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Preliminary Use and Substitutes Analysis of Lead and Cadmium in Products in Municipal Solid Waste

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PRELIMINARY USE AND SUBSTITUTES ANALYSIS FOR LEAD AND CADMIUM IN PRODUCTS IN MUNICIPAL SOLID WASTE

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Prepared for:

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TABLE OF CONTENTS

TABLE OF CONTENTS
(Continued)

LIST OF TABLES

LIST OF TABLES
(Continued)

LIST OF TABLES
(Continued)

LIST OF FIGURES

SUMMARY REPORT

The use of lead- and cadmium-containing articles that ultimately are disposed of in municipal solid waste (MSW) facilities is the focus of a joint project by the Office of Toxic Substances and the Office of Solid Waste. Disposal of lead- and cadmium-containing products is a concern because incineration of these items concentrates the metals in the ash residue which, when landfilled, may lead to groundwater contamination.

The Pollution Prevention Act of 1990, passed by Congress on October 27, 1990, asserts that, "pollution should be prevented or reduced at the source wherever feasible (EPA 1990)." This report identifies lead- and cadmium-containing products that are disposed of in MSW, and provides information regarding potential substitutes for these metals in various applications. The identification of technically feasible substitutes for lead and cadmium in products found in MSW can be an important preliminary step towards pollution prevention.

In 1989, EPA issued a report entitled "Characterization of Products Containing Lead and Cadmium in Municipal Solid Waste in the United States, 1970 to 2000." The current report examines technologically feasible lead and cadmium substitutes for each of the products identified in the 1989 report. To provide perspective on the sources of lead and cadmium in MSW, Table SR-1 provides estimates for 1986 discards of both metals in each product use area. A full copy and/or the Summary Report of this document, "Preliminary Use and Substitutes Analysis for Lead and Cadmium in Products in Municipal Solid Waste," may be obtained by calling the EPA Resource Conservation and Recovery Act (RCRA) hotline number: (800) 424-9346.

Table SR-1. Discards of Lead and Cadmium by Use Area in MSW in 1986

Product Area	Lead Discards (tons)	Cadmium Discards (tons)
Lead Acid Batteries	138,043	0
Plastics	3,174	564
Pigments[a]	1,131	70
Solder	8,369	0
Nickel/Cadmium Batteries	- 0	927
Glass and Ceramic Products	60,714	29
Brass and Bronze Products	321	0
Plated Products	0	185
Collapsible Tubes	639	0
Rubber Products	70	6
Other Products[b]	671	1

[a] Discards of pigments do not include pigments consumed in plastics, glass/ceramic products, or rubber products. These discards are covered in the sections on plastics, glass/ceramic products, and rubber products.

[b] Other products include used oil, foil wine wrappers, electric blankets and heating pads, and television and radio chassis. 279 tons of lead were discarded as part of television and radio chassis, but future discards are expected to be zero due to a change in technology which has discontinued the use of lead in these products.

Sources: EPA 1989, Franklin 1990.

LIMITATIONS

This report should be considered as a preliminary analysis due to the limitations of its scope. EPA has not performed primary research to identify the substitutes for lead and cadmium described in this report. Only substances identified in published sources or by industry contacts and that were known or considered to be potential substitutes have been included in this analysis. Because this report characterizes substitutes for both lead and cadmium products, lead and cadmium are not considered as substitutes for each other although this sometimes may be technically feasible. Furthermore, the substitution in this report is based only on technical feasibility and does not quantitatively assess economic factors that affect substitution or the effect of potential substitutes on end products (e.g., different service lives for substitute products). While some information is provided on the cost of potential substitute compounds, no economic analysis has been performed to estimate the impacts of substituting for lead and/or cadmium products. This report, therefore, is not intended to draw conclusions about the viability of actual substitution. No economic analysis has been performed to estimate the impacts of substituting for lead and/or cadmium products.

In addition, toxicities of substitutes are not discussed in this report and toxicity was not a criterion for identifying potential substitutes. Many of the classes of chemicals assessed have intrinsic toxicities that would be of great concern in other parts of the manufacturing processes where there would be human or environmental exposure to more bio-available forms of the chemical or chemicals. A more focused, in-depth substitute characterization for each chemical substitute in each use area would be required to adequately assess the hazard presented by potential substitutes.

LEAD AND CADMIUM SUBSTITUTES

The range of consumer products that contain lead and/or cadmium and are disposed of in MSW facilities is quite broad. The remainder of this report focuses on potential substitutes for lead-and cadmium-containing products in each of the following areas:

- plenty plastics (pigments and heat stabilizers);
- pigments*;
- solder;
- lead-acid batteries;
- nickel-cadmium batteries;
- glass and ceramic products;
- brass and bronze products;
- cadmium-plated products;
- collapsible tubes; and
- other products (foil wine wrappers, used oil, rubber products, and electric blankets/heating pads).

Plastics

Lead- and cadmium-containing additives are used in plastics as both pigments and heat stabilizers. Table SR-2 lists lead and cadmium pigments and their possible substitutes. Table SR-3 lists lead- and cadmium-based heat stabilizers and their potential substitutes.

For many of the lead- and cadmium-based colorants, potential substitutes that provide similar hues have been identified. However, for specific applications hue may not be the most important factor influencing the choice of a pigment. For example, while some organic pigments match the hue of cadmium pigments, individual substitute pigments may not be adequate in terms of brilliance, lightfastness, or high-temperature stability for some applications. Furthermore, the costs of these substitutes may be

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* Pigments containing lead and/or cadmium are used in paint, ink, paper, rubber, glass, and plastic products. The discussion of pigments is summarized separately, but the majority of information on pigments is contained in the plastics section.

Table SR-2. Lead and Cadmium Pigments and Potential Substitutes

Hue[a]	Lead and Cadmium Pigments	Potential Substitutes	Performance[b]
Yellow	Lead chromate Cadmium sulfide Cadmium sulfide and Zinc	Nickel titanium (NiTi)(inorganic)	General suitability, but greatly reduced tinting strength
		Monoazo (organic)	Suitable for low density polyethylene, and polystyrene. Not suitable for PVC.
		Pyrazolone derivative (dye)	Suitable for polymethyl methacrylate, unplasticized PVC, and polystyrene.
Red	Lead molybdate[a] Cadmium/sulfide selenide	Iron oxide (inorganic)	General suitability
		Monoazo naphthol (organic)	Caution is needed in the case of high density polyethylene articles sensitive to distortion.
		Azo dye (dye)	Suitable for polymethyl methacrylate, unplasticized PVC, and polystyrene.
		Quinacridone (organic)	Suitable for polystyrene, PVC, low density polyethylene. Caution is needed in high density polyethylene articles sensitive to distortion.
		Perylene (organic)	Suitable for polystyrene, PVC, and low density polyethylene. Caution is needed in high density polyethylene articles sensitive to distortion.

[a] Potential substitutes are based on similar hue or color (i.e., any of the substitutes in a color group is assumed to be able to substitute for any lead- or cadmium-based pigment with the same hue). In some cases this may not be the most important characteristic (e.g., heat stability may be an important factor).

[b] For dyes, lightfastness and heat stability depend on the plastic to be colored.

Sources: Plastic Additives Handbook 1987, Bayer Mobay 1989, and BASF 1989.

Table SR-3. Lead- and Cadmium-based Heat Stabilizers and Potential Substitutes

Stabilizer	Potential Substitutes	Performance Comments

Lead Stabilizers
  Tribasic lead sulfate
  Dibasic lead phosphite
  Dibasic lead phthalate
  Dibasic lead stearate
	Organotin stabilizers	Suitable for a wide range of rigid and flexible PVC applications although different organotin stabilizers have different areas of suitability.

Normal lead stearate Dibasic lead carbonate	Barium/zinc stabilizers	Suitable for flexible PVC applications such as shoes, sandals and soles.
	Teflon[a]	Technically feasible substitute for cable insulation and jacketing but not as a one-for-one substitute for lead-based heat stabilizers.

Cadmium Stabilizers
  Barium/cadmium decanoate
  (and other fatty acid salts)
	Zinc/calcium stabilizers	Suitable for a wide range of flexible PVC applications.

Barium/cadmium alkyl phenols Barium/cadmium benzoates	Organotin stabilizers	Suitable for a wide range of rigid and flexible PVC applications although different organotin stabilizers have different areas of suitability.
	Barium/zinc stabilizers	Suitable for a wide range of rigid and flexible PVC applications

PVC = polyvinyl chloride.

[a] Teflon is a different class of substitute in that it would replace the end-product, PVC coatings, used for wire and cable insulation.

Sources: Argus 1989a, 1989b, 1989c; and Bedford 1989.

significantly higher than their lead- and cadmium-containing counterparts. Although the majority of companies no longer supply lead-based pigments, cadmium pigments are still produced because their performance characteristics are difficult to reproduce.

Potential substitute products that can replace lead- and cadmium-containing heat stabilizer products continue to be investigated due to the toxicity of lead and cadmium compounds and the availability of an increasing number of technically superior alternate products. Lead and cadmium heat stabilizers have seen widespread use because of their relatively low cost compared to newer substitute products.

The replacement of lead-based heat stabilizers in electrical cable insulation and jacketing (power wiring, telephone cable, and cords and connectors for appliances and other consumer items) has been difficult due to the critical properties of weathering, humidity resistance, and thinness of the jacket that lead imparts. Potential substitutes for cadmium-containing stabilizers have been identified.

<u>Pigments</u>

A pigment is defined as a substance that imparts color to other materials. Pigments are normally insoluble in the material in which they are dispersed and usually are classified as either organic or inorganic.

Pigments are used in a wide variety of products: paint, ink, plastic, paper, rubber, and glass. The discussion of pigments found in the Plastics section above is applicable to lead- and cadmium-containing pigment substitution in general.

<u>Solder</u>

Solder is used in a variety of products to form both electrical and structural bonds between various types of materials. The most common use of

solder is to attach electrical components to printed circuit boards (Arconium 1989). Tin/lead soldering alloy is the most common soldering alloy currently in use (Kapp 1989). The chief reason tin/lead solder is used to produce consumer electronics is low cost (Talco 1989). Products containing solder that enter the municipal waste stream include consumer electronics, cans, and light bulbs.

Cadmium-containing solder is not used commonly to manufacture consumer electronics. Manufacturers avoid the use of cadmium because of health-related concerns including the generation of poisonous fumes during the soldering operation (IPC 1989a, Keeler 1987, Indium 1989c). Cadmium-containing solder also is not used in the manufacture of cans, but has been used in the past in light bulb manufacturing (NFPA 1989, Sylvania 1989b).

Four types of potential substitute solder alloys have been identified for consumer electronics applications (see Table SR-4). All of these solders employ exotic metals making them much more expensive than tin/lead solder. The characteristics of the potential substitute solder alloys differ from tin/lead solder in terms of melting temperature, required flux type, ability to wet the surfaces to be soldered, and bond strength.

Lead-acid Batteries

Batteries are classified as primary and secondary cells. Primary battery cells are also known as "fuel cells" because the active chemicals are used in an irreversible reaction. This type of cell typically is disposed of after use. By contrast, secondary battery cells may be recharged because their chemistry is based on a highly reversible reaction. After charging, however, the materials do not return exactly to their previous (charged) state, limiting the number of times the secondary battery can be reused.

Table SR-4. Potential Substitute Solders and Processes for Lead- and Cadmium-containing Solder in Consumer Electronic, Consumer Can, and Light Bulb Applications

Application Area	Potential Substitutes	Performance Comments
Consumer Electronics	Bismuth/tin solder	Suited to surface mount assembly technology. Some bismuth alloys may have unacceptably low melting temperatures for use in consumer products.
	Tin/silver solder	Can be used to solder silver-plated base metal without significantly solubilizing the silver. Less ductile than indium and bismuth solder alloys. Higher cost than tin/lead solder.
	Indium/tin solder	Suited to surface mount assembly technology. Compatible with gold and other precious metals. Low melting point not suitable for high temperature applications. As much as 20 times the cost of tin/lead solder.
	Indium/silver solder	Suited to surface mount assembly technology. Compatible with gold and other precious metals. Low melting point not suitable for high temperature applications. As much as 20 times the cost of tin/lead solder.
Consumer Can	Crimping process[a]	Eliminates the need for solder.
	Welding process[a]	Eliminates the need for solder.
	Tin solder	Eliminates the possibility of lead leaching into canned food products. May be used in non-food cans. More expensive than tin/lead solder.
Light Bulb	Indium-based solder	More expensive than tin/lead solder. Oxidizes when used in light bulb manufacturing process. Tin/zinc solderDoes not flow as well as tin/lead solder.

[a] Welding and crimping processes are in a different class of substitutes in that they would replace the soldering process used for consumer cans.

Sources: ADL 1990; CMI 1989a, 1989b; Indium 1989b, 1989c; IPC 1989b; Kapp 1989; Keeler 1987; Manko 1979; NFPA 1989b; Sylvania 1989b, 1989c.

Lead-acid batteries are currently the most commonly used type of rechargeable battery. These batteries are used for starting, ignition, and lighting in virtually all motorized vehicles, and are used in other applications where rechargeable portable power is desired (e.g., consumer electronics such as power tools). Lead-acid batteries continue to be widely used because, based on performance and cost of potential alternatives, no acceptable substitutes currently exist. Technologies that were examined for this report include nickel-zinc, nickel-iron, and silver-zinc batteries (nickel-cadmium batteries are not considered to be substitutes within the scope of this analysis).

Nickel-zinc batteries have a lower power density than lead-acid batteries, a limited lifetime, relatively poor reliability, and are two to three times the cost of an equivalent sized lead-acid battery. Nickel-iron batteries also have a relatively low power density, as well as poor low-temperature performance and charge retention. Silver-zinc batteries cost 20 to 100 times as much as an equivalent sized lead-acid battery. They also have a limited lifetime and decreased performance at low temperatures (Palmer 1988).

Nickel-cadmium Batteries

Nickel-cadmium (Ni-Cd) batteries are a type of secondary cell often used in applications that consume large amounts of power (e.g., portable stereos and photographic strobes). Table SR-5 presents potential substitute batteries that have been identified. The potential substitutes examined are lithium, silver-zinc, nickel-zinc, nickel-hydrogen, and primary (alkaline, lithium, and carbon-zinc) batteries. With the exception of primary batteries, none of these substitutes have been used much in consumer products because of technical complications, reduced service life, and high cost. In addition,

Table SR-5. Potential Substitutes for Nickel Cadmium Batteries

Potential Substitute	Performance Comments
Lithium Battery	Less than half the lifetime of nickel cadmium battery. Sensitive to abuse.
Silver-Zinc Battery	Less than one-fifth the lifetime of nickel-cadmium battery.
Nickel-Zinc Battery	Less than one-tenth the lifetime of nickel-cadmium battery.
Nickel-Hydrogen Battery	High atmospheric pressure required in cell.
Primary Battery (alkaline, lithium, and carbon-zinc)	Not able to be recharged; must be replaced.

Sources: Yardney 1989a, 1989b; SAFT 1989a; Chemical Business 1989.

many of these technologies are currently in an embryonic stage of development and their costs are quite high. As experimentation and development proceeds, the limitations and the costs of these substitute products may be reduced.

One of the more promising technologies is the rechargeable lithium cell which is already used to a very limited extent in some consumer applications. According to one supplier, rechargeable lithium batteries have greater charge capacity than Ni-Cd batteries of a comparable size (SAFT 1989a, Moli 1989). However, lithium batteries are currently much more expensive (at least twice the price) than Ni-Cd batteries and they are more sensitive to abuse such as overcharging. Advantages of lithium rechargeable batteries include their light weight, ability to provide energy in sub-freezing temperatures, and very high efficiency. Possible applications for lithium batteries include portable cellular phones, lap-top computers, portable radios, and military applications (Panasonic undated).

Another battery technology currently in use is the silver-zinc system. This system, which has a high energy density, is used primarily (90 percent of the time) for military and space applications (Kirk-Othmer 1978, SAFT 1989c). There are many limitations that may restrict its use in consumer applications such as high cost and limited service life.

The nickel-zinc cell is a potential substitute that offers a charge density greater than that available from nickel-cadmium batteries, but at a lower cost than silver-zinc. Although its performance is not as high as its silver-based counterpart, it is also not subject to the wide fluctuations in price resulting from speculation in precious metals markets.

An additional battery system that currently is found only in exotic applications (e.g. satellite applications) is the nickel-hydrogen cell. The hydrogen in the cell is in the gaseous form, and the operating pressure is

much higher than other cells, ranging from 3-20 times atmospheric pressure, as compared to 0-3 atmospheres for a nickel-cadmium cell. Because of these high operating pressures, construction is labor-intensive and very expensive.

Glass and Ceramic Products

The use of lead in glass products is primarily due to its good performance properties and low cost relative to potential substitutes. As an intermediate, lead monoxide adds to the brilliance of glass products, and as a modifier, it lowers the melting temperature, thereby simplifying glass processing. Lead-containing glass also can shield high energy radiation and the high refractive index of lead yields excellent properties for optics and for hand-formed art ware. Cadmium in glass and ceramic products is used as a pigment in a glaze, as a colorant in the glass itself, or as a phosphor (EPA 1989).

Table SR-6 lists potential substitutes for lead and cadmium in glass and ceramic products. The potential substitutes for lead- and cadmium-based glass/ceramic products usually involve switching to alkaline earth metals (primarily strontium and barium) and zirconium, that are expensive in comparison to lead and cadmium. The performance properties of the potential substitutes for lead-based glass/ceramic products lack the refractive indices, the radiation absorption characteristics, and the ease of processing of lead-based glass/ceramic products. There are also reports of supply problems with strontium and zirconium (Corning 1989c).

Brass and Bronze Products

Lead is generally added to brass to improve the free machining characteristics of the alloy. Lead also may be present as an impurity in some brass products due to the lead content of scrap materials used in the

Table SR-6. Potential Substitutes for Lead and Cadmium in Glass and Ceramics

Lead and Cadmium Use	Potential Substitute	Performance Comments
Glass Television Parts:		

Neck and funnel
    (28 and 22 percent PbO
    respectively)
	Strontium
	Barium
		Processing problems, lower durability,
		larger quantity required.

Faceplate (panel) (2% PbO)	Zirconium	Supply problem, marginal cost difference (6 percent higher).
Leaded Glass:		
X-ray shielding	Thicker glass	Expensive; increased space requirements and decreased visual clarity.
Neon/fluorescent tubing	Strontium/barium	Processing problems
Light bulb	Cerium	Under development; processing problems.
	Alkaline earth metals	Under development; processing problems.
Optical Glass	Barium/zinc oxides zinc, lithium, and barium oxides	Lower achievable index of refraction than with lead. Commercially available.
Ceramics Glazes/enamels	Zirconium dioxide	Satisfactory brilliance and alkali resistance; some application problems.
	Chrome tin salt	Color instability.
PZT/PZLT (68% PbO)	Barium lead titanate (10% lead)	Not as piezoelectrically efficient; cannot be used in temperatures over 100°C; 25 percent less expensive.
	Quartz	Not as piezoelectrically efficient; 3-4 times more expensive.
	Rochelle Salts	Not effective in humid environment; more piezoelectrically efficient.

