment in order to use UV-curable adhesives.

The application equipment for EB-curable adhesives would be a hot-melt coating system. Many tape and label manufacturers have a hot-melt line at their facilities; therefore, the EB-curing system could be easily added. However, for facilities that do not have a hot-melt line, the equipment necessary to liquefy the adhesive would need to be purchased.

The radiation-curing equipment can be easily installed onto an existing thermal system with minimal downtime if enough horizontal (i.e., floor) space is available between the application equipment and the dryers. Several radiation-curing equipment manufacturers have suggested that the equipment can be installed under the thermal dryers if the dryers are elevated approximately 10 ft (3 m) off the ground. If insufficient room exists between the application equipment and the thermal dryer or if the dryer is not elevated, the installation of the radiation-curing equipment will be much more difficult and time consuming, and will require either removing the thermal dryer completely or moving the application equipment to another area.

6.2. *Material availability*

At this time, few facilities are commercially producing tapes or labels using radiation-cured coatings. This is due in part to the lack of available radiation-curable pressure-sensitive adhesives. A few smaller adhesive manufacturing companies have developed potentially applicable adhesives, but have had limited success in presenting these new formulations to the tape and label manufacturers. Several large adhesive manufacturers state that no radiation-cured technology is currently available that will provide the tape and label manufacturers with a radiation-curable adhesive that has the same physical properties as the solvent-based adhesives. However, these same large adhesive coating manufacturers stated that their research and development teams are working on the radiation-curable alternatives, and that the technology should be available within the next 2 years.

The development of solventless adhesives is very time consuming. With each new adhesive developed, the adhesive manufacturer must ensure that each hazardous component of the adhesive is registered under the Toxic Substances Control Act (TSCA). TSCA registration can be very time consuming and costly [20]. In some cases, the registration process can take up to 3 yr.

In addition to the need for development of radiation-curable adhesives with the same physical properties as the solvent-based adhesives, the release coatings may need to be reformulated to be compatible with the new adhesives. As with adhesives, each new release coat component must be TSCA registered. The increased tack associated with EB-curable adhesives makes the release coating a very important part of the tape and label manufacturing process. It is critical that the release coat allow for a smooth release of the tape or label, or consumer satisfaction may be affected. A further discussion of physical properties is included in the following section.

6.3. Product and adhesive performance characteristics

As discussed earlier in this paper, the physical properties of the radiation-curable adhesives are some of the most difficult barriers to overcome. The solvent-based adhesives have very specific properties that have been established as 'standard' (e.g., color, lack of clarity) that consumers believe are critical to the tape or label and its end-use. Until recently, radiation-curable adhesives did not achieve those standard properties.

Liquid UV-curable adhesives lack many of the physical properties of solvent-based adhesives. One such property is the cure window or the time period during which the adhesive can be properly cured. The cure window for liquid UV-curable adhesives is short; therefore, the adhesive can be undercured or overcured very easily. This curing problem can lead to poor tack and increased creep (wrinkling). Other properties that have prevented liquid UV-curable adhesives from being considered as alternatives to the solvent-based adhesives include: increased viscosity, making the adhesive difficult to apply with conventional application equipment; residual odors from the undercured adhesive; and appearance problems [15]. The problems associated with the UV-curable adhesives led to the creation of the EB-curable products. Hot-melt/EB-curable adhesives do not possess many of the problems that UV-curables exhibit and offer some advantages over solvent-based formulations such as increased temperature and chemical resistance. This makes them attractive for some high-performance applications.

Due to the lack of data from any commercial application of either of these radiation-curable technologies, it is difficult to discuss aesthetic properties. However, it is important to mention, that in discussions with marketing representatives from the tape and label companies, aesthetics are very important to their customers. Poor perception of a low polluting product which does not look or feel like a solvent-based product, even though it may actually perform better, may lead to lack of market acceptability. This could be a considerable barrier.

6.4. Health and safety issues

In general, even with the increase in knowledge of radiation-curing technologies that has occurred over the last 20 years, health and safety concerns are evident. Even though radiation-curable adhesives would be handled in the same manner as solvent-based adhesives, with the use of gloves and eye protection at all times, facilities still question effects on workers' health. There is the potential for skin to become sensitized to the adhesives, if the coating is not washed off quickly. However, if the adhesive is handled properly, this potential is minimal.

7. Economic barriers

In addition to the technical barriers described above, coated and laminated substrate manufacturers must evaluate the economics associated with making significant raw material and process changes. This section discusses the economic barriers to using radiation-curable adhesives including capital investment, pricing pressure, payback periods, and operating costs. Due to the lack of data from actual production facilities using liquid UV-curable adhesives, this section focuses on EB-curable adhesive systems.

7.1. Capital investment for new systems

A comparison of thermal and EB-curing technology must examine the capital investment costs for new equipment. The costs reported below were provided by a supplier of both EB-curing and thermal machinery. For a 60 in (152.4 cm) wide substrate and a line speed of 600 fpm (182.9 m/min), the new EB machinery plus a hot-melt chill roller with the chiller system is less expensive than the new thermal equipment without control equipment. In terms of retrofit, a facility would need to add an EB-curing mechanism, listed at approximately $750 000, for each coating line. Assuming the facility already has a hot-melt adhesive system and release coating equipment in place, additional add-on costs for a retrofit would be minimal [16].