Sources: Blanche 1989; Corning 1989a, 1989b, 1989c, 1989d; Degussa 1989; Piezo Kinetics 1989; Sylvania 1989a.

manufacture of brass products. Lead is present, therefore, in virtually all kinds of brass at least to a small degree. Leaded bronze may contain up to 30 percent lead. The lead is included because it improves workability and conformability (Copper Development Association 1989).

Two methods can be used to substitute away from lead in brass and bronze. Alternative metals can be incorporated with copper to create alloys with similar properties to lead-containing products, or alternative materials (e.g., plastics or steel) can be used in the final products.

Table SR-7 identifies the potential substitutes by use area for leaded brass and bronze products. The choice of potential substitute depends to a large extent on the properties that the consumer requires most and which, if any, properties offered by leaded brass and bronze can be forfeited. Different substitutes will be chosen if hardness, color, strength, or another property is critical or must remain constant. Bearings and fittings made from unleaded tin bronze and aluminum bronze are already used in heavier load applications for which leaded bronze is not hard enough. Machinable leaded brass and bronze used for screw parts and plumbing fixtures can be substituted by other copper alloys to a large degree. The addition of tellurium, selenium, or sulfur offers the possibility of improving the machining characteristics of copper and its alloys without the use of lead (Copper Development Association 1989, Kirk-Othmer 1978).

Other potential substitutes for leaded brass can replace specific end products. For example, some plumbing fixtures and valves currently manufactured with brass or bronze may be replaced by PVC or other plastic materials, but these materials are not suitable for the bulk of brass and bronze applications. Machined screws may be replaced by steel screws or another machinable metal depending on the importance of corrosion resistance.

Table SR-7. Potential Substitutes for Lead-based Brass and Bronze Products

Lead Use	Potential Substitutes	Performance Comments

Machined Products
    Plumbing Fixtures
    Machine Screw Parts
	Steel[a]	Poor corrosion resistance

	PVC[a]	Not able to handle all applications; poor shear resistance.
	Tellurium bronze	Not commercially available; marginal difference in machinability.
	Selenium bronze	Not commercially available; marginal difference in machinability.
	Sulfur bronze	Not commercially available; marginal difference in machinability.
Bushing/Bearing Products	Tin bronze	Harder, requires lubrication.
	Aluminum bronze	Harder, requires lubrication.
	Manganese bronze	Harder, requires lubrication.

[a] Steel and PVC are a different class of potential substitute in that they replace the end-product uses of brass and bronze instead of the use of lead in brass and bronze.

Sources: Copper Development Association 1989, Nielsen undated, Kirk-Othmer 1978.

Cadmium Plated Products

Cadmium plating is used on fabricated steel and cast iron parts and can be electroplated on plastics or metal in some appliance and consumer applications. Cadmium is used because it has a combination of properties: natural lubricity, corrosion resistance to salt water and alkalis, high deposition rate on application, good solderability and ductility, and a long-lasting silvery-white luster.

Cadmium plating is used to protect bolts and screws used in marine applications from corrosion due to prolonged exposure to moisture and salt. In general, cadmium plated products have a longer service life due to their corrosion resistance and natural lubricity that help in applications where mechanical seizures would impair function. Automotive uses such as seat belt fasteners and brake linings are examples of applications for which these features are important. Cadmium plated fasteners also are used because their natural lubricity reduces the torque experienced during fastening, thereby reducing the potential for fatigue and failure.

Potential substitutes for cadmium in plating operations can be classified into two groups: (1) alternative materials and technologies for applications that do not require the properties imparted by cadmium plating and (2) alternative coatings with similar properties that can be used in place of cadmium. Table SR-8 contains a list of the potential substitutes for cadmium in plating operations.

The substitution that has already taken place in the majority of household applications has used alternative materials. Cadmium plated parts in washing machines and dishwashers have been replaced to a great degree by the increased use of plastic construction that does not require cadmium plated bolts to hold the frames together (EPA 1989).

Table SR-8. Potential Substitutes for Cadmium Plating

Cadmium Use	Potential Substitutes	Performance
Electronics (chassis)	Resinous printed circuit boards[a]	Substitution already occurring; superior technology.
Fasteners (nuts, bolts)	Plastic construction[a]	Substitution already occurred in consumer household appliances, but not possible in most cases.
	Zinc plating	Lower corrosion resistance, loss of lubricity, loss of solderability.
	Tin plating	Good solderability, poor corrosion resistance.
	Gold plating	Good corrosion resistance, very expensive, poor wear resistance.
	Chrome plating	Good wear properties, better corrosion resistance for acids, lower corrosion resistance for salts and neutral pH.

[a] Plastic construction and resinous printed circuit boards are a different class of substitute in that they eliminate the need for the end-product use of cadmium plated parts.

Sources: AESF 1989, Cadmium Council 1989, Iron Age 1980, Kirk-Othmer 1978.

Additional substitutions for cadmium plating may use similar technology or alternative coatings. The choice of replacement plating will depend on which properties of cadmium coating are most important. Although inferior in terms of solderability and lubrication, zinc is already used whenever possible because of reduced health and environmental concerns compared to cadmium (AESF 1989). Electroplated tin and gold are readily solderable, although gold is very expensive. Tin is not effective in corrosion resistance, but the development of tin-zinc alloys and a zinc-nickel alloy as possible substitutes for cadmium is progressing (AESF 1989, Kirk-Othmer 1978). Chrome plating also is an economical process to improve corrosion resistance of steel where appearance is not important. Chrome offers the advantage of a low friction surface and good wearability, but does not offer the same corrosion resistance as cadmium (Iron Age 1980, AESF 1989).

Collapsible Tubes

Collapsible tubes are used to dispense a number of products ranging from medicines to epoxy resin adhesives. While these tubes can be manufactured from a variety of materials, lead tubes are used to dispense corrosive products (lead is difficult to corrode) or to satisfy customer packaging preferences. Lead tubes represent a very small fraction (less than one percent) of the tube market. Of the lead tubes currently manufactured, most are used for artists colors and the remainder for corrosive glues.

One of the possible substitutes for lead tubes is aluminum tubes with phenolic epoxy lining. This aluminum technology does not differ in cost and offers similar performance to the lead tubes. Another potential substitute technology, laminate tubes manufactured with alternating layers of plastic and aluminum, also can replace lead tubes and have similar costs (see Table SR-9).

Other Products

There are a variety of other products that contain lead and/or cadmium that are disposed of in MSW facilities. These products, however, account for a very small percent of the total amount disposed. The Other Products category includes foil wine wrappers, used oil, rubber (elastomers), and electric blankets/heating pads. Potential substitutes for these lead and cadmium use areas are presented in Table SR-9.

Table SR-9. Potential Substitutes for Miscellaneous Products Containing Lead or Cadmium

Lead or Cadmium Use	Potential Substitute	Performance Comments
Collapsible Tubes	Aluminum lined with phenolic epoxy	Similar in performance to lead tubes.
	Plastic and aluminum laminates	Similar in performance to lead tubes.
Foil Wine Wrappers	Plastic	Similar cost and performance to lead.
	Aluminum foil	Similar cost and performance to lead.
Used Oil	Zinc organo-phosphates Iron and zinc chlorides Iron sulfides	Similar cost and performance to lead- and cadmium-based products.

Rubber (elastomer) Products
  Pigments[a]
  Vulcanizing agents
	Dithiocarbamates (bismuth, copper, selenium, tellurium, zinc, piperidium, thiazoles)	Cost and performance of potential substitute varies depending on formulation.

Printing Inks	Dialyrid yellow	More expensive than lead chromate and lead sulfochromate. Less lightfast and opaque than lead chromate and lead sulfochromate.
	Dialyrid orange	More expensive than lead chromate and lead sulfochromate. Less lightfast and opaque than lead chromate and lead sulfochromate.
Electric Blankets and Heating Pads	Undetermined[b]	Undetermined

[a] For a discussion of potential substitutes for pigments in rubber, see previous discussion of pigments in the Plastics section.

[b] Although the use of cadmium-containing wires for electric blankets and heating pads has not been characterized and potential substitutes have not been evaluated, it is likely that other copper alloy wires will be able to fully supplant cadmium-containing wires for this use.

Sources: AMPA 1989; BASF 1989a; EPA 1989; Kirk-Othmer 1983; NAPIM 1989; Teledyne 1989; Wine Institute 1989.

REFERENCES

ADL. 1990. (November 15). Lead Use and Substitutes. Report to Lead Industries Association. Prepared by Arthur D. Little, Inc., Cambridge, MA.

AESF. 1989 (July 31). American Electroplaters and Surface Finishers Society. W. Safranek. Orlando, FL. Transcribed telephone conversation with Louis Gardner, ICF Incorporated, Fairfax, VA.

ANPA. 1989a (August 14). American Newspaper Publishers Association. G. Cashau, Director of Technical Research. Reston, VA. Transcribed telephone conversation with Thomas Hok, ICF Incorporated, Fairfax, VA.

Arconium. 1989 (July 24). J. Hamilton, Sales Representative. Providence, RI. Transcribed telephone conversation with Thomas Hok, ICF Incorporated, Fairfax, VA.

Argus. 1989a (May 10). M. Croce. New York, NY. Transcribed telephone conversation with Mark Wagner, ICF Incorporated, Fairfax, VA.

Argus. 1989b (May 11). D. Stimpfl. New York, NY. Transcribed telephone conversation with Mark Wagner, ICF Incorporated, Fairfax, VA.

Argus. 1989c (May 17). D. Brilliant. New York, NY. Transcribed telephone conversation with Mark Wagner, ICF Incorporated, Fairfax, VA.

BASF. 1989a (May 16). Basic Organics Group. Transcribed telephone conversation with Tanya Yudleman, ICF Incorporated, Fairfax, VA.

BASF. 1989b (August 14). R. Wagner, Manager in Charge of Product Compliance, BASF, Clifton, NJ. Transcribed telephone conversation with Thomas Hok, ICF Incorporated, Fairfax, VA.

Bayer-Mobay Corporation. 1989 (May 16). Transcribed telephone conversation with Tanya Yudleman, ICF Incorporated, Fairfax, VA.

Bedford Chemical. D. Gauw. 1989 (May 4). Bedford Chemical, Division of Ferro Corporation. Bedford, OH. Transcribed telephone conversation with Mark Wagner, ICF Incorporated, Fairfax, VA.

Blanche, S.T. 1989. "Chrome-Tin Pink Glazes," _Ceramic Engineering Scientific Proceedings_, Vol. 10, pp. 65-68.

Cadmium Council. 1989 (July 27). H. Murrow. New York, NY. Transcribed telephone conversation with Louis Gardner, ICF Incorporated Fairfax, VA.

Chemical Business. 1989 (July/August). "The Assault on Batteries," p. 35-36.

CMI. 1989a (June 1). Can Manufacturers Institute. D. Karmol. Counsel. Washington, DC. Transcribed telephone conversation with Thomas Hok, ICF Incorporated, Fairfax, VA.

CMI. 1989b (July 28). Can Manufacturers Institute. D. Karmol. Counsel. Washington, DC. Transcribed telephone conversation with Thomas R. Hok, ICF Incorporated, Fairfax, VA.

Copper Development Association. 1989 (July 21). A Cohen. Greenwich, CT. Transcribed telephone conversation with Louis Gardner, ICF Incorporated, Fairfax, VA.

Corning Glass. 1989a (July 21). T. Seward. Transcribed telephone conversation with Peter Weisberg, ICF Incorporated, Fairfax, VA.

Corning Optics. R. Thompson. 1989b (July 21). Transcribed telephone conversation with Peter Weisberg, ICF Incorporated, Fairfax, VA.

Corning Glass. D. Lopata. 1989c (May 30). Transcribed telephone conversation with Peter Weisberg, ICF Incorporated, Fairfax, VA.

Corning Glass. J. Connelly. 1989d (July 26). Transcribed telephone conversation with Peter Weisberg, ICF Incorporated, Fairfax, VA.

Degussa Corporation. D. Gillier. 1989 (August 14). Transcribed telephone conversation with Louis Gardner, ICF Incorporated, Fairfax, VA.

EPA. 1989 (January). U.S. Environmental Protection Agency. Characterization of Products Containing Lead and Cadmium in Municipal Solid Waste Facilities, 1970 to 2000. Prepared by Franklin Associates, Ltd. Prairie Village, KS.

EPA. 1990 (November). U.S. Environmental Protection Agency. Summary of Pollution Prevention Act of 1990. Prepared by the Office of Pollution Prevention, U.S. EPA. Washington, D.C.

Franklin Associates. 1990 (August). Characterization of Lead in Plastic Products in Municipal Solid Waste, 1970 to 2000. Prairie Village, KS.

Indium Corporation of America. 1989a (July 19). R. Altieri. Applications and Engineering, Utica, NY. Transcribed telephone conversation with Thomas Hok, ICF Incorporated, Fairfax, VA.

Indium Corporation of America. 1989b (July 28). R. Altieri. Applications and Engineering, Utica, NY. Transcribed telephone conversation with Thomas Hok, ICF Incorporated, Fairfax, VA.

Indium Corporation of America. 1989c (August 15). J. Ferriter. Applications and Engineering. Utica, NY. Transcribed telephone conversation with Thomas Hok, ICF Incorporated, Fairfax, VA.

IPC. 1989a (July 20). Institute of Printed Circuits. D. Bergman. Chicago, IL. Transcribed telephone conversation with Thomas R. Hok, ICF Incorporated, Fairfax, VA.

IPC. 1989b (July 28). Institute of Printed Circuits. D. Bergman. Chicago, IL. Transcribed telephone conversation with Thomas R. Hok, ICF Incorporated, Fairfax, VA.

Iron Age. 1980 (January 14). Cadmium's Plight Opens Field to Alternative Coatings. p. 50.

Kapp Alloy and Wire, Inc. 1989 (July 19). D. Porter, Technical Director, Altoona, PA. Transcribed telephone conversation with Thomas Hok, ICF Incorporated, Fairfax, VA.

Keeler, R. 1987 (July). "Specialty Solders Outshine Tin/Lead in Problem Areas." Electronic Packaging and Production, pp. 45-47.

Kirk-Othmer. 1978. Encyclopedia of Chemical Technology. John Wiley and Sons Publishing Co., Inc. Volume 3, pp. 674-77; Vol. 3, pp. 569-639; Volume 6, p. 166; Volume 7, p. 45; Volume 8, pp. 827-869; Volume 15, pp. 241-274.

Kirk-Othmer. 1983. Encyclopedia of Chemical Technology. John Wiley and Sons Publishing Co. Vol. 6, Vol. 14, pp. 168-183, 493-496; Vol. 18, pp. 184-206; Vol. 20, p. 338.

Manko, H.H. 1979. Solders and Soldering. Published by McGraw-Hill Book Company, New York, NY. Second edition.

Moli Energy. 1989 (January). Product literature on Molicel Lithium batteries.

NAPIM. 1989 (August 14). National Association of Printing Ink Manufacturers. P. Volpe, Technical Coordinator. Westchester, NY. Transcribed telephone conversation with Thomas Hok, ICF Incorporated, Fairfax, VA.

NFPA. 1989 (July 31). National Food Processors Association. E. Elkins. Washington, DC. Transcribed telephone conversation with Thomas Hok, ICF Incorporated, Fairfax, VA.

Nielsen, WD. Undated. Metallurgy of Copper Base Alloys. Casting Engineering & Foundry World. Reprint.

Palmer, J.G. 1988 (September). Executive Vice President, Pacific-Dunlop-GNB, Incorporated, St. Paul, MN. "A Cleaner Environment: Removing the Barriers to Lead-Acid Battery Recycling." Written in collaboration with M.L. Sappington, P.E., President, Lake Engineering, Incorporated, Atlanta, GA.

Panasonic. Undated. "Batteries," a publication of Panasonic, Secaucus, NJ.

Piezo Kinetics Inc. 1989 (May 30 and July 27). R. Turner. Transcribed telephone conversation with Peter Weisberg, ICF Incorporated, Fairfax, VA.

Plastic Additives Handbook. 1987. Hanser Publishers. Munich, Germany.

SAFT America. 1989a (July 14). G. Lupul. Maryland. Transcribed telephone conversation with Donald Yee, ICF Incorporated, Fairfax, VA.

SAFT America. 1989b (July 14). G. Lupul. Maryland. Transcribed telephone conversation with Donald Yee, ICF Incorporated, Fairfax, VA.

SAFT America. 1989c (August 15). P. Scardaville, Director of Engineering. Valdosta, GA. Transcribed telephone conversation with Alex Greenwood, ICF Incorporated, Fairfax, VA.

Sylvania and Laxman Ltd. 1989a (June 1). R. Marlor. Transcribed telephone conversation with Peter Weisberg, ICF Incorporated, Fairfax, VA.

Sylvania and Laxman, Limited. 1989b (July 18). R. Marlor. Manager, Glass and Ceramics. Salem, MA. Transcribed telephone conversation with Thomas Hok, ICF Incorporated, Fairfax, VA.

Sylvania and Laxman, Limited. 1989c (July 28). R. Marlor, Manager, Glass and Ceramics, Salem, MA. Transcribed telephone conversation with Thomas R. Hok, ICF Incorporated, Fairfax, VA.

Talco Metals. 1989 (July 18). C. Carabello, Sales Representative. Philadelphia, PA. Transcribed telephone conversation with Thomas R. Hok, ICF Incorporated, Fairfax, VA.

Teledyne Packaging. 1989 (May 31). K. Barry. New Jersey. Transcribed telephone conversation with Thomas Hok, ICF Incorporated, Fairfax, VA.

Wine Institute. 1989 (June 1). W. Lee. San Francisco, CA. Transcribed telephone conversation with Peter Weisberg, ICF Incorporated, Fairfax, VA.

Yardney Battery. 1989a (July 13). T. Aretakis. Connecticut. Transcribed telephone conversation with Donald Yee, ICF Incorporated, Fairfax, VA.

Yardney Battery. 1989b (July 20). D. Wissocker. Massachusetts. Transcribed telephone conversation with Donald Yee, ICF Incorporated, Fairfax, VA.

I. INTRODUCTION

The use of lead- and cadmium-containing articles that ultimately are disposed of in municipal solid waste (MSW) facilities is the focus of a joint project by the Office of Toxic Substances and the Office of Solid Waste of the U.S. Environmental Protection Agency. The use and substitutes analysis provided in this report characterizes and discusses technologically feasible substitutes for lead and cadmium in products identified in an earlier EPA report entitled "Characterization of Products Containing Lead and Cadmium in Municipal Solid Waste, 1970 to 2000." The products discussed in this report are as follows:

- plastics;
- pigments;
- solder;
- nickel-cadmium batteries;
- glass and ceramic products;
- brass and bronze products;
- cadmium plated products;
- collapsible tubes;
- lead-acid batteries; and
- other products.[*]

Table 1 identifies the amount of lead and cadmium in each of these product areas discarded in MSW in 1986. As the table indicates, the majority of discards is in the battery, plastics, pigments, solder, and glass categories. These uses account for 99 percent of the lead[**] and 89 percent of the cadmium disposed of in MSW.

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[*] Other products containing lead and/or cadmium include rubber products, printing inks, used oil, foil wine wrappers, and electric blankets and heating pads.

[**] Lead acid batteries accounted for 138,043 tons of lead discards in 1986, about 2/3 of the total lead discards in MSW (EPA 1989). This use of lead is not a major focus of this report, however, because lead-acid batteries have been characterized in other reports prepared for and by EPA (e.g., Palmer 1988) and because substitutes for this battery system are not currently available.

- 1 -

Table 1. Discards of Lead and Cadmium by Use Area in MSW in 1986

Product Area	Lead Discards (tons)	Cadmium Discards (tons)
Lead Acid Batteries	138,043	0
Plastics	3,174	564
Pigments[a]	1,131	70
Solder	8,369	0
Nickel/Cadmium Batteries	0	927
Glass and Ceramic Products	60,714	29
Brass and Bronze Products	321	0
Plated Products	0	185
Collapsible Tubes	639	0
Rubber Products	70	6
Other Products[b]	671	1

[a] Discards of pigments do not include pigments consumed in plastics, glass/ceramic products, or rubber products. These discards are covered in the sections on plastics, glass/ceramic products, and rubber products.

[b] Other products include used oil, foil wine wrappers, electric blankets and heating pads, and television and radio chassis. 279 tons of lead were discarded as part of television and radio chassis, but future discards are expected to be zero.

Source: EPA 1989, Franklin 1990.

Lead and cadmium have been used in the products identified in this report as additives, components, and coatings to improve performance, fulfill certain customer preferences, and to impart certain characteristics to end products based on the physical/chemical properties of the metals and/or compounds made from them. The use of lead- and cadmium-containing products is characterized for each product area with emphasis on the critical properties that they provide to finished products.

Potential and existing substitutes that can replace lead and cadmium in these uses are characterized to the extent that information is available from secondary data sources. Technical feasibility is the only basis used in this analysis to identify substitutes. Thus, only in cases where no alternative is currently available that imparts the same properties provided by lead or cadmium does this report fail to present potential substitutes. Information on potential substitutes was identified from published sources (standard texts and journal articles) and conversations with industry contacts.

Some qualitative cost information is presented for potential substitutes, but estimates of the likely market shares that potential substitutes would absorb in the event that lead and cadmium products were no longer available have not been developed in this study. However, the information presented here along with other background data developed during the project provides a solid foundation for estimating market shares and other more detailed economic information for potential substitutes.

A. Limitations

This report should be considered as a preliminary analysis due to the limitations of its scope. EPA has not performed primary research to identify the substitutes for lead and cadmium described in this report. Only substances identified in published sources or by industry contacts and that

were known or considered to be possible substitutes have been included in this analysis. Because this report characterizes substitutes for both lead and cadmium products, lead and cadmium products are not considered as substitutes for each other although these products sometimes may be technically feasible options. Furthermore, the substitution in this report is based only on technical feasibility and does not quantitatively assess economic factors that affect substitution or the effect of potential substitutes on end products (e.g., different service lives for substitute products). This report, therefore, is not intended to draw conclusions about the viability of actual substitution. No economic analysis has been performed to estimate the impacts of substituting for lead and/or cadmium products.

In addition, toxicities of substitutes are not discussed in this report and toxicity was not a criteria for identifying potential substitutes. Many of the classes of chemicals assessed have intrinsic toxicities that would be of great concern in other parts of the manufacturing processes where there would be human or environmental exposure to more bio-available forms of the chemical or chemicals. A more focused, in-depth substitute characterization for each chemical substitute in each use area would be required to adequately assess the hazard presented by potential substitutes.

B. References

EPA. 1989 (January). U.S. Environmental Protection Agency. Characterization of Products Containing Lead and Cadmium in Municipal Solid Waste Facilities, 1970 to 2000. Prepared by Franklin Associates Ltd., Prairie Village, KS.

Franklin Associates. 1990 (August). Characterization of Lead in Plastic Products in Municipal Solid Waste, 1970 to 2000. Prairie Village, KS.

Palmer, J.G. 1988 (September). Executive Vice President, Pacific-Dunlop-GNB, Incorporated, St. Paul, MN. "A Cleaner Environment: Removing the Barriers to Lead-Acid Battery Recycling." Written in collaboration with M.L. Sappington, P.E., President, Lake Engineering, Incorporated, Atlanta, GA.

II. PLASTICS

A. Overview of the Plastics Industry

Plastics can be categorized into two major groups, thermoplastic and thermoset, based on how the plastic reacts when heated. Thermoplastic resins can be melted and solidified in a reversible process, while thermosetting resins initially liquify with heat, but then permanently solidify with further heating. Because of the advantages associated with using thermoplastic resins (i.e., that they can be reworked or reformed and are therefore easier to handle), over 90 percent of all resins produced are thermoplastic (Kirk-Othmer 1983). Table 2 identifies some of the most common thermoplastic resins.

Thermosetting resins are exemplified by certain types of polyesters and polyurethanes, as well as phenol-formaldehyde, urea-formaldehyde, and melamine-formaldehyde resins. Thermoset resins are characterized by irreversible bond formation (cross-linking) between polymer chains that occurs during the heat curing stages of processing. Table 2 identifies the major categories of thermosetting resins.

Processing of resins takes place through a number of different techniques including extrusion, molding, thermo- or vacuum-forming, casting, and calendaring. Approximately half of all resins are converted into products by extrusion. The extrusion process is continuous, making products of uniform cross-section and infinite length that can be rolled or coiled, cut into lengths, or otherwise packaged. Typical products that are made by extrusion include film, sheet, pipe, tubing, profiles,* coated wire, and coated paper (Kirk-Othmer 1983).

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* Profiles are typified by such products as channels, gaskets, decorative trim, siding panels, window frames, and other rigid structures used in indoor and outdoor construction and building.

- 5 -

Table 2. Representative Thermoplastic and Thermosetting Resins

Amorphous[a] Thermoplastic Resins

Acrylonitrile-butadiene-styrene (ABS)
Cellulose acetate
Polycarbonates
Polyacrylates and methacrylates
Polystyrene
Polyvinyl chloride (PVC)
Styrene-acrylonitrile (SAN)

Crystalline[b] Thermoplastic Resins

Polyethylene, low density (LDPE)
Polyethylene, high density (HDPE)
Polypropylene
Polyacetals
Nylons
Polyesters[c]
Fluoropolymers

Thermosetting Resins

Phenol-formaldehyde
Urea-formaldehyde
Melamine-formaldehyde
Polyesters
Polyurethanes

[a] Amorphous thermoplastics are characterized by no distinct melting and freezing points.

[b] Crystalline thermoplastics have well defined melting and freezing points.

[c] Some polyesters are thermoplastics, while others (e.g., phenol-formaldehyde resins) are thermosetting.

Source: Kirk-Othmer 1983.

Molding is a process by which molten thermoplastic resins are injected under pressure into a mold and cooled until the article can be removed from the mold without distortion. Thermoforming of amorphous resins, e.g., polystyrene, polyvinyl chloride (PVC), and polymethyl methacrylate, is also common, as is casting of acrylates between two glass sheets. Calendaring operations consist of making sheets from PVC and acrylonitrile butadiene-styrene (ABS) resins that are used in the manufacture of luggage, wall paneling, and furniture. Thermosetting resins are processed almost exclusively by molding operations, although some flexible polyurethane foams are processed in the form of a slab (Kirk-Othmer 1983).

B. Additives Used in the Processing of Plastics

A wide range of plastic processing chemicals (additives) are available to serve various functions in some or all of the resin types identified in Table 2. Additives can impart a particular characteristic to the end product or may be required to preserve the integrity of the plastic resin during processing or use. The range of all chemical additives (lead and cadmium as well as non-lead/cadmium additives) are grouped into the following categories (Radian 1987):

- Antioxidants;
- Antistatic agents;
- Blowing agents;
- Catalysts and cure agents;
- Colorants;
- Coupling agents;
- Fillers and reinforcers;
- Flame retardants;
- Free radical initiators;
- Heat stabilizers;
- Lubricants and mold release agents;
- Plasticizers;
- Preservatives;
- Solution modifiers; and
- UV stabilizers.

Fillers and reinforcers, plasticizers, and flame retardants make up the vast majority of additives consumption in the plastics industry, accounting for almost 92 percent of consumption by weight (Modern Plastics 1982). Colorants and heat stabilizers, major compounds formulated with lead and/or cadmium, account for 3.9 and 1.0 percent by weight of all plastic additives consumption, respectively.

1. Additives Containing Lead and/or Cadmium

Additives that contain lead and cadmium do not account for a large proportion of total additive consumption, but due to the large volume of plastic produced annually, approximately 57 billion pounds in 1988, a substantial amount of these products is consumed (Modern Plastic 1988). Section C of this chapter provides an in-depth discussion of actual consumption of these lead- and cadmium-containing products.

In addition to heat stabilizers and colorants, there is a small amount of lead and cadmium present in certain polymerization catalysts and lubricants. Lubricants based on metallic soaps, including lead and cadmium stearates as well as the more common calcium, aluminum, magnesium, and zinc stearates, are used with many types of resins (including PVC resins) where they also act as heat stabilizers. Lead and cadmium may also be present in certain metal oxide and other catalysts, either incorporated intentionally or present as impurities in other metal-based catalysts (Radian 1987). These lubricant and catalyst uses of lead- and cadmium-based products account for a small amount of the lead- and cadmium-based plastic additives and hence, are not discussed in the remainder of this report.

a. Lead- and Cadmium-containing Pigments Used with Plastic Resins

Colorants used in plastic resins number into the hundreds. Combined with the wide variety of polymers, the permutations that exist in coloring plastics are enormous. In many cases, "color houses" exist to match a given polymer with a compatible colorant. While hue and shade requirements eliminate a fair share of the possible combinations of colorants and plastics, solubility of the colorant in the medium is also important in the selection process. Solubility determines whether a dye or a pigment is used. If the colorant must be soluble, a dye is normally chosen; if solubility is not a factor, pigments are usually used because they are less expensive (Plastics Engineering Handbook 1987).

Dyes are soluble in plastics and present minimal problems when mixed with a polymer. Pigments, on the other hand, are supplied in the form of a finely ground powder and must be dispersed or distributed evenly in the polymer. Dispersion of a pigment is a physical process consisting of a number of separate steps. First, the dry powder must be broken down into the desired particle size; second, the powder is blended with a resin or binder so that the pigment is "wetted" and a homogenous mix is produced; and finally, to counteract the cohesive forces that normally try to reagglomerate the particles, the dispersion must be stabilized. Dispersability is also important since it is one of the few ways to broadly classify pigments into either inorganic or organic* (Plastic Additives Handbook 1987). Generally,

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* Organic pigments, by definition, are compounds containing carbon and although some organic molecules may contain metal or metal salts, the inorganic component is considered secondary (responsible more for undertones than primary hue color) (Brannon 1988). In addition, not only lead and cadmium ions, but other metal ions could impart the desired properties to these organic pigments. Lead and cadmium based organic pigments, therefore, are not considered significant products and are not discussed in this report.

- 9 -

inorganic pigments have a fairly uniform particle size and are easier to disperse than organic pigments, which tend to have non-uniform particle size (Plastics Engineering Handbook 1987).

Other performance properties that must be considered in the selection of a colorant include heat stability, lightfastness, opacity, and chemical resistance. Lead and cadmium pigments have most of the same characteristics as other inorganic pigments for these properties and so this discussion focuses primarily on the properties for inorganic pigments in general. Where possible, indications are also given as to the specific performance properties of lead and cadmium pigments.

During the manufacturing or processing of colored plastics, heat can be the cause of coloristic change. Heat or thermal stability is not only dependent on the processing temperature, but also the duration of exposure and the acceptable shade tolerance (Plastic Additive Handbook 1987). In general, inorganic pigments possess greater heat stability than organic pigments, which degrade or sublime when exposed to high temperatures for extended periods of time (Brannon 1988).

Lightfastness of plastics is another important characteristic of pigments and is defined as the probability that a plastic will lose its color intensity due to light, especially sunlight. This property is not solely dependent on the pigment, but is dependent on the polymer system as well. Lightfastness of a colorant is analyzed, therefore, in terms of the full colorant/plastic system (Plastic Additives Handbook 1987). In addition, color loss due to exposure to solvents, acids, or alkalies is not just a chemical property of the pigment, but is attributable to the polymer system (Brannon 1988). In general, neutral organic pigments exhibit good chemical resistance,

whereas varying degrees of chemical sensitivity exist for inorganics and organic metal salts.

Opacity and hiding power also may be important characteristics for pigments. These terms usually are used to describe the ability of a pigment to scatter light and hide the resin matrix (Brannon 1988). Whether a pigment is described as being opaque, semi-opaque, or transparent depends on the pigment's refractive index. Differences in the refractive indices between pigments and polymer systems may result in a greater scattering of light, which gives greater hiding power or opacity. In general, the larger pigments (inorganics), exhibit hiding power, but smaller pigments (organics), have greater transparency (Brannon 1988). Table 3 provides some of the performance characteristics for lead and cadmium-based pigments.

i. Lead-containing Pigments

Lead-based pigments used in plastics include chromates and molybdate oranges. The plastics industry has been cited as one of the largest consumer uses of lead chromate pigments[*] (EPA 1989). Currently, the use of lead-based pigments is declining because of health-related concerns (EPA 1989). Most users of these pigments have cited the relatively low cost (about $2/pound in 1985 for molybdate orange) as a reason for their continued use (Modern Plastics 1985). The hue associated with lead-based pigments range from greenish or light yellows to deep oranges and primrose for lead chromates and from reddish yellows to red-shade oranges for molybdate orange. Lead pigments are inexpensive, provide good tint strength and have a high degree of hiding power (opacity). Lead chromates darken upon exposure to light, heat,

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[*] Other uses of lead chromate pigments include interior and exterior paints, automotive finishes, textiles, and paper products (EPA 1989).

Table 3. Lead and Cadmium Inorganic Pigments and Their Performance Properties

Pigment	Hues	Chemical Formula	Heat Stability[a] ($^\circ$C)	Lightfastness[b]	Chemical Resistance	Opacity/ Hiding Power	Remarks on Performance[c] (Compatible Polymer/ Resin)
Lead:		Pb				Opaque	
Chromate	Orange	$PbCrO_4$	230-250	6-8	Sensitive to acids/bases		PVC, LDPE +; HDPE, PS -
Sulfate	Yellow-orange	$PbSO_4$	230-250	6-8	Sensitive to acids/bases		PVC, LDPE +; HDPE, PS -
Molybdate	Reddish orange	$PbMoO_4$	220-250	6-8	Sensitive to acids/bases		PVC, LDPE +; HDPE, PS -
Chromate + Iron Blue	Greenish yellow to Medium shades of olive green	--	-	-	-		
Cadmium:		Cd				Opaque	
Sulfide	Orange shade of yellow	CdS	300	8	Sensitive to acids		General suitability
Sulfide + Zinc	Greenish yellow	Cd + Zn	-	-	-		
Sulfide + Selenium	Red and maroon	CdS + Se	300	8	Sensitive to acids		General suitability
Sulfide + Mercury	Reddish orange to bluish red	CdS + Hg	-	-	-		

[a] For heat stability, the temperature is stated at which no coloristic changes occurred during normal dwell times (approximately 5 minutes) in processing machines.

[b] Determination of lightfastness is carried out in accordance with DIN 53 389. 1 is the lowest value; 4 has 8 times the fastness level of 1; the highest value is 8, testing not normally being carried out beyond this level. See Plastic Additives Handbook (1987) for more information.

[c] Polymer Codes: PS = polystyrene; LDPE = low density polyethylene; PMMA = polymethyl methacrylate; HDPE = high density polyethylene; PVC = polyvinyl chloride; H-PVC = Unplasticized PVC.

Polymer Performance: + denotes suitable/recommended; = limited suitability/recommended; - denotes not suitable/recommended; () denotes a qualification of the statement; * denotes caution is needed in the case of HDPE articles sensitive to distortion.

Source: Plastic Additives Handbook 1987, Brannon 1988.

(excess of 400°F) and in the presence of sulfides. They also demonstrate sensitivity to acids and bases (Brannon 1988).

ii. Cadmium-containing Pigments

Cadmium-based pigments are actually classified as sulfides, sulfoselenide or mercury complexes. Pure cadmium sulfide is an orange shade of yellow, but when zinc sulfide is added, the shade shifts to greenish yellow. On the other hand, cadmium sulfoselenide is found when selenium is added to the cadmium sulfide compound producing a red to maroon shade. Finally, mercadmiums are produced when mercury combines with the cadmium sulfide compound yielding a reddish orange to bluish red hue. Cadmium pigments are expensive (about $15.00/lb. for cadmium sulfide) and the cost continues to increase (BASF 1989). For example, the price of cadmium pigments rose 50 percent from September 1987 to September 1988 due to a 900 percent increase in the cost of cadmium metals from December 1986 to September 1988, (Modern Plastics 1988). Cadmium pigments exhibit brilliant shades of color, have a high heat stability (cadmiums are considered irreplaceable in high temperature nylon and polyester applications), have good lightfastness, and are sensitive to acids (Brannon 1988).

b. Lead- and Cadmium-based Heat Stabilizers Used in PVC and Other Resins

Heat stabilizers are used to prevent the degradation of resins during processing, when molten plastic resins are exposed to high temperatures, or are used to extend the life of the final products into which they are incorporated. Polyvinyl chloride is especially vulnerable to decomposition and degradation during processing; consequently this resin accounts for the major share of consumption of heat stabilizers. In addition,

- 13 -

chlorinated polyethylene and blends of ABS and PVC often require stabilization (Plastics Engineering Handbook 1987).