Cost in dollars for a new solvent-based system:	
Solvent-based silicone release coater and drive	235 000
Solvent-based silicone adhesive coater and drive	400 000
Solvent-based silicone release coat dry/cure system	700 000
Dryer system for solvent-based silicone adhesives:	
120 ft, 5 zones	1 100 000
Subtotal	2 435 000
Installation (22 percent of subtotal)	535 700
Grand total with installation	2 970 700
Cost in dollars for a new EB-cured system:	
EB five roll release coater	350 000
EB adhesive coater (drum unloader/melter)	360 000
EB curing system (release)	750 000
EB curing system (adhesive)	750 000
Subtotal	2 210 000
Installation (22% of subtotal)	486 200
Grand total with installation	2 696 200

7.2. Pricing pressure

The profit margin for many coated and laminated substrate products is very low, pennies per square foot. Because of the low profit margins, facilities must consider the effect of environmental regulations on product costs. Upcoming environmental regulations may affect a facility's emissions requirements, requiring them to reduce, control, or eliminate much of their solvent emissions, or pay large fines or close the facility. Additionally, the cost for maintaining and operating emission control devices and following record-keeping requirements may be substantial. These costs will cause the price of most products to increase. These costs could be avoided if reasonable alternative technologies could be obtained. Alternative technologies must not only address the production issue and be affordably priced, but provide fewer emission problems than a solvent-based system.

7.3. Payback period for retrofit systems

In order to compare the costs for retrofitting a single-line solvent-based system with an EB-curing system, several assumptions must be made: the coating head/area will not be significantly altered, a hot-melt system will be preexisting for the production line, substrate types will not change, the dryer will not be used with the EB-curing system, and the radiation-curing equipment will be retrofitted to the present coater. In terms of retrofit equipment costs, the EB release and adhesive cure systems, valued at $750 000 each, will be the major equipment investment a facility must consider. Unlike the equipment investment for a new EB-curing system of approximately $2.7 million, the retrofit should require only the two curing systems. The decision to retrofit one solvent-based line to an EB-curing line must consider annual costs for energy, solid waste, hazardous waste, air emissions, and other annual costs. Using these factors, it was estimated that a retrofit to EB-curing could save approximately $100 000–130 000/yr.

Using the savings per year from switching to the EB-curing equipment, and the cost for the solvent-based release and adhesive coating lines, at a discount rate of 2.1%, the net present value theory estimates that approximately 11 yr would be required to recover the capital costs of the EB investment.

Additional savings, such as reduced raw material use (due to increased mileage of the radiation-curable adhesives), reduced maintenance, floor space saved for other uses, lower shipping costs for solid materials, and less cleanup time for EB-curable coatings, should also be considered in examining EB-curing system implementation costs and savings.

7.4. Operating costs

Actual operating costs for radiation-curable adhesive applications are not available due to the proprietary nature of that information. However, as described earlier, operating and maintenance costs for an EB-curing system were lower than for conventional thermal systems.

8. Pollution prevention/source reduction research opportunities

In spite of the identified barriers to radiation-curable adhesives, several opportunities exist which could help in reducing or removing these barriers. As stated throughout this paper, the lack of data on the commercial use of radiation-curable adhesives in the coated and laminated substrate manufacturing industry is the greatest barrier to overcome.

In order to facilitate the transfer of information on this alternative technology to the industry, a focus group could be convened containing representatives from industry, trade associations, environmental agencies, radiation-curable coating and equipment suppliers, hot-melt coating and equipment suppliers, water-based coating and equipment suppliers, and other interested parties. The charter of the focus group could be to identify any technological barriers not discussed in this paper, exchange information on alternative technologies (including research and development opportunities), and develop good working relationships between adhesive manufacturers and coated and laminated substrate manufacturers. By forming the focus group, technical, economic, and educational barriers could be discussed and eliminated. To further the information exchange, the focus group could encourage demonstrations at host facilities using the alternative adhesives, host educational seminars on alternative technologies, and provide guidance to EPA on the focus of their research efforts.

In addition to the information exchange within the focus group, another area of further study is to investigate the European market. It has been suggested that production facilities in Europe are using radiation-curable adhesives. It would be valuable to pursue the European market to determine what problems or opportunities they have discovered as a result of actual production using these alternative adhesives.

Additional opportunities for research into the marketing problems associated with alternative technologies would be beneficial. Many companies state that their customers are hesitant to purchase non-solvent-based products because of aesthetics. Surveys could be developed to better determine the specific characteristics that are lacking in the alternative adhesives. Coated and laminated substrate manufacturers should continue to encourage radiation-curable adhesive manufacturers to develop products that overcome the aesthetic problems that have been identified. As part of the marketing study, purchasing personnel from retail outlets could be included in the technology transfer, allowing customers to learn about the new technologies, their physical properties, and their environmental benefits. By providing these people with the appropriate information, better purchasing practices can be implemented that will help prevent pollution.

Economic incentives for the use of low-polluting emitting adhesives is another area that could be studied. Under section 182(g)(4) of the CAAA, states are encouraged to adopt economic incentive programs (EIPs) to encourage the development of low-VOC surface coatings, specifically adhesives. The study would include a review of applicable state EIPs to determine which areas of the country are eligible for these incentives. Information could be transferred to coated and laminated substrate manufacturing facilities, or adhesive manufacturing facilities that are in those areas of the country to assist them in meeting the applicable requirements to receive the financial benefits.

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