Polyvinyl chloride stabilizers prevent changes in color and performance during processing and use, and are usually based on lead, organotin or cadmium/barium systems. The specific choice of heat stabilizer is determined by the specific effect on end-products that is required. Many formulations are available in two forms: liquid and solid. Liquids (there are no liquid lead-based stabilizers) are usually used with flexible polyvinyl chloride, and solids, with higher metal concentrations, are used in rigid polyvinyl chloride because it is processed at higher temperatures. Table 4 presents some representative lead- and cadmium-based products that are used in polyvinyl chloride resins (Plastic Additives Handbook 1987).

i. Lead-containing Heat Stabilizers

Lead compounds are the oldest group of stabilizers. Among their advantages is the ability to form complexes with chlorine, preventing the formation of free radicals that destabilize PVC. The lead chloride complexes that form do not have any destabilizing effect on PVC and thus co-stabilizers such as polyols and phosphites are not required (Plastic Engineering Handbook 1987).

One lead stabilizer, lead stearate, has the added characteristic of being an excellent lubricant, providing it with a second function during PVC processing. Lead stearate, therefore, is added to the basic lead salts to create an excellent mixture that is compatible with all PVC types.

Because neither lead stabilizers nor their reaction products with chlorine increase the conductivity of PVC, they are used predominantly in wire and cable insulation applications. Lead stabilizers are the best products available in this area, providing good electrical properties (e.g.,

- 14 -

Table 4. Representative Cadmium and Lead-based Heat Stabilizers and Their Properties

Stabilizer	Concentration of Stabilizer in PVC (phr)	Typical Uses	Properties and Reasons for Use
Lead Stabilizers			
Tribasic lead sulfate	2.0-4.0	• Wire and cable insulation material	• Do not require co-stabilizers or other
Dibasic lead phosphite	2.0-4.0	• Pressure pipes and fittings	additives to increase performance
Dibasic lead phthallate	0.5-1.0	• Interior and exterior sheets and profiles	• Do not increase the conductivity of PVC
Dibasic lead stearate	0.5-1.0		articles
Normal lead stearate	0.5-1.0		• Good processability
Dibasic lead carbonate	0.5-1.5		• Impart good mechanical properties to end products
Cadmium Stabilizers[a]			
Liquids			
Ba/Cd decanoate (and	1.5-2.0	• White outdoor profiles	• Light co-stabilizing effect
other fatty acid salts)		• Furniture film	• Good transparency
Ba/Cd alkyl phenols	1.5-2.0	• Floor tiles	• Used in a wide range of products
Ba/Cd benzoates	1.5-2.0	• Shoes and soles	• Ease of handling
		• Hoses	• Excellent heat stability and self-lubricating
Solids			
Ba/Cd decanoate	1.5-2.5	• High performance applications	• Same as for liquid cadmium stabilizers
Ba/Cd alkyl phenols	1.5-2.5		
Ba/Cd benzoates	1.5-2.5		

NOTE: phr = parts per hundred parts of resin.

[a] Cadmium containing stabilizers are numerous and the properties that each impacts to finished products can vary significantly.

Sources: Plastic Additives Handbook 1987, Plastics Engineering Handbook 1987.

insulation) and the heat stability required during service (Bedford 1989,

Plastics Additives Handbook 1987).

Lead-based stabilizers, although effective in many other applications,

have been and continue to be eliminated from most applications. Their use in

pressure pipes, sewage pipes, gas pipes, gutters, profiles and other

applications continues to decline because of toxicity concerns and because

economically and technically feasible substitutes are available for these

applications (Argus 1989a). For these reasons, lead-containing PVC

stabilizers currently consumed are used almost exclusively in the electrical

cable insulation industry (Argus 1989b). Table 5 shows some of the advantages

and disadvantages of lead heat stabilizers and Table 6 presents current and

past applications. In 1983, expectations that the National Sanitation

Foundation would approve lead-based stabilizers for PVC in potable water pipe

promoted growth in lead stabilizers (Modern Plastics 1983), but approval was

not granted causing a move away from use in non-potable water pipe as well

(Bedford 1989).*

ii. Cadmium-containing Heat Stabilizers

The predominant cadmium heat stabilizers are actually

mixtures of barium and cadmium salts of natural straight chain fatty acids,

branched synthetic acids, and occasionally alkyl phenols and benzoic acid

derivatives. The combination of barium and cadmium salts provides a

synergistic effect, the cadmium salts providing good color stability in

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* If non-potable water pipe were continued to be manufactured with lead,
while potable water pipe was made with non-lead products, there would be
problems with cross contamination, dual inventories, and confusion during
installation. As economically feasible substitutes for lead heat stabilizers
in water and sewage pipes are available, lead use is expected to be completely
eliminated from these uses (Bedford 1989).

Table 5. Advantages/Disadvantages of Lead-based Heat Stabilizers

Advantages	Disadvantages
• Excellent electrical properties	• Too alkaline for some applications
• Excellent lubrication	
• Good processability	• Cannot be used with transparent PVC articles
• Inexpensive	• Certain pigments are incompatible with lead salts
• Wide range of forms: oiled powders, flakes and pellets to reduce dusting	• Dust formation and worker exposure problems
	• Health and toxicity concerns associated with end-products

Sources: Plastics Additive Handbook 1987, Bedford 1989, Kirk-Othmer 1983, Radian 1987, Vinyl Institute 1989b.

Table 6. Current and Declining Uses of Lead-based Heat Stabilizers

Current Uses	Declining Uses
● Electrical cable insulation	● Water pipe
● Electrical conduit	● Sewage pipe
● Wire coating	● Gutters
● Telephone cable insulation	● Indoor and outdoor profiles
● Garden hose	● Sound records (LPs)
● Footwear	● Floppy disk jackets
	● Traffic cones

Sources: Bedford 1989, Franklin 1990, Kirk-Othmer 1983, Radian 1987, Vinyl Institute 1989b.

initial processing and the barium salts providing good long-term thermal stability during use (Chemical Additives Handbook 1987).

Cadmium stabilizers yield cadmium chloride, which unlike lead chloride, has a destablizing effect on PVC, necessitating the addition of deactivating components such as polyols, phenolic antioxidants, and phosphites. These co-stabilizing agents further improve the performance of the barium/cadmium heat stabilizers.

The complex composition of barium/cadmium stabilizers requires that special attention be paid to other components of plastic additives systems (e.g., antioxidants, plasticizers, and fillers) so as to ensure optimum properties. Special attention is also necessary during processing (heating and formulating) technique and when selecting characteristics of the end product, thereby accounting for the wide variety of barium/cadmium stabilizers.

Barium/cadmium (Ba/Cd) stabilizers can be separated into liquid and solid formulations. Solids in the form of powders are metal salts of fatty acids with phenolic antioxidants and polyols used in combination with liquid phosphites and liquid epoxy plasticizers. Formulations containing 10 percent cadmium or more are used extensively in rigid PVC applications such as pigmented profiles and sheets for the building sector. Powders containing less than 10 percent cadmium are used in flexible PVC for shoes, hoses, and profiles. Powdered stabilizers are self-lubricating, but processing conditions requiring a large amount of stabilizer may result in over lubrication. This problem can be overcome by combining liquid and powdered Ba/Cd stabilizers (Argus 1989b).

Liquid stabilizers are not self-lubricating, but are easier to handle than solids because they are liquid and because they already have phosphites

mixed in. Because of lower metal content they are sufficient only for lower temperature processing (i.e., flexible PVC only). Often liquid Ba/Cd stabilizers also contain zinc compounds that improve early color and sulfide stain resistance (Vinyl Institute 1989b). Table 7 presents the advantages and disadvantages of barium-cadmium heat stabilizers, and Table 8 presents use areas for Ba/Cd stabilizers.

C. Consumption of Lead- and Cadmium-containing Products in Plastics

Most of the consumption of lead and cadmium in plastics can be broken down into the four following areas: lead-based pigments, cadmium-based pigments, lead-based heat stabilizers, and cadmium-based heat stabilizers. Although lead and cadmium may be present in other plastic additives (e.g., lubricants, mold release agents, catalysts, or blowing agent "kickers") or may be impurities in certain metal-based additives, these minor sources of lead and cadmium are not analyzed in this report. The remainder of this section identifies consumption by major use area.

1. Consumption of Lead-based Pigments

Table 9 shows the amount of discarded lead-based pigments at intervals for the period from 1970 until 1986. Although the discards of plastic resins have more than tripled over that period, the discards of lead-based pigments have increased much more slowly. This difference may be due to increasing concern about possible health effects of lead in plastic products.

By calculating the amount of lead in pigments lost during plastics manufacturing (assumed to be about 2 percent for this analysis), the amount of lead that is found in plastic products can be estimated (EPA 1989). The resin quantity used in calculating the lead/resin weight ratio includes resins containing no lead pigments and therefore does not reflect a typical or

Table 7. Advantages and Disadvantages of Cadmium-based
Heat Stabilizers

Stabilizer Type	Advantages	Disadvantages
Powdered Ba/Cd	• Very good heat stability • Self-lubricating • Wide range of products • High metal content • Excellent for outdoor applications when combined with liquid phosphites and epoxy plasticizers	• Must be combined with liquid phosphites and epoxy plasticizers • Sensitivity to water causing reversible cloudiness in transparent products • Dust problems
Liquid Ba/Cd	• Easier to handle • Wide range of products • Prevents stabilizer plate-out and dispersion problems • Added light stability because of phosphites and epoxy plasticizers -- excellent for outdoor applications	• Limited self-lubrication • Odor that may be maintained in finished products • Water sensitivity

Sources: Plastics Additives Handbook 1987, Bedford 1989, Kirk-Othmer 1983, Radian 1987.

Table 8. Uses for Cadmium-based Heat Stabilizers

Stabilizer Type	Uses
Powdered Ba/Cd	● Extruded pigmented rigid PVC profiles
	● Extruded rigid sheets
Liquid Ba/Cd	● Extruded flexible PVC profiles and articles
	● Injection molded sandals and shoe soles
	● Calendared films for furniture, decoration, or agricultural uses

Sources: Plastics Additives Handbook 1987, Bedford 1989, Kirk-Othmer 1983, Radian 1987.

Table 9. Discards of Lead in Pigments for Plastic in MSW

Year	Lead in Pigments Discarded[a] (tons)	Total Resin Discarded in Nonfood Applications[b] (thousands of tons)	Lead/Resin Ratio
1970	647	2,061	0.00031
1975	813	3,098	0.00026
1980	967	5,103	0.00019
1986	990	8,111	0.00012

Note: The term resin refers to the type of plastic. The resins included in this consumption table could include all of the resins identified in Table 2.

[a] Adjusted for net exports and with manufacturing losses estimated to be 2 percent; although the source discusses cadmium pigments, lead-based pigments are found in similar forms, and therefore similar losses are expected (Yost and Greenkorn 1984).

[b] Total resin figure includes resins containing no lead-based pigments.

Sources: EPA 1989, Franklin 1990.

average concentration of lead that may be found in lead containing plastic. It serves, however, as a measure of the demand for lead-based pigments relative to the demand for plastics. As can be seen in the lead/resin weight ratio, the use of lead-based colorants has declined significantly.

2. Consumption of Cadmium-based Pigments

The trend for cadmium in pigments discarded is illustrated in Table 10. Although used in applications slightly different from those for lead-based pigments, cadmium-containing compounds often have been replaced by organic colorants (or sometimes by other inorganic compounds) largely because of health concerns. Another factor that may have contributed to this decline has been that the tremendous increase in the price of cadmium as other applications (e.g. nickel-cadmium batteries) has placed additional demands on the available supply of cadmium (Bedford 1989).

Calculating the weight of cadmium found in pigments was not necessary; the amount of cadmium used in colorant manufacture was available from the U.S. Bureau of Mines. However, it was still necessary to estimate the amount of cadmium lost during the manufacture of plastics. From the net quantity of cadmium remaining, the cadmium/resin weight ratio was calculated. As can be seen in Table 10, demand for cadmium pigments (relative to resin demand) has decreased.

3. Consumption of Lead-based Heat Stabilizers

The change in demand for lead-based heat stabilizers (relative to resin demand) has not been great over the 17 year period shown in Table 11 (1970 to 1986). The discards of PVC resin have increased by slightly more than 200 percent. Unlike consumption of lead-based pigments, however, the demand for lead-based heat stabilizers has increased, albeit at a lower rate than the demand for resin. Because heat stabilizers affect the working properties of

Table 10. Discards of Cadmium in Pigments for Plastic in MSW

Year	Cadmium in Pigments Discarded[a] (tons)	Total Resin Discarded in Nonfood Applications[b] (thousands of tons)	Cadmium/Resin Ratio
1970	162	2,061	0.000079
1975	256	3,098	0.000083
1980	259	5,013	0.000052
1986	259	8,111	0.000032

Note: The term resin refers to the type of plastic. Practically, plastics are classified by the nature of the major resin(s) used in their manufacture. The resins included in this consumption table could include all of the resins identified in Table 2.

[a] Adjusted for net exports and with manufacturing losses assumed to be 6 percent (Yost and Greenkorn 1984).

[b] Total resin figure includes resins containing no cadmium-based pigments.

Source: EPA 1989.

Table 11. Discards of Lead in Stabilizers for PVC in MSW

Year	Lead in Stabilizers Discarded[a] (tons)	Total Resin Discarded in Nonfood Applications[b] (thousands of tons)	Lead/Resin Ratio
1970	770	275	0.0028
1975	1,284	523	0.0025
1980	1,746	624	0.0028
1986	2,184	879	0.0025

Note: The term resin in this table refers only to polyvinyl chloride (PVC) resins.

[a] Based on 1 percent manufacturing losses (Yost and Greenkorn 1984).

[b] Total resin figure includes PVC resin containing stabilizers other than lead based stabilizers.

Source: EPA 1989, Franklin 1990.

the resin, it is generally more difficult to find suitable replacements for lead-based products in this application.

Lead-based heat stabilizers are used predominantly in PVC resins. After accounting for lead lost during manufacturing, the amount of lead in PVC products was estimated. From this figure, the lead/PVC weight ratio could be calculated. Similar to the methodology used for pigments, the resin quantity used to estimate the lead/resin ratio includes PVC not containing any lead.

4. Consumption of Cadmium-based Heat Stabilizers

Table 12 shows the trend in the discards of cadmium-containing heat stabilizers for the period 1970-1986. From the net quantity of cadmium, the cadmium/resin weight ratio was calculated. As can be seen in the table, unlike the lead compounds, demand for cadmium heat-stabilizers (relative to resin demand) has decreased dramatically. The difference in the patterns of use (compared to lead) may be a result of the increase in cadmium's price and resultant attention to reformulating with lower cadmium content (Argus 1989b, Bedford 1989).[*]

D. Potential Substitutes for Lead- and Cadmium-containing Additives for Plastics

The selection of a particular lead or cadmium pigment and/or heat stabilizer is dependent on processing requirements, resin characteristics, and end-product uses. Identification of potential substitutes is, therefore, a complicated and application-specific task. There are, however, some general classes of substitutes available for each cadmium and lead-based additive type. The following sections describe the performance, cost, feasibility, and

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[*] Another source at Argus (unknown) considers the 1970 data presented in Table 10 to be suspect. He characterizes lead and cadmium consumption to be essentially constant for more than ten years (Vinyl Institute 1989b).

Table 12. Discards of Cadmium in Stabilizers for PVC in MSW

Year	Cadmium in Stabilizers Discarded[a] (tons)	Total Resin Discarded in Nonfood Applications[b] (thousands of tons)	Cadmium/Resin Ratio
1970	241	275	0.00088
1975	280	523	0.00054
1980	273	624	0.00044
1986	305	879	0.00035

Note: The term resin in this table refers only to polyvinylchloride (PVC) resins.

[a] Manufacturing losses are assumed to be 2 percent (Yost and Greenkorn 1984).

[b] Total resin includes PVC resins containing stabilizers without cadmium.

Source: EPA 1989.

other considerations that dictate how potential substitutes can replace traditional lead and cadmium products.

1. Potential Substitute Colorants and Their Properties

Although there is some agreement on the performance characteristics of pigments (i.e., chemical compatibility, light and heat fastness, hue, and intensity) which are of concern to most consumers (plastics manufacturers), the selection of a substitute will depend in large part upon the individual consumer's ranking of the importance of these attributes. For example, a manufacturer of beach balls may worry mostly about hue and intensity and not be concerned about heat fastness. On the other hand, a manufacturer of high-performance automotive polymers may find a less vibrant color acceptable if the substitute is heat-resistant and performs suitably in the other areas.

Particular colorant-polymer combinations may also be ruled out for a variety of other reasons. The first problem that might be encountered is a chemical incompatibility between the colorant and the polymer solvent, resin, or manufacturing by-products. For example, some pigments may not be used in PVC because of their sensitivity to acid (Kirk Othmer 1983). In addition to a chemical resistance problem, the colorant may not be able to survive harsh processing conditions for certain polymer resins. For example, although the end use of a plastic polymer may not require high temperatures, extensive heating during processing is often required to melt and mold a plastic. In addition to these obstacles, a colorant-polymer combination may be ruled out because of the end use of the plastic product. A combination that is sufficiently lightfast and suitable for indoor use may be ruled out for exterior applications. Table 13 provides possible substitutes and their performance properties for lead and cadmium pigments.

For purposes of this analysis, potential substitutes for lead and cadmium pigments are chosen based only on the characteristic of having a similar hue as reported in the Plastic Additives Handbook (1987). Because application-specific considerations are often critical for establishing exact substitution patterns, lead- and cadmium-based pigments are grouped together (i.e., substitutes are considered for the color yellow; not chrome yellow (lead) and cadmium yellow). A potential substitute for each major hue (red and yellow) was chosen from the chemical families that are comprised of inorganic and organic pigments and dyes. In addition, two potential organic substitutes, quinacridone and perylene pigments, were chosen based on information from Mobay (1989) that reported they could be used with high performance polymer systems (e.g., nylon, polyesters).

a. Costs of Lead- and Cadmium-based Pigments and Their Potential Substitutes

For most of the lead-based and cadmium-based colorants, many technically acceptable substitutes are available, although as mentioned above, the costs of the substitutes may be significantly higher. The price of cadmium has increased as other markets, such as that for nickel-cadmium batteries, increase the demand for cadmium. On the other hand, lead pigments have remained inexpensive. Table 14 shows recent prices for the most common lead- and cadmium-based pigments, as well as prices for some pigments (mostly organic) that could be used as substitutes in various applications.

According to one industry contact, as a rule of thumb, the performance of organic pigments increases as the price does (Hoechst-Celanese 1989). Certain pigments may not perform as well as less expensive organics in a few measures of performance, but the quality must be higher in at least one aspect of performance or there would be no demand for the product. For example,

Table 13. Potential Substitutes for Lead and Cadmium Pigments and Their Performance Properties

Potential Substitute Colorant	Hues	Heat Stability[a] (°C)	Lightfastness[b]	Opacity/ Hiding Power	Remarks on Performance[c] (Compatible Polymer/Resin)	Possible Substitute For:[d]
Inorganic						
Nickel titanium	Yellow	300	8	Opaque	General suitability, but greatly reduced tinting strength	Lead chromate; cadmium sulfide; cadmium sulfide + zinc
Iron oxide	Red	300	8	Opaque	General suitability, but only in mixtures of dark shades	Lead molybdate; cadmium/sulfide selenide H-PVC =
Organic						
Monoazo	Yellow	260	7-8	Transparent	LDPE, PS +; PVC -	Lead chromate; cadmium sulfide; cadmium/sulfide selenide
Monoazo naphthol	Red	280	5-7	Transparent	PVC, PS, LDPE +; HDPE (+*)	Lead molybdate; cadmium/sulfide selenide;
Quinacridone	Red	240-280	7-8	Transparent	PS, PVC, LDPE +; HDPE (+*)	Lead molybdate; cadmium/sulfide selenide
Perylene	Red	220-300	7-8	Transparent	PS, PVC, LDPE +; HDPE (+*)	Lead molybdate; cadmium/sulfide selenide
Dyes						
Pyrazolone derivative	Yellow	300[e]	7-8[e]	Transparent	PMMA, H-PVC, PS +	Lead chromate; cadmium sulfide; cadmium sulfide + zinc
Azo dye	Red	260[e]	2-5[e]	Transparent	PMMA, H-PVC, PS +	Lead molybdate; cadmium/sulfide selenide

[a] For heat stability, the temperature is stated at which no coloristic changes occurred during normal dwell times (approximately 5 minutes) in processing machines.

[b] Determination of lightfastness is carried out in accordance with DIN 53 389. 1 is the lowest value; 4 has 8 times the fastness level of 1; the highest value is 8, testing not normally being carried out beyond this level. See Plastic Additives Handbook (1987) for more information.

[c] Polymer Codes: PS = polystyrene; LDPE = low density polyethylene; PMMA = polymethyl methacrylate; HDPE = high density polyethylene; PVC = polyvinyl chloride; H-PVC = Unplasticized PVC.

Polymer Performance: + denotes suitable/recommended; = limited suitability/recommended; - denotes not suitable/recommended; () denotes a qualification of the statement; * denotes caution is needed in the case of HDPE articles sensitive to distortion.

[d] Possible substitutes were based primarily on colorant hue as reported in the Plastic Additives Handbook (1987).

[e] For dyes, lightfastness and heat stability depends to an especially high degree on the plastic to be colored.

Source: Brannon 1988, Plastic Additives Handbook 1987, Vinyl Institute 1989b.

Table 14. Costs: Lead- and Cadmium-based Pigments
and Potential Substitutes

Hue		Cost ($/lb.)[b]
Yellow	**Lead/Cadmium Pigments**	
	Lead chromate	$ 1.55
	Cadmium sulfide	$14.60
	Cadmium sulfide + zinc	$14.60
	Substitute Colorants[a]	
	Nickel titanium (inorganic)	$ 3.50
	Monoazo (organic)	$17.95
	Pyrazolone derivative (dye)	$20.32
Red	**Lead/Cadmium Pigments**	
	Lead molybdate	$ 2.25
	Cadmium/sulfide selenide	$18.15
	Substitute Colorants[a]	
	Iron oxide (inorganic)	$ 0.79
	Monoazo naphthol (organic)	$24.25
	Quinacridone (organic)	$32.00
	Perylene (organic)	$41.20
	Azo dye (dye)	$10.30

Note: It has not been possible to establish the exact colorant to resin ratio required to achieve equal coloring properties for potential substitute products as compared to the lead- and cadmium-containing pigments. As a result, it is not possible to develop a cost per pound of resin for substitute products.

[a] The substitute colorants listed are based on having a similar hue (i.e., red or yellow) as reported in the Plastic Additives Handbook (1987). In addition to cost, specific selection of a substitute is dependent on a diverse set of performance properties. For a comparison of these properties, see Table 13.

[b] Costs were determined by contacting chemical companies and requesting prices on given pigments (from Plastic Additives Handbook). The costs are based on the most commonly used (standard) packaging sizes (40-60 lb. containers) reported by the chemical companies.

Sources: BASF 1989, Bayer-Mobay 1989, Plastic Additives Handbook 1987.

prices generally increase as the acceptable processing temperatures rise. This consideration, combined with the smaller production scales of specialty and high-performance plastics help maintain the price differential.

In addition, the amount of product used for an application is dependent mainly on the shade and brilliance required. For example, if a faint yellow is required, less lead chromate is used than would be required for a darker yellow. In general, for similar hues, 25 percent less organic pigment by volume is required compared to an inorganic pigment (Hoechst-Celanese 1989). Estimates are not available as to the amount of dye required for coloring.

b. Other Factors Affecting Selection of Substitutes and Substitute Costs

If lead and cadmium pigments were not available, chemical companies may be more willing to invest in the research and development of substitutes, because there would be less low-cost competition for any new substitutes developed. From Table 13, it is evident that there are many substitutes available for lead and cadmium pigments; however, it may be impossible to find exact replacements for some pigments (such as some of the very high- performance cadmiums used in nylons) at any cost. In those cases, it may be necessary for the plastic manufacturer to sacrifice one aspect of performance, such as hue or brilliance, in exchange for another, such as heat or lightfastness.

Several of the companies contacted (Harshaw 1989, Heubach 1989) are still committed to the manufacturing and/or distribution of lead-based pigments, but the majority of the companies contacted have ceased to supply them. The same cannot be said for some of the cadmium-containing colorants; their performance characteristics are more difficult to reproduce using either organic or other inorganic pigments. Although there are organic pigments which match cadmium

pigments in brilliance, hue, and lightfastness, they generally are not
adequate in high-temperature situations. On the other hand, although many of
the inorganic compounds are quite heat resistant, they are tinctorially weak
or colorless (white).

The toxicity of heavy metals is well known, and therefore many
manufacturers have shied away from using compounds containing metals such as
lead and cadmium. For example, General Electric stopped using lead pigments
approximately 10 years ago and ceased use of cadmium pigments at the beginning
of 1989 (General Electric 1989).

Research by many other manufacturers continues in order to find potential
substitutes for lead and cadmium compounds that are compatible with high-
performance engineering resins such as polycarbonate, nylon, and other
polyesters (Modern Plastics 1987). Combinations of substances are sometimes
used to complement each other and improve the overall qualities of products.
For example, in an application requiring some hiding power and resistance to
heat, a mix of a high performance organic colorant and an inorganic compound
may work. The inorganic pigment lends its hiding power while the organic
provides intense color. In some instances the inorganic compound may also
provide some color, thereby reducing the need for large quantities of organic
colorant, which would be required if the inorganic pigment were colorless
(white) like titanium dioxide.

Although dyes can often be used in place of pigments, they currently do
not hold a large share of the market for colorants. Because dyes must be
soluble in the resins they are used in, each variety of dye may be compatible
with only a few types of resins. In addition, the lead- and cadmium-based
pigments are generally applied in a solid form, either as color concentrates
or dry powders. Although dyes are also found in solid form, they are usually

used as liquids which would require some changes in the plant equipment and result in additional costs to the plastic manufacturer.

2. Potential Substitute Stabilizers and Their Properties

Potential substitute products that could replace lead- and cadmium-containing heat stabilizer products have been developed and continue to be investigated for several reasons. The toxicity of lead and cadmium compounds, the availability of an increasing number of technically superior alternate products, the lower costs of substitutes, and increasing costs associated with using lead and especially cadmium products have all been influencing factors. This section addresses potential substitute products, compares costs to existing lead and cadmium products when possible, and discusses important factors that affect substitution.

The majority of lead-based heat stabilizers have been replaced in applications where substitution is technically and/or economically feasible. For example, organotin stabilizers (e.g., alkyltin mercaptides, alkyltin carboxylates, and estertin mercaptides), barium/zinc, and metal-free stabilizers can be used in rigid applications, pipes and fittings, pigmented profiles, foamed profiles, and phonograph records that previously used lead-based products (Argus 1989c). Table 15 identifies PVC articles and stabilizer systems that can replace lead-based products in rigid PVC applications (Plastics Additives Handbook 1987).

Lead stabilizers also have been used in flexible PVC applications. These applications can be split into those for which cost-effective and reliable substitutes have been developed (shoes, sandals, and soles), and those for which substitution has lagged (electrical insulation and jacketing). Electrical insulation applications appear to use the majority of lead-based

Table 15. Potential Substitutes[a] for Lead-based Heat Stabilizers
in Rigid PVC Products

PVC Item	Methyl, Butyl and/or Octyltin Mercaptides	Butyltin Esters	Metal- Free Stabilizers
Pipes and Fittings	X		
Pigmented Sheets and Profiles	X	X	
Foamed Profiles	X		
Phonograph Records			X

[a] Ba/Cd stabilizers are not considered to be substitutes for lead stabilizers due to toxicity considerations and the scope of this analysis (i.e., lead and cadmium products are both under investigation and therefore are not considered to be substitutes for one another), although they may be technically and economically feasible in some applications.

[b] Phonograph records may be stabilized with certain metal-free stabilizers.

Source: Plastics Additives Handbook 1987.

stabilizers because of the critical non-conducting nature of lead products
(Vinyl Institute 1989a).

The use of electrical cable insulation and jacketing can be divided
among three major use areas:

- power wiring,
- telephone cable, and
- cords and connectors for appliances and
  other consumer items.

The critical properties of weathering, humidity resistance, and thickness of
the jacket in the power wiring and telephone cable applications have made
substitution difficult given that lead imparts these properties. Lead heat
stabilizers for these applications provide outstanding use characteristics and
there currently are no products available on the market that can replace these
lead-based products (BF Goodrich 1989).

The power and telephone cable uses account for about 50 percent of lead
stabilizer usage for jacketing and insulation, while the cord/connector
applications account for the remaining 50 percent. It is believed that these
lower performance cord/connector applications can be replaced with alternate
stabilizers (Argus 1989c, BF Goodrich 1989). The reformulated products were,
however, too experimental or could not be identified at this time.

Teflon® is a technically feasible substitute for PVC coatings, but is
not a one-for-one substitute in that heat stabilizers are not replaced, but
rather reformulation is required (i.e., Teflon® replaces PVC not lead). The
use of Teflon® has not been examined by the industry as a viable replacement
for cable insulation and is expected to be on the order of five to ten times
more expensive (Bedford Chemical 1989). Teflon® also may not possess
sufficient flexibility for many applications (Vinyl Institute 1989b).

Table 16. Potential Substitutes[a] for Lead-based Heat Stabilizers
in Flexible PVC Products

PVC Item	Ba/Zn Stabilizers	Butyltin Esters
Cable Insulation and Jacketing[b]		
Shoes, Sandals, Soles	X	X

Note: Ba = barium; Zn = Zinc

[a] Barium/cadmium stabilizers are not considered to be substitutes for lead stabilizers due to toxicity considerations and the scope of this analysis (i.e., lead and cadmium products are both under investigation and therefore, are not considered to be substitutes for one another), although they may be technically and economically feasible in some applications.

[b] Teflon® is a technically feasible substitute for PVC coatings, but is not a one-for-one substitute in that heat stabilizers are not replaced, but rather reformulation is required (i.e., Teflon® replaces PVC not lead). The use of Teflon® has not been examined by the industry as a viable replacement for cable insulation and is expected to be on the order of five to ten times more expensive (Bedford Chemical 1989). Teflon® also may not possess sufficient flexibility for many applications (Vinyl Institute 1989b).

Sources: Argus 1989c, Bedford 1989, Plastic Additives Handbook 1987.

Table 16 identifies the potential substitutes for lead-based stabilizers used in flexible PVC applications.

Barium/Cadmium heat stabilizers have a wide range of applicability in rigid and flexible PVC applications. The products and potential substitutes are identified in Tables 17 and 18. There is some overlap with lead-based stabilizers, but these are not considered to be substitutes for cadmium-containing products and vice-versa. The processing techniques (e.g., calendaring, extrusion, injection molding, blow molding, pressing, coating), the processing conditions (temperature, mixing, alkalinity) and a host of other reasons, including the presence of other additives, the end use of the product (indoor/outdoor), and the costs of potential substitutes, influence which products are ultimately considered to be substitutes. In general, there are adequate substitutes for cadmium-containing stabilizers, including barium/zinc, calcium/zinc, and tin-based stabilizers.

a.   Costs of Lead- and Cadmium-based Heat Stabilizers and Potential Substitutes

Lead and cadmium heat stabilizers have seen widespread use because of their relatively low cost compared to newer substitute products. As concern has mounted regarding the toxicity of lead and cadmium products, substitute products have been perfected and costs of substitutes have declined (Argus 1989b). Table 19 presents the relative costs of lead, cadmium, substitute products.

It must be noted that the actual substitution pattern for lead and cadmium stabilizers is very complicated. The wide range of applications, processing considerations, and other factors that affect potential substitute development and entry into the market make it difficult to distinguish exact

Table 17. Potential Substitutes[a] for Cadmium-based
Heat Stabilizers in Rigid PVC Products

PVC Item	Butyltin Mercaptides	Butyltin Esters	Barium/ Zinc Solids
Films for Non-food Applications	X		X
Pigmented Profiles			
-- Indoor	X		X
-- Outdoor		X	X
Foamed Profiles	X		X

[a] Lead stabilizers are not considered to be substitutes for Ba/Cd stabilizers due to toxicity considerations and the scope of this analysis (i.e., lead and cadmium products are both under investigation and therefore, are not considered to be substitutes for one another), although they may be economically and technically feasible in some applications.

Source: Plastic Additives Handbook 1987.

Table 18. Potential Substitutes[a] for Cadmium-based
Heat Stabilizers in Flexible PVC Products

PVC Item	Butyltin Mercaptides or Esters	Barium/ Zinc Stabilizers	Calcium/ Zinc Stabilizers
Films for Non-food Applications	X	X	X
Profiles and Flexible Tubes for Non-food Applications		X	X
Shoes, Sandals and Soles		X	
Artificial Leather Coatings		X	X
Dippings		X	X

[a] Lead stabilizers are not considered to be substitutes for Ba/Cd stabilizers due to toxicity considerations and the scope of this analysis (i.e., lead and cadmium products are both under investigation and therefore, are not considered to be substitutes for one another), although they may be economically and technically feasible in some applications. The relative amount of cadmium in liquid stabilizers can be reduced by the addition of zinc fatty acid salts that replace the corresponding cadmium salts (Modern Plastics 1987).

Source: Plastic Additives Handbook 1987, Vinyl Institute 1989b.

Table 19. Costs of Lead, Cadmium, and Potential Substitute Heat Stabilizers

Stabilizer Class	Approximate Cost Range ($/lb.)	Amount Used Per Hundred Parts of Resin
Lead		
Lead compounds	0.50-1.00	1.0-3.0
Organotin stabilizers	1.00-3.00	1.5-2.5
Barium/zinc stabilizers	2.00-4.00	1.5-3.0
Teflon[*]	a	Not Applicable
Cadmium		
Barium/cadmium liquids	0.95-1.75	1.0-4.0
Barium/cadmium solids	1.85-2.75	1.5-3.0
Barium/cadmium/zinc products	0.95-1.70	1.0-3.0
Zinc/calcium products	1.00-3.00	1.0-3.0
Liquid organotin stabilizers	3.00-4.50	2.0-4.0
Solid organotin stabilizers	8.00-10.00	1.5-3.0
Barium/zinc liquids	1.25-2.50	1.0-4.0
Barium/zinc solids	2.00-4.00	1.5-3.0

[a] Teflon[*] is a different class of substitute in that it would replace the end product, PVC coatings, used for wire and cable insulation. It is not currently considered a stable substitute for economic reasons. The cost of PVC coatings is roughly $0.50 to $1.00/lb. and for Teflon[*] >$5/lb.

Sources: Argus 1989a, 1989b, 1989c; Bedford 1989.

substitution patterns. The costs presented in Table 19 should be considered, therefore, rough approximations.

b. Other Factors Affecting Selection of Substitutes and Substitute Costs

There are a number of considerations that must be included in the selection of stabilizer substitutes and estimation of costs for comparison to costs for lead and cadmium stabilizers. It has not been possible to characterize each of these considerations, but they are provided for completeness:

- Potential substitute stabilizer packages that can replace lead or cadmium products may be required in quantities greater or lesser than the products they replace. They may be cheaper or more expensive, at the concentration level required, or they may be viable only for some applications.

- The addition of co-stabilizing* products may reduce potential substitute costs, improve performance to a level above that of the lead or cadmium product, or increase product service life.

- It may be possible to combine stabilizers so that a synergistic effect is achieved, thereby improving performance and/or reducing costs.

- New potential substitutes are constantly being developed and made available. Some of these, based on antimony and metal-free stabilizer systems (e.g., diphenylthioureas, and ß-aminocrotonates) have not been widely accepted, but may influence the stabilizer market over the next few years.

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* Co-stabilizers are usually organic compounds that enhance the solvency of stabilizers or provide some other benefit, but are not stabilizers if used alone.

- 43 -

E. References

Argus. 1989a (May 10). M. Croce. New York, NY. Transcribed telephone conversation with Mark Wagner, ICF Incorporated, Fairfax, VA.

Argus. 1989b (May 11). D. Stimpfl. New York, NY. Transcribed telephone conversation with Mark Wagner, ICF Incorporated, Fairfax, VA.

Argus. 1989c (May 17). D. Brilliant. New York, NY. Transcribed telephone conversation with Mark Wagner, ICF Incorporated, Fairfax, VA.

BASF. 1989 (May 16). Basic Organics Group. Transcribed telephone conversation with Tanya Yudleman, ICF Incorporated, Fairfax, VA.

Bayer-Mobay Corporation. 1989 (May 16). Transcribed telephone conversation with Tanya Yudleman, ICF Incorporated, Fairfax, VA.

Bedford Chemical. 1989 (May 4). D. Gauw. Bedford Chemical, Division of Ferro Corporation. Bedford, OH. Transcribed telephone conversation with Mark Wagner, ICF Incorporated, Fairfax, VA.

Brannon, SM. 1988 (February 1-5). 43rd Annual Conference, Composites Institute, the Society of the Plastics Industry. Colorants for Composites -- A Review.

EPA. 1989 (January). U.S. Environmental Protection Agency. Characterization of Products Containing Lead and Cadmium in Municipal Solid Waste Facilities 1970 to 2000. Prepared by Franklin Associates Ltd., Prairie Village, KS.

Franklin Associates. 1990 (August). Characterization of Lead in Plastic Products in Municipal Solid Waste, 1970 to 2000. Prairie Village, KS.

General Electric Color Lab. D. Bryant. 1989 (May 4). Transcribed telephone conversation with Peter Weisberg, ICF Incorporated, Fairfax, VA.

B.F. Goodrich. 1989 (May 17). G. Lefebvre. Cleveland, OH. Transcribed telephone conversation with Mark Wagner, ICF Incorporated, Fairfax, VA.

Harshaw Colors. 1989 (May 12). M. DiLorenzo. Division of Eagelhard Corp. Transcribed telephone conversation with Don Yee, ICF Incorporated, Fairfax, VA.

Heubach, Inc. 1989 (May 12). Transcribed telephone conversation with Don Yee, ICF Incorporated, Fairfax, VA.

Hoechst-Celanese. 1989 (May 9). D. Wave. Transcribed telephone conversation with Don Yee, ICF Incorporated, Fairfax, VA.

Kirk-Othmer. 1983. Encyclopedia of Chemical Technology. John Wiley and Sons Publishing Co., Inc. Vol. 18, pp. 184-206; Vol. 14, pp. 168-183; Vol. 6.

Mobay. 1989 (May 3). J. Graff. Transcribed telephone conversation with Don Yee, ICF Incorporated, Fairfax, VA.

Modern Plastics. 1982 (July). McGraw-Hill Publishing Co., p. 44.

Modern Plastics. 1983 (September). Chemicals and Additives Special Report. McGraw-Hill Publishing Co.

Modern Plastics. 1985 (September). Chemicals and Additives Special Report. Colorants -- pp. 60-62; Heat Stabilizers -- pp. 68-69. McGraw-Hill Publishing Co.

Modern Plastics. 1987 (September). Colorants -- pp. 68-71; Heat Stabilizers -- pp. 70-71. McGraw-Hill Publishing Co.

Modern Plastics. 1988 (September). Chemicals and Additives Special Report. McGraw-Hill Publishing Co.

Modern Plastics. 1989 (January). Resin Report. McGraw-Hill Publishing Co.

Plastics Engineering Handbook. 1987. 4th Edition. Van Nostrand Reinhold Publishing Company.

Plastic Additives Handbook. 1987. Hanser Publishers. Munich, Germany.

Radian. 1987. Chemical Additives for the Plastics Industry. Radian Corporation. Noyes Data Corporation. Park Ridge, NJ.

Vinyl Institute. 1989a (May 15). R. Gottesman. Little Falls, NJ. Transcribed telephone conversation with Mark Wagner, ICF Incorporated, Fairfax, VA.

Vinyl Institute. 1989b (July 11). R. Gottesman. Comments received on the Draft Plastics Section.

Yost, K. and K. Greenkorn. 1984 (January). Source Specific Impacts and Exposure Mechanisms for Cadmium. Purdue University.

III. PIGMENTS

A. Overview of the Pigment Industry

A pigment can be defined as a substance that imparts color to other
materials. Depending on the size of the pigment particles, different
wavelengths of light can be selectively absorbed thereby producing a desired
color. Pigments are normally insoluble in the medium that they are dispersed.
Pigments are often chosen for incorporation into a final product based on
tinctorial strength, brightness, texture, durability, and cost. Pigments are
usually classified as being inorganic or organic. Organic pigments by
definition contain carbon.

B. Uses of Lead- and Cadmium-containing Pigments

Pigments are used in a wide variety of products: in paints and inks; and
to color plastics, paper, rubber, and glass. Although the use of lead- and
cadmium-containing pigments in plastics is representative of their use in the
other use areas discussed in the EPA 1989 report, certain properties such as
heat resistance may be more important in other use areas such as glass and
ceramics. For a discussion of the uses of lead- and cadmium-containing
pigments refer to Chapter II on plastics.

C. Consumption of Lead and Cadmium in Pigments

Lead and cadmium-containing pigments are used in plastic, glass/ceramic,
and rubber products that are disposed in municipal solid waste facilities.
The consumption of lead and cadmium in pigments is discussed in Section C of
Chapter II on plastics, Chapter VI on glass, and Chapter XI on rubber. The
tables are repeated here for ease of reference.

D. Potential Substitutes of Lead- and Cadmium-containing Pigments

The potential substitutes for lead- and cadmium-containing pigments are
discussed in Section D of the Plastics Chapter (Chapter II). The potential

Table 20. Discards of Lead in Pigments for Plastic in MSW

Year	Lead in Pigments Discarded[a] (tons)	Total Resin Discarded in Nonfood Applications[b] (thousands of tons)	Lead/Resin Ratio
1970	647	2,061	0.00034
1975	813	3,098	0.00026
1980	967	5,103	0.00019
1986	990	8,111	0.00012

Note: The term resin refers to the type of plastic. Practically, plastics are classified by the nature of the major resin(s) used in their manufacture. The resins included in this consumption table could include all of the resins identified in Table 2.

[a] Adjusted for net exports and with manufacturing losses estimated to be 2 percent; although the source discusses cadmium pigments, lead based pigments are found in similar forms, and therefore similar losses are expected (Yost and Greenkorn 1984).

[b] Total resin figure includes resins containing no lead-based pigments.

Source: EPA 1989.

Table 21. Discards of Lead in Pigments in Rubber Products in MSW

Year	Discards of Lead in Tire Pigments (tons)	Discards of Lead in Fabricated Rubber Products (tons)	Total Discards of Lead in Rubber Pigments[a] (tons)
1970	45	16	52
1975	44	15	53
1980	83	33	104
1986	56	21	70

[a] Ten to fifteen percent of tires and other rubber products are diverted or recovered annually.

Source: EPA 1989.

Table 22. Discards of Lead in Pigments in
Ink and Miscellaneous Products in MSW

Year	Discards of Lead in Ink Pigments[a] (tons)	Discards of Lead in All Other Miscellaneous Pigments[b] (tons)	Total Discards of Lead in Ink and Miscellaneous Pigments (tons)
1970	19,192	7,828	27,020
1975	13,819	3,198	17,017
1980	8,222	1,642	9,864
1986	265	866	1,131

Note: Total consumption includes only pigments
      other than those found in plastics,
      rubber, glass, and ceramic glazes.

[a] Based on net consumption of lead in inks, assuming 5
percent manufacturing losses and adjusted to exclude
inks in recycled papers.

[b] Includes pigments in textiles, adhesives, artists'
paints, and miscellaneous applications.

Source: EPA 1989.

Table 23. Discards of Cadmium in Pigments in Plastic in MSW

Year	Cadmium in Pigments Discarded[a] (tons)	Total Resin Discarded in Nonfood Applications[b] (thousands of tons)	Cadmium/Resin Ratio
1970	162	2,061	0.000079
1975	256	3,098	0.000083
1980	259	5,013	0.000052
1986	259	8,111	0.000032

Note: The term resin refers to the type of plastic. Practically, plastics are classified by the nature of the major resin(s) used in their manufacture. The resins included in this consumption table could include all of the resins identified in Table 2.

[a] Adjusted for net exports and with manufacturing losses assumed to be 6 percent (Yost and Greenkorn 1984).

[b] Total resin figure includes resins containing no cadmium-based pigments.

Source: EPA-1989.

Table 24. Discards of Cadmium in Pigments for Glass, Ceramics, and
Miscellaneous Products in MSW

Year	Cadmium Discarded in Pigments for Glass and Ceramics[a] (tons)	Cadmium Discarded in Pigments for Miscellaneous Products[b] (tons)	Total Discards of Cadmium in Pigments for Glass, Ceramics and Miscellaneous Products[c] (tons)
1970	32	79	111
1975	27	65	92
1980	23	56	79
1986	29	70	99

[a] Half of the glass and ceramics with cadmium pigments are assumed to
end up in MSW. Discards are assumed to be in the year of manufacture
for the glass product.

[b] Includes pigments in products other than plastics, rubbers, and
glass/ceramics. Products are assumed to be discarded in the year of
manufacture.

[c] Includes pigments other than those found in rubbers and plastics.

Source: EPA 1989.

Table 25.   Discards of Cadmium in Pigments
           for Rubber Products in MSW

Year	Cadmium in Pigments for Rubber-Products[a] (tons)
1970	10
1975	13
1980	8
1986	6

[a] Consumption of cadmium pigments in rubber was assumed to be one percent of total consumption of cadmium pigments.

Source: EPA 1989.

substitutes for these pigments used in glass/ceramic* and rubber products are assumed to be similar to those discussed in the plastics chapter.

E. <u>References</u>

EPA. 1989 (January). U.S. Environmental Protection Agency. Characterization of Products Containing Lead and Cadmium in Municipal Solid Waste Facilities 1970 to 2000. Prepared by Franklin Associates Ltd., Prairie Village, KS.

Yost, K. and K. Greenkorn. 1984 (January). Source Specific Impacts and Exposure Mechanisms for Cadmium. Purdue University.

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* Pigments are used in glazes and enamels. Glazes and enamels are discussed in the glass/ceramic chapter (Chapter VI). The consumption of lead pigments used in glass products is not available. The EPA 1989 report identifies lead consumption in glass only at the aggregated level. The proportion of this total lead use that is attributable to lead pigments is, therefore, not available.

IV. SOLDER

A. Overview of the Soldering Industry

Solder is used in a variety of products to form both electrical and structural bonds between various types of materials.[*] The most common use of solder is to attach electrical components to printed circuit boards (Arconium 1989). The soldering process is useful in that it allows manufacturers to easily automate the simultaneous attachment of multiple components. The major markets for these printed circuit boards are in computers, communication devices, and government/military uses. It should be noted that the products discussed in this chapter are those that are disposed of in municipal solid waste (MSW) and therefore, may exclude certain applications. For example, solder is used in the manufacture of automobile bodies and automobile parts that are assumed to be disposed in other types of waste facilities (EPA 1989).

The soldering process is defined as a metallurgical joining method using a filler metal (the solder) with a melting point below 600°F (316°C). Soldering relies on wetting[**] for the bond formation and does not require diffusion[+] with base metals to achieve bonding (Manko 1979). The limit of 600°F was set arbitrarily; many people consider 800°F (427°C) the upper

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[*] Both electrical and structural bonds join parts physically. Unlike an electrical bond, however, a structural bond is not required to transmit electricity.

[**] "Wetting" describes the relationship between molten solder and the surfaces of materials that are being soldered. Solder with good wetting ability forms intimate continuous contact with the materials to be soldered.

[+] In the context of bonding, "diffusion" means the joining of parts by melting them together. Under certain chemical conditions, the materials in soldered parts can also diffuse into each other without being heated.

temperature limit for soldering.[*] Soft solders are characterized by melting

temperatures below 375°F, while hard solders melt between 375°F and 800°F

(Manko 1979, Belser 1954).

1. Solder Characteristics

Solder is available in a wide variety of compositions and forms,

but is almost always an alloy composed of two to six types of metal.[**] While

tin and lead are the most common elements found in solder, solder alloys can

also include indium, bismuth, cadmium, antimony, silver, gold, zinc, copper,

mercury, gallium, germanium, aluminum, arsenic, and silicon. (Indium 1988,

Manko 1979, Alpha Metals 1989, Warwick 1985). The most common type of solder

used in consumer electronics, however, is tin/lead solder (Kapp 1989).

B. Solder Use Areas

While solder is used in a wide variety of military, industrial, and

commercial products, this report addresses only the use of solder in consumer

(commercial) products that are disposed of in MSW facilities. Three solder

use areas in consumer products have been identified: consumer electronics,

light bulbs, and cans (for food and non-food products).

1. Consumer Electronics

Consumer electronics disposed of in MSW facilities include

products such as televisions, radios, and video cassette recorders. This

report assumes that all of the solder found in consumer electronics is used to

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[*] The upper temperature limit of soldering separates soldering operations
from brazing operations. While both bonding operations rely on a filler
metal, brazing is done at a temperature level sufficient to partially melt the
base metals to help form the bond.

[**] Most solder alloys contain only two or three types of metal (Indium
Corporation of America 1988).

make electrical bonds in printed circuit boards in these electronic devices.[*]
In 1986, consumer electronics accounted for 11.7 percent of the printed
circuit market (EPA 1989).

Although home computers are a popular type of solder-containing consumer
product, the printed circuit boards found in home computers are not usually
disposed of in MSW. Instead, these circuit boards are removed for repair and
returned to manufacturers for recovery of components such as memory chips (EPA
1989). Therefore, this report assumes the home computer circuit boards become
industrial waste rather than MSW. This report also assumes consumer
communications equipment (e.g., telephones) enters industrial waste rather
than MSW (EPA 1989).

The chief reason tin/lead solder is used to produce consumer electronics
is cost (Talco 1989). Because specialty solders employ more exotic metals,
the tin/lead alloy can be many times cheaper than a substitute solder.
Tin/lead solder also has advantageous physical properties -- it has good
wicking tendencies;[**] has some pliancy to resist breakage from vibration,
bonds aggressively at a relatively low temperature, which avoids the
possibility of thermally shocking the parts to be soldered; and it has good
electrical continuity (IPC 1989b, Sylvania 1989a). Tin/lead solder also works
well in the manufacture of solder clad printed circuit boards (printed circuit
board manufacturing is discussed below).

Cadmium-containing solder is not commonly used to manufacture consumer
electronics. Manufacturers avoid the use of cadmium because of health-related

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[*] This assumption is based on the methodology found in EPA 1989 report.

[**] The "wicking" ability of solder is its tendency to produce strong
bonds by travelling up the holes used to mount components on some printed
circuit boards.

concerns including the generation of poisonous fumes during the soldering operation (IPC 1989b, Keeler 1987, Indium 1989d).

a. Through-hole and Surface Mount Printed Circuit Boards

Two technologies can be used to attach electrical components to printed circuit boards -- through-hole assembly technology or surface mount assembly technology. With surface mount technology (SMT), components are attached directly to the board without drilling or punching holes (see Figure 1). Without holes, components can be densely packed on the board thereby reducing the size of the board. Texas Instruments cites a 40 percent reduction in size of the printed circuit board assembly over through-hole technology when surface mount technology is used (Mullen 1984).

With through-hole technology, the leads of the electrical components are placed into holes that have been drilled in the circuit board (see Figure 1). Usually the circuit board is soldered on the side of the board from which the leads protrude (IPC 1989c).

b. Printed Circuit Board Manufacturing

There are several methods used to manufacture the circuit board to which components are attached. The oldest technique is called "subtractive" and can be used to make either single- or double-sided circuit boards.* The process begins with a copper clad circuit board in its initial state -- a laminate such as fiberglass or epoxy that has been coated with copper on one or both sides. A protective pattern of "etch resist" is deposited on the copper surface, and the unwanted copper is etched away (hence the name "subtractive"). The subtractive process can be further categorized according to the type of etch resist used (Manko 1986).

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* A single-sided board can accept components on only one side, while a double-sided board can accept components on both sides.
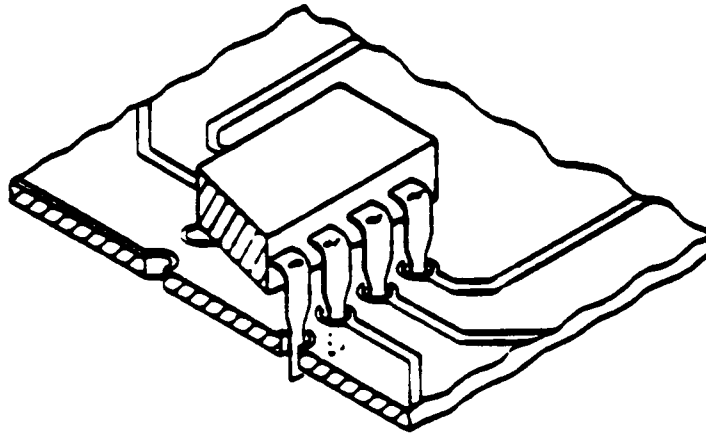
i) DIP Through-hole Component.
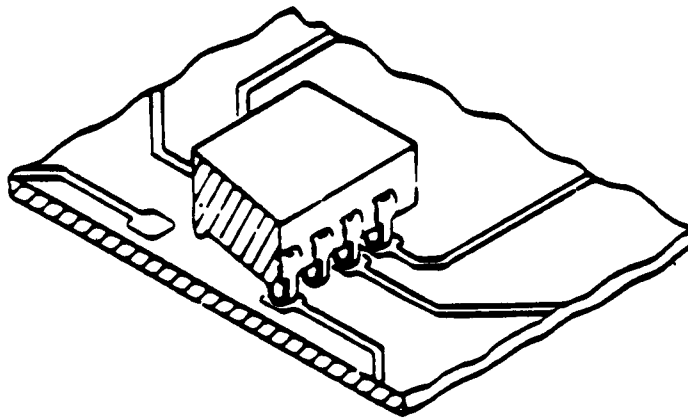
ii) SMC J-lead Surface-Mount Component.

Figure 1. Comparison of Through-Hole and Surface Mount Technologies.
(Source: Mullen 1984.)

The most common subtractive method used to produce double-sided and multilayer boards employs tin/lead plating as the etch resist. The first step involves coating the board with organic resist in a negative image of the circuit pattern. Next, tin/lead is applied with an electroplating process to create a positive image of the circuit pattern. The organic resist and the copper are then stripped, leaving a copper circuit pattern protected by the tin/lead plating (Manko 1986, IPC 1989c). This method of circuit board production can be used for through-hole and surface mount assemblies.

The advantage of tin/lead plating is that it protects the copper from oxidizing, allowing the circuit board to be stored for long periods (IPC 1989b). The use of tin/lead clad circuit boards encourages the use of tin/lead solder during assembly of the printed circuit board because the solder blends with the alloy already plated on the circuit board. The use of a different solder alloy, while possible, can lead to problems as the resulting solder alloy will be an unknown and possibly weak or low-melting composition. Unfortunately, most of the desirable alloys for soldering are not suitable for electroplating, making their use more difficult (Manko 1986).

Circuit boards may also be manufactured with a "print and etch" or an "additive" process resulting in printed circuit boards with bare copper that needs to be protected from oxidation. Organic coatings can be applied over the copper to provide good protection for several months, but this oxidation protection method does not last as long as a tin/lead coating that can protect boards from oxidation for periods of 2-3 years (IPC 1989b).

2. Cans for Consumer Uses

Cans may be categorized as one of two types -- a two piece can or a three piece can. A two piece can consists of two pieces -- a cup-shaped bottom and a top. The bottom of a two piece can is seamless and the top is

always attached by crimping without the use of solder. A three piece can consists of three pieces -- a top, bottom, and the cylindrical middle piece. Three piece cans have a seam down the side that must be sealed (CMI 1989b).

Cans used in consumer applications can be grouped into three major categories: food, beverage, and non-food (general packaging) cans. Non-food cans are used primarily for aerosol products (CMI 1989a).* Virtually all beverage cans are two piece cans that do not require solder for manufacturing. Some food and non-food cans, however, do contain solder to seal the can seams.**

The small number of food cans that are currently manufactured with solder employ solder that does not contain lead (with the possible exception of cans containing dry foods such as coffee that will not leach lead into the product). Some imported food cans, however, may contain lead solder (NFPA 1989b). Non-food cans (such as those used for aerosols) may also use lead-containing solder (CMI 1989a, NFPA 1989a).

Lead solder is used in cans because of its low cost and because its low melting temperature makes it easy to work with. Cadmium-containing solder is not used in the manufacture of cans (CMI 1989b).

3. Light Bulbs

Consumer light bulbs can be grouped into two major categories-- incandescent and fluorescent. Solder is used only in the manufacture of incandescent bulbs. Tin/lead solder is used in one of the final steps in the manufacture of incandescent bulbs when the ends of the filament wire that

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* Aerosol products account for approximately two thirds of non-food cans. Other non-food cans include paint, varnish, and automotive product cans (CMI 1989a).

** Only 3 percent of all food cans contain solder (CMI 1989b).

protrude from the threaded end of the bulb are soldered to the small metal tab at the base of the light bulb. Soldering not only prevents the filament wire from snapping off during use, it also enhances the ability of the filament to make good contact in the light socket (Sylvania 1989a).

Tin/lead solder is used to manufacture light bulbs for several reasons. It is a low cost solder and melts at a relatively low temperature. The low melting temperature of tin/lead solder is critical in light bulb manufacturing as soldering is a final operation that could destroy the quality of the bulb if the bulb glass is allowed to heat up to the point where it will release CO_2 and water into the light bulb assembly. Tin/lead solder also works fast and bonds parts together aggressively (Sylvania 1989a).

C. Consumption of Lead and Cadmium in Solder

Lead is used in solder for the manufacture of consumer electronics, cans, and light bulbs. Although specialty solders that do not contain lead can be used to manufacture these items, lead-containing solders dominate the solder market (Talco 1989).

1. Consumption of Lead in Solder

Eutectic[*] tin/lead alloy (63 percent tin/37 percent lead) is the most common soldering alloy currently in use (Kapp 1989). Almost all the lead used to solder consumer electronics, cans, and light bulbs is contained in tin/lead solder (Sylvania 1989a, Talco 1989, CMI 1989b). The amount of lead used to manufacture and subsequently discarded in MSW for each of these items

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[*] A eutectic solder is an alloy of a certain composition such that it melts at the lowest temperature of any alloy containing the metals involved. This allows the alloy to melt at a specific temperature. Most alloys melt over a temperature range and have a "mushy" state between the solid and liquid states.

is presented in Table 26. All of the lead consumption presented in this table is attributable to the use of lead-containing solder (EPA 1989).

a. Consumer Electronics

The amount of lead consumed in consumer electronics has increased steadily from 1970 to 1986. Consumer electronics were the fourth largest contributor of lead in MSW in 1970, but by 1975 they were the second largest contributor, a position they continue to hold (EPA 1989). The Bureau of Mines, however, reports a general decline in the use of lead in solder in electronic devices. Discards of lead in printed circuit boards found in consumer electronics are projected to decline to less than 1,000 tons and less than 1 percent of total discards by 2000 (EPA 1989). Because virtually no cadmium is consumed in solder in the manufacture of consumer electronics, cadmium-containing solder is not treated in this discussion (IPC 1989b).

b. Cans for Consumer Uses*

Solder is used in the manufacture of three piece cans to form bonds along the seams. Due to consumer law suits and pressure from the Food and Drug Administration, however, the use of lead-containing solder to manufacture cans used for food and beverage products has declined significantly over the past ten years (CMI 1989a). Lead-containing solder is still used to manufacture non-food containers and some cans for dried food (such as coffee) that cannot leach lead, but this application accounts for a small amount (approximately 3 percent) of total can production (NFPA 1989a, CMI 1989b). The sharp decline in the use of lead-containing solder to manufacture food cans is reflected in Table 26, as indicated by discard

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* Cadmium-containing solder is not used in the manufacture of cans (Elkins 1989).

Table 26. Discards of Lead in Solder in MSW

Year	Discards of Lead in Solder from Containers and Metal Cans[a] (tons)	Discards of Lead in Solder from Consumer Electronics[b] (tons)	Discards of Lead in Solder from Light Bulbs[c] (tons)	Total Discards of Lead in Solder (tons)
1970	24,117	1,417	156	25,690
1975	20,122	1,759	161	22,042
1980	9,675	3,441	197	13,313
1986	2,052	6,092	225	8,369

[a] Metal cans are assumed to be discarded in the year of manufacture. Containers are assumed to last 3 years. All cans are assumed to go into MSW, but only 20 percent of containers. Adjustments were made for recycling, which constituted 2, 3, 5, and 4 percent of all discards in 1970, 1975, 1980, and 1985 respectively. These assumptions and adjustments reflect the methodology found in the EPA 1989 report.

[b] Consumer electronics are assumed to have a product life of 8 years. This category includes the circuit boards and chassis of electronic equipment.

[c] Light bulbs are assumed to be discarded one year after manufacture. Although some newer bulbs have longer lifespans, discards of solder from light bulbs increased due to the continued use of shorter lifespan bulbs employed for cost reasons and because of the increased number of incandescent lamps in use (Roach 1989).

Source: EPA 1989.

figures for lead-containing solder that have dropped by a factor of 12 between 1970 and 1986.

c. Light Bulbs

Light bulbs are not a large source of lead solder in MSW, but are of interest because they contain two sources of lead -- solder and leaded glass. The discards of lead in light bulbs shown in Table 26 addresses only lead solder. Because the manufacture of fluorescent bulbs does not require solder, the consumption figures address only the manufacture of incandescent bulbs (EPA 1989).

Although lead-containing solder consumption in light bulbs has not risen as fast as consumption in consumer electronics, 1986 consumption is about 40 percent higher than 1970 consumption. In the past, cadmium solder was used in the manufacture of light bulbs. Virtually all bulbs made today, however, contain tin/lead solder. Solder used in light bulb manufacturing contains about 70 to 80 percent lead to keep solder costs down. Lead is relatively cheap and the metallurgy of the solder in this application is not critical (Indium 1989e). Cadmium-containing solders are no longer used to make light bulbs (Sylvania 1989a).

d. Plumbing Solder

Until recently, tin/lead solder was the most commonly used alloy for soldering plumbing. Recent legislation promulgated under the Safe Drinking Water Act Amendments of 1986, however, prohibits the use of lead-containing solder to bond pipes for plumbing in public potable water systems if the solder contains more than 0.2 percent lead (42 U.S.C. 300f). States were required to enforce this law as of June 19, 1988. The substitute solders that dominate the plumbing solder market are 95 tin/5 antimony solder alloy, and silver-containing solder (2 to 3 percent silver) for use on ferrous base

metals (PDI 1989, NAPHCC 1989). It is important to note, however, that the majority of plumbing solder would not be expected to be disposed of in MSW.

2. Consumption of Cadmium in Solder

While cadmium occasionally may be used in specialty solders, it is a toxic compound that can emit poisonous fumes during the soldering process and is, therefore, not used in consumer applications disposed at MSW. The use of solders containing cadmium demands a controlled process under a hood (Keeler 1987). Although light bulbs were once manufactured with a cadmium-containing solder, virtually all bulbs are currently manufactured with tin/lead solder (Sylvania 1989a). Cans and consumer electronics also do not contain cadmium solder (NFPA 1989a, IPC 1989c).

D. Potential Substitutes for Lead- and Cadmium-containing Solders

Potential substitutes for lead-containing solders may be broken into two groups -- substitute solders and substitute processes. Depending on the soldering process used, some alternative solders may be used as drop-in substitutes, and others may require redesign of soldering equipment or other processing equipment. Substitute processes usually eliminate the use of lead-containing solder by eliminating the need for solder during manufacturing. For example, can manufacturers may eliminate solder use by substituting a welding process that requires no solder. The availability and cost of potential substitutes for each of the market areas identified is discussed in the remainder of this section. Consumer electronics manufacturers will continue to use lead-based solders, as will manufacturers of light bulbs. Lead-containing solders used in can manufacturing have for the most part been eliminated through the use of substitute processes (CMI 1989a). Because the use of cadmium in consumer electronics, cans, and light bulbs is rare, substitutes for cadmium-containing solders are not discussed.

- 65 -

1. <u>Substitutes for Lead-containing Solder in Consumer Electronics</u>

Although many types of solder may substitute for tin/lead solder used in the manufacture of printed circuit boards in consumer electronics, none of the substitutes have exactly the same characteristics as tin/lead solder. The use of a substitute solder usually changes the soldering characteristics of melting temperature, required flux type, ability to wet the surfaces to be soldered, and bond strength. Depending on the substitute solder and the particular application for which it is used, the soldering characteristics may be enhanced or diminished. The advantages and disadvantages of the common specialty alloy families are presented in Table 27.

The trend of the printed circuit board industry toward surface mounted components will probably increase the use of indium and bismuth alloys due to their low melting point and superior thermal fatigue resistance to slow-cycle fatigue. These qualities are important for manufacturing surface mounted circuit boards because of the stresses induced by the small size of the bonds and the large coefficients of thermal expansion (Manko 1988, Keeler 1987).

Other alloy families may also be used for soldering surface mounted components. The choice of solder depends primarily on the material compatibility with components, melting temperature, strength, and cost (IPC 1989c, Alpha Metals 1989). Because the variety of custom compositions is extensive, it is not possible to describe the soldering characteristics of all alternative solders. Instead, some of the most important general attributes of each alternative solder family are discussed below.

Table 27. Advantages and Disadvantages of Potential Substitute Solders for Consumer Electronic Applications

Solder Alloy Family	Advantages	Disadvantages
Bismuth/Tin	● Well-suited to the new surface mount assembly technology	● May have unacceptably low melting temperatures for use in consumer electronics applications ● Higher cost than tin/lead solder
Tin/Silver	● Can be used to solder silver-plated base metal without significantly solubilizing the silver	● Less ductile than indium and bismuth solder alloys ● Higher cost than tin/lead solder
Indium/Tin	● Well suited to the new surface mount assembly technology ● Compatible with gold and other precious metals	● Low melting point may not be suitable for high temperature applications ● As much as 20 times the cost of tin/lead solder
Indium/Silver	● Well suited to the new surface mount assembly technology ● Compatible with gold and other precious metals	● Low melting point may be not suitable for high temperature applications ● As much as 20 times the cost of tin/lead solder

Sources: ADL 1990, IPC 1989c, Manko 1979, Keeler 1987, Indium 1989e.

a. Indium Alloys

Indium alloys are one of the most important potential substitutes for tin/lead solder used in printed circuit board manufacturing. Unlike tin, indium is compatible with gold and other precious metals (Keeler 1987). Most indium alloy solder is used to solder gold or gold-plated parts (Indium 1989b). Also, indium alloys do not require radically different soldering temperatures; in comparison to the tin/lead alloy family, many indium alloys melt at a lower or equivalent temperature (see Figure 2).

The low melting temperature of indium alloys not only reduces thermal shock to electrical components, it also imparts ductility to a solder joint so it will not crack (Keeler 1987). Mismatched coefficients of expansion between the circuit board and the electrical components can create serious stress problems (especially with surface mount technology) (Manko 1986). The ductility of indium solders not only relieves this thermal stress, it also helps the solder bonds to withstand excessive vibration (Keeler 1987). On the other hand, the high operating temperature of many consumer products combined with this low melting temperature may make indium solder unsuitable for some applications (ADL 1990).

b. Bismuth Alloys

Bismuth alloys melt from 300°F down to 100°F -- well below the boiling point of water (Manko 1979). Extremely low temperature solders are not used in consumer electronics because such products may endure high heat levels during use (Kapp 1989, Indium 1989e). Bismuth alloys with relatively high melting temperatures, however, can be used with success (Manko 1979, IPC 1989c). Because all bismuth alloys melt at a relatively low temperature compared to other soldering alloys (see Figure 2), bismuth solder
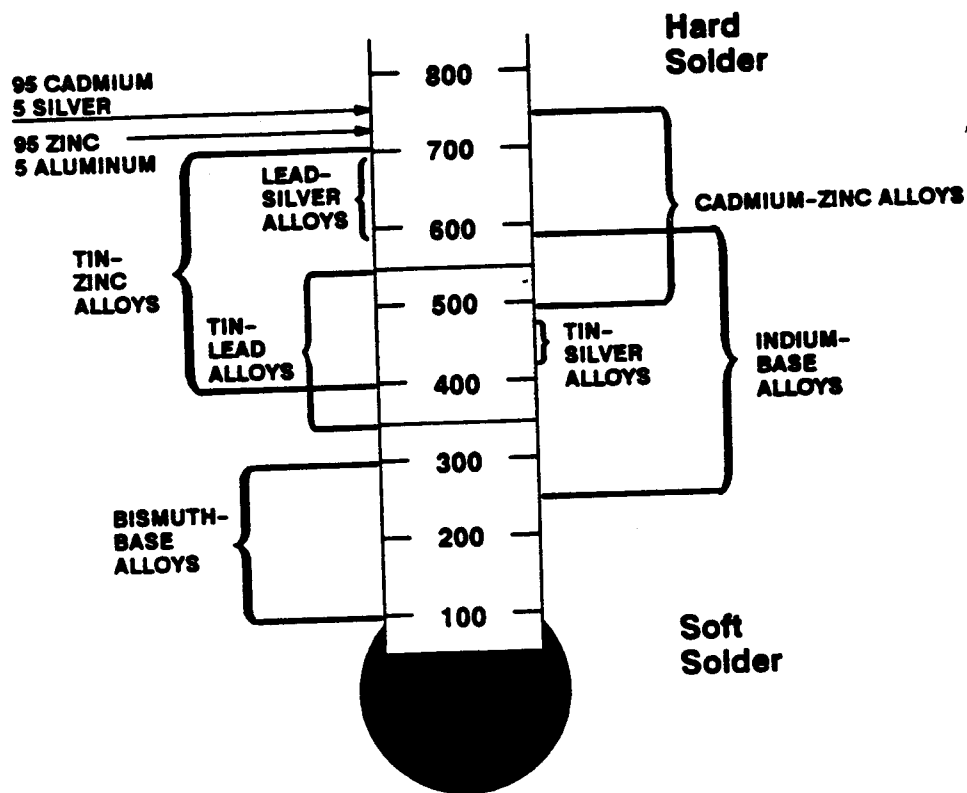
Figure 2. Melting Temperatures of Common Soldering Alloys (°F). (Adapted from Manko 1979.)

can be used to rework or repair solder joints without melting surrounding solder bonds. Bismuth also tends to improve the wetting ability of solder (Manko 1979).

c. Tin/Silver Alloys

Because tin/lead solder can easily dissolve silver off a part during soldering due to the solubility of silver in tin, alternative solder alloys are useful for soldering silver-plated electrical contacts. While the use of alloys containing little tin seems to be a logical solution, such alloys generally melt at high temperatures and have poor wetting characteristics. Because the solubility of silver in tin increases with an increase in temperature, one might try a low melting alloy. With the exception of the very low temperature bismuth alloys, however, most low temperature solder alloys are rich in tin. Therefore, the most satisfactory solution to soldering silver-plated parts is to use solder that already contains silver to decrease the solubility of the silver plating in the tin component of the solder. Tin/silver alloys are a good alternative for soldering silver-plated electrical contacts. This type of alloy generally contains little silver due to the expense of silver (Manko 1979).

d. Other Considerations

The soldering method used has a bearing on the type of alloy a manufacturer can use. Wave soldering machines must use eutectic or near-eutectic solders (Berke 1989a). Most wave soldering machines can be adjusted to use substitute solders of eutectic or near-eutectic composition. The majority of printed circuit boards manufactured today are wave soldered (Indium 1989d).

An increasing number of circuit boards employ surface mount technology. In this process, printed circuit boards are manufactured through the use of a

reflow soldering process. This process requires solder paste/cream (lead-containing or non-lead-containing solders can be employed) that does not need to be a eutectic composition. Approximately 30 percent of the printed circuit boards manufactured today employ surface mount assembly technology (IPC 1989c).

The suitability of a soldering alloy for a particular application must be determined on a case-by-case basis. Although history of other applications can be used as a guideline, there are no scientific rules to predetermine the wetting ability of solder on the materials to be soldered (Manko 1979).

e. Cost of Substitute Solders

The main determinant of solder cost is the cost of the metals that compose the solder. The cost of the metals used in the consumer electronics substitute solder alloy families listed in Table 27 are as follows:

- indium $180/lb.
- silver $89/lb.
- bismuth $6.40/lb.
- tin $4.10/lb.

Even a small difference in price between solders can have a large impact on the consumer when a large purchase is made (Indium 1989e). The cost for the metals used in the eutectic compositions of the solder alloy families listed in Table 27 are as follows:

- 52 indium/48 tin $96.05/lb.
- 97 indium/3 silver $177.28/lb.
- 58 bismuth/42 tin $5.85/lb.
- 96.5 tin/3.5 silver $8.04/lb.

Because of the expense of indium solders, they are not commonly used (Indium 1989e). The main reason for the use of indium solder is to bond precious metal contacts such as gold (unlike tin, indium will not solubilize precious metals) (Indium 1989b). Bismuth/tin and tin/silver alloys are commonly used

for electronics, but many variations in the component metals and their composition may be used to solder consumer electronics depending on the particular application. The solder compositions discussed here should serve only as an initial guide to determining suitable substitutes for lead-containing solder used in consumer electronics.

While solder prices depend primarily on the cost of the constituent metals, the solder form* also has a bearing on cost. Simple solder forms, such as ingots, are relatively cheap to produce compared to specialized forms such as solder tubing. The manufacturing cost for ingots is approximately $4.00 per pound (Federated 1989b). Because the ease that a solder may be formed depends on its composition, the price of different types of solder is not proportional across the range of available forms (Indium 1989c). In general, however, the cost of bismuth/tin and tin/silver alloys is approximately the same as the cost of tin/lead alloys, while indium alloys cost up to 20 times as much as tin/lead alloys (Talco 1989, Indium 1989e). Eutectic tin/lead alloy (the commonly used composition of 63 percent tin and 37 percent lead) costs $3.75 per pound in ingot form (Talco 1989).

2.   Potential Substitutes for Lead-containing Solder in Cans.

Soldering is a metallurgical bonding process in which metallic continuity from one metal to another is established. Brazing and welding, two other common metallurgical joining processes, can also create metallic continuity between metals. Although these substitute processes are not appropriate joining methods for the printed circuit board applications where the majority of solder is used, welding is commonly used in the manufacture of cans (CMI 1989a). The crimping and drawing process also accounts for a large

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    * Some common solder forms are wire, paste, and ingot.

portion of can manufacturing. The common substitutes used to eliminate tin/lead solder in cans (see Table 28) are discussed below.

a. Welding and Brazing

Welding is defined as a metallurgical joining process that relies on the diffusion of the base metals with or without filler metal for joint formation (Manko 1979). Welding is the most commonly used substitute process for soldering (NFPA 1989c).

The welding process requires the use of copper electrodes to produce smooth seams with no impurities. Both the welding and soldering processes are used to produce three piece cans (CMI 1989a).

b. Drawing and Crimping

As explained previously in this chapter, cans may be categorized as two piece or three piece cans. Virtually all beverage cans are now two piece cans, although beverages were packaged in soldered three piece cans in the past (CMI 1989a).

The technology used to produce all two piece cans is drawing and crimping. This process entails drawing sheet metal into a cup shape, and then attaching a metal lid on top of the cup by squeezing a folded seam between the cup and lid. Beverage cans constitute the majority of cans produced in the U.S. (CMI 1989a, 1989b).

c. Substitute Solders

Some food and non-food products are still produced in solder-containing three piece cans, but almost no solder used in domestic can

Table 28. Advantages and Disadvantages of Substitute Processes
and Solders for Consumer Can Applications

Process or Solder	Advantages	Disadvantages
Crimping	● Eliminates the need for solder	● None identified
Welding	● Eliminates the need for solder	● None identified
Tin Solder	● Eliminates the possibility of lead leaching into canned food products[a] ● May be used in non-food cans	● Tin solder is more expensive than tin/lead solder

Note: The costs associated with crimping and welding of cans are comparable to
the costs associated with soldering.

[a] Domestic soldered food cans for dried food such as coffee may contain lead
in the solder. Dried food, however, does not leach the solder into the food
product. Some imported food cans for foods packed in juice (such as
grapefruit sections) may employ lead-containing solder.

Sources: Karmal 1989a, 1989b; Elkins 1989b.

manufacturing contains lead (NFPA 1989b, CMI 1989b).* Some dry food products such as coffee may still be packaged in cans soldered with relatively cheap lead solder because there is no danger of lead leaching into the food product. Imported food cans also may contain lead solder. The substitute solder used by domestic manufacturers is plain tin solder (NFPA 1989b). The quality of the joints produced with tin solder is equal to those produced with tin/lead solder, but pure tin solder is more expensive than tin/lead solder (NFPA 1989b).

3. Potential Substitutes for Lead-containing Solder in Light Bulbs

Lead/tin solder is used in light bulb manufacturing because it is low cost, works fast, and bonds materials aggressively. Some substitute materials, however, are available (see Table 29).

Relatively expensive indium solder could be used instead of lead/tin solder, but it tends to oxidize easily during the light bulb soldering process. (The final step is to heat the solder with torch flame so that the solder will spread over the base of the bulb.) Oxidation of indium solder could be prevented by flowing nitrogen over the molten solder (to displace the oxygen in the air) or by soldering in a vacuum. Both measures will increase the cost of the soldering process. Tin/zinc solder could also be used, but it needs to be tested for this application (Sylvania 1989a). Tin/zinc solder does not flow as well as tin/lead solder (Kapp 1989).

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* Approximately 3 percent of food cans for dried food contain lead alloy solders. No beverage cans contain lead alloy solders. Although data is not available for general packaging cans, this type of can represented only 5 percent of total can manufacturing in 1988 (food and beverage cans represented 95 percent) (CMI 1989a).

Table 29. Advantages and Disadvantages of Potential
Substitute Solders for Light Bulb Applications

Substitute Solder	Advantages	Disadvantages
Indium-Based Solder	● Does not contain lead	● More expensive than tin/lead solder
		● Oxidizes when used in the light bulb manufacturing process
Tin/Zinc	● Does not contain lead	● Does not flow as well as tin/lead solder

Sources: Sylvania 1989a, 1989b; Kapp 1989.

4. Future Trends and Developments

Conductive adhesives are a potential future substitute for tin/lead solder used in electrical applications such as consumer electronics and light bulbs. The use of conductive adhesives would eliminate the need for fluxing and post-soldering flux cleaning (Locktite 1989b). However, several problems currently prohibit the widespread use of conductive adhesives.

Most conductive adhesives are silver-filled to achieve the desired level of conductivity. Even though conductive adhesives usually consist of more than 50 percent silver (compared to only a few percent silver contained in tin/silver solder), they still do not conduct as well as solders (Locktite 1989a, 1989b). Furthermore, the high silver content means the price of conductive adhesives is high relative to solders (Locktite 1989b). The high cost may be somewhat mitigated by the elimination of flux and flux cleaning costs.

Conductive adhesives are currently used in some instances where the surface of a part may not be conductive to solder bonding or where solder may be too brittle for the application (Locktite 1989b). The wholesale replacement of tin/lead solder with conductive adhesives, however, is not currently considered a realistic option (IPC 1989c).

Some research is also being done on conductive polymers. This potential substitute is in early development stages and little information is available regarding performance (Locktite 1989b).

E. <u>References</u>

ADL. 1990 (November 15) Lead Use and Substitutes. Report to Lead Industries Association. Prepared by Arthur D. Little, Inc., Cambridge, MA.

Arconium. Undated. Arconium, 400 Harris Avenue, Providence, RI. "Arconium Specialty Alloys."

Arconium. 1989 (July 24). J. Hamilton, Sales Representative. Providence, RI. Transcribed telephone conversation with Thomas Hok, ICF Incorporated, Fairfax, VA.

Alpha Metals. 1989 (July 14). S. Arora. Senior Chemist. Jersey City, NJ. Transcribed telephone conversation with Thomas Hok, ICF Incorporated, Fairfax, VA.

Bannos, T.S. 1988 (October). "Lead-Free Solder to Meet New Safe Drinking Water Regulations." <u>Welding Journal</u>, Vol. 67, pp. 23-26.

Belser, R.B. 1954. "Indium -- A Versatile Solder to Metals and Non-metals," found in <u>Intermediate Indalloy Solders</u>, published by the Indium Corporation of America, Utica, NY.

CMI. 1989a (June 1). Can Manufacturers Institute. D. Karmal, Counsel. Washington, DC. Transcribed telephone conversation with Thomas R. Hok, ICF Incorporated, Fairfax, VA.

CMI. 1989b (July 28). Can Manufacturers Institute. D. Karmal, Counsel. Washington, DC. Transcribed telephone conversation with Thomas R. Hok, ICF Incorporated, Fairfax, VA.

EPA. 1989 (January). U.S. Environmental Protection Agency. Characteristics of Products Containing Lead and Cadmium in Municipal Solid Waste Facilities 1970 to 2000. Prepared by Franklin Associates, LTD. Prairie Village, KS.

Federated-Fry Metals. 1989a (July 20). W. Hockenberry. Sales. Altoona, PA. Transcribed telephone conversation with Thomas Hok, ICF Incorporated, Fairfax, VA.

Federated-Fry Metals. 1989b (August 15). W. Hockenberry. Sales. Altoona, PA. Transcribed telephone conversation with Thomas Hok, ICF Incorporated, Fairfax, VA.

FPMSA. 1989 (July 28). Food Processing Machinery and Supplies Association. L. Herbert. Executive Vice President. Alexandria, VA. Transcribed telephone conversation with Thomas Hok, ICF Incorporated, Fairfax, VA.

Hollis Automation. 1989a (July 18). E. Berke. Marketing Services Supervisor. Nashua, NH. Transcribed telephone conversation with Thomas R. Hok, ICF Incorporated, Fairfax, VA.

Hollis Automation. 1989b (July 28). E. Berke. Marketing Services Supervisor. Nashua, NH. Transcribed telephone conversation with Thomas R. Hok, ICF Incorporated, Fairfax, VA.

Indium Corporation of America. 1988. Indium Corporation of America, 1676 Lincoln Avenue, Utica, NY. "Indalloy® Specialty Solders & Alloys."

Indium Corporation of America. 1989a (July 19). M. DeMarco, Sales Representative, Utica, NY. Transcribed telephone conversation with Thomas Hok, ICF Incorporated, Fairfax, VA.

Indium Corporation of America. 1989b (July 19). R. Altieri. Applications and Engineering. Utica, NY. Transcribed telephone conversation with Thomas Hok, ICF Incorporated, Fairfax, VA.

Indium Corporation of America. 1989c (July 20). M. DeMarco, Sales Representative, Utica, NY. Transcribed telephone conversation with Thomas Hok, ICF Incorporated, Fairfax, VA.

Indium Corporation of America. 1989d (July 28). R. Altieri. Applications and Engineering. Utica, NY. Transcribed telephone conversation with Thomas Hok, ICF Incorporated, Fairfax, VA.

Indium Corporation of America. 1989e (August 15). J. Ferriter. Applications and Engineering. Utica, NY. Transcribed telephone conversation with Thomas Hok, ICF Incorporated, Fairfax, VA.

IPC. 1989a (May 31). Institute of Printed Circuits. D. Bergman. Chicago, IL. Transcribed telephone conversation with Thomas Hok, ICF Incorporated, Fairfax, VA.

IPC. 1989b (July 20). Institute of Printed Circuits. D. Bergman. Chicago, IL. Transcribed telephone conversation with Thomas Hok, ICF Incorporated, Fairfax, VA.

IPC. 1989c (July 28). Institute of Printed Circuits. D. Bergman. Chicago, IL. Transcribed telephone conversation with Thomas Hok, ICF Incorporated, Fairfax, VA.

Kapp Alloy and Wire, Inc. 1989 (July 19). D. Porter, Technical Director. Altoona, PA. Transcribed telephone conversation with Thomas Hok, ICF Incorporated, Fairfax, VA.

Keeler, R. 1987 (July). "Specialty Solders Outshine Tin/Lead in Problem Areas." Electronic Packaging and Production, pp. 45-47.

Locktite Corporation. 1989a (May 31). R. Thompson. Newington, CT. Transcribed telephone conversation with Thomas Hok, ICF Incorporated, Fairfax, VA.

Locktite Corporation. 1989a (July 28). J. Jesowski. Commercial Development Specialist, Newington, CT. Transcribed telephone conversation Thomas Hok, ICF Incorporated, Fairfax, VA.

Manko, H.H. 1979. <u>Solders and Soldering</u>. Published by McGraw-Hill Book Company, New York, NY. Second edition.

Manko, H.H. 1986. <u>Soldering Handbook for Printed Circuits and Surface Mounting</u>. Published by Van Nostrand Reinhold Company, New York, NY.

Mullen, J. 1984. "How to Use Surface Mount Technology." Texas Instruments Publishing Center, Dallas, TX.

NAPHCC. 1989 (August 10). National Association of Plumbing-Heating-Cooling Contractors, R. Warren, Technical Director. Falls Church, VA. Transcribed telephone conversation with Thomas Hok, ICF Incorporated, Fairfax, VA.

NFPA. 1989a (June 1). National Food Processors Association. E. Elkins. Washington, DC. Transcribed telephone conversation with Thomas Hok, ICF Incorporated, Fairfax, VA.

NFPA. 1989b (July 31). National Food Processors Association. E. Elkins. Washington, DC. Transcribed telephone conversation with Thomas Hok, ICF Incorporated, Fairfax, VA.

NFPA. 1989c (August 15). National Food Processors Association. E. Elkins. Washington, DC. Transcribed telephone conversation with Thomas Hok, ICF Incorporated, Fairfax, VA.

PDI. 1989 (August 10). Plumbing and Drainage Institute. S. Baker, Executive Secretary. Indianapolis, IN. Transcribed telephone conversation with Thomas Hok, ICF Incorporated, Fairfax, VA.

Sylvania and Laxman, Limited. 1989a (July 18). R. Marlor, Manager, Glass and Ceramics. Salem, MA. Transcribed telephone conversation with Thomas Hok, ICF Incorporated, Fairfax, VA.

Sylvania and Laxman, Limited. 1989b (July 28). R. Marlor, Manager, Glass and Ceramics. Salem, MA. Transcribed telephone conversation with Thomas Hok, ICF Incorporated, Fairfax, VA.

Sylvania and Laxman, Limited. 1989c (August 30). W. Roach. Engineer, Fluorescent Bulb Plant. Danvers, MA. Transcribed telephone conversation with Louis Gardner, ICF Incorporated, Fairfax, VA.

Talco Metals. 1989 (July 18). C. Carabello, Sales Representative. Philadelphia, PA. Transcribed telephone conversation with Thomas R. Hok, ICF Incorporated, Fairfax, VA.

Warwick, M.E. 1985 (Spring). "The Wetting and Mechanical Properties of Lead-free Capillary Plumbing Solders." <u>Brazing and Soldering</u>, No. 8.

V. LEAD-ACID BATTERIES

Lead-acid batteries are currently the most commonly used type of rechargeable battery. These batteries are used for starting, ignition, and lighting in virtually all motorized vehicles, and are used in other applications where rechargeable portable power is desired (e.g., consumer electronics such as power tools). The drawback of lead-acid batteries is the emission of lead and sulfuric acid when these batteries are disposed. Lead-acid batteries continue to be widely used because based on performance, cost, and toxicity of potential alternatives, there are currently no acceptable substitutes. The discussion presented below outlines the disadvantages of the potential substitutes that have been considered[*].

Nickel-zinc batteries have a lower power density[**] than lead-acid batteries, a limited lifetime (50 to 200 recharging cycles), and relatively poor reliability. Nickel-zinc batteries are two to three times the cost of an equivalent sized lead-acid battery (Palmer 1988).

The power density of nickel-iron batteries is only one fourth to one third that of lead-acid batteries, and they have very poor low temperature performance and charge retention (Palmer 1988).

Silver-zinc batteries are very expensive -- 20 to 100 times the cost of an equivalent sized lead-acid battery. These batteries also have a limited

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[*] Nickel-cadmium batteries are not considered as substitutes because of the scope of this study but even they do not match lead-acid batteries in performance. Nickel cadmium batteries are five to ten times the cost of an equivalent sized lead-acid battery. The power density of nickel-batteries is 20 to 30 percent lower than lead-acid batteries so that the cost of delivered power per unit cost is 6.67 to 13.33 times more expensive, assuming equal service lives (Palmer 1988).

[**] The power density of a battery is the amount of power the battery can produce relative to its weight.

lifetime (approximately 250 cycles) and decreased performance at low temperatures (Palmer 1988).

Even future advance secondary battery systems are not promising. Zinc-chlorine batteries involve the danger of chlorine leakage and require complex plumbing and refrigeration. Zinc-bromine batteries present safety problems when used for automobile ignition applications, and are also bulky. Aqueous redox flow cells are only being considered for power storage or standby power, while conductive polymer batteries have low power density and very poor performance at temperature extremes. Secondary metal-air batteries have low energy density and may be unstable. Finally, lithium metal-sulfide and sodium-sulfur high temperature systems require a high operating temperature and are not suited for power cranking (Palmer 1988).

Reference

Palmer, J.G. 1988 (September). Executive Vice President, Pacific-Dunlop-GNB, Incorporated, St. Paul, MN. "A Cleaner Environment: Removing the Barriers to Lead-Acid Battery Recycling." Written in collaboration with M.L. Sappington, P.E., President, Lake Engineering, Incorporated, Atlanta, GA.

VI. NICKEL-CADMIUM BATTERIES

A. Overview of the Battery Industry

Secondary (rechargeable) battery systems are based primarily on the same chemical principles used in the construction of primary (one charge) batteries. The latter are sometimes called "fuel" cells, because the active chemicals are consumed in an irreversible reaction. Both types of cells are based on the difference in electrochemical potential between the anode and cathode of the cell, which are generally metal plates. This potential is the driving force that provides the energy to force electrons through the load. When the difference in potential between the anode and cathode is reduced sufficiently, there is insufficient energy to overcome the resistance of the load, and the battery ceases to function. With primary cells, the battery must be discarded at this point, because the electrochemical reaction cannot be reversed sufficiently to derive a reasonable performance after charging (Kirk-Othmer 1978).

The main difference between a primary and secondary cell is in the nature of the active substances; a secondary battery may be recharged because it is based on a highly reversible reaction. This allows the battery to be discharged and then recharged multiple times. A discharge and charge bring the battery back to its original state, and this pair of actions is called a cycle. The active substances in a primary battery cannot be recharged.

However, even after charging secondary batteries, the materials do not return exactly to their previous (charged) state, and therefore, a secondary battery may be put through only a limited number of cycles. Eventually the battery's efficiency deteriorates (measured by the battery's output during discharge relative to the energy input during charging) and may drop to an

unacceptable level, or the battery may fail to charge altogether (Kirk-Othmer 1978, Moli Energy 1989).

The most common type of secondary battery currently in use is the lead-acid battery, which is used for starting and ignition in virtually all motorized vehicles. Sealed lead acid batteries are also quite common and are found in home security and emergency power systems, as well as in consumer electronics (VCR's, home computers, camcorders), power tools, toys, and other applications where portable power is desired.

B. Nickel-cadmium Batteries

Another type of secondary battery which finds widespread use in consumer applications is the rechargeable nickel-cadmium (Ni-Cd) battery. It is found in many of the same applications as the sealed lead-acid battery and may be used in many applications for which the lead-acid is too large. In addition, Ni-Cd batteries are also frequently substituted for primary batteries, in applications such as personal tape players, where frequent use and high discharge rates can result in unacceptably high battery costs.

Ni-Cd batteries are often integrated into an appliance or toy with a dedicated charger. In such cases, the battery often cannot be removed by the user and cannot be changed except at an authorized service center for the product. Because Ni-Cd batteries may last for over 1000 cycles in some instances, the battery may outlast the useful life of the product. Such applications (cordless hand vacuums, electric shavers, power tools, etc.) constitute a large segment of the demand for Ni-Cd batteries.

The other major consumer application of nickel-cadmium batteries is as a substitute for primary batteries such as the common carbon-zinc battery and the alkaline battery. As mentioned before, Ni-Cd batteries are most cost-effective in applications which consume large amounts of power, such as

- 84 -

portable stereos and photographic strobes, rather than for applications such as electric quartz clocks, which generally require only a single alkaline cell each year.

As the popularity of laptop computers, portable video equipment, cellular phones, and other portable electronic devices increases, the demand for rechargeable power sources also will increase. Given Ni-Cd batteries' long cycle life (on the order of 1000 charge-discharge cycles versus 200 for sealed lead acid batteries), moderately high charge capacity,* availability in many popular sizes, low cost (roughly ten times the cost of carbon-zinc batteries, but with more than 100 times the lifetime of carbon-zinc batteries), and resistance to abuse (overcharge and deep discharge) make them ideal for consumer applications.

The only drawback to Ni-Cd cells is concern about the toxicity of the cadmium in the batteries, which eventually ends up in the waste stream. Sealed lead-acid batteries, although currently commonly available, would not be an acceptable alternative, because of similar concerns over lead in the waste stream. Fortunately however, there are other battery systems which, although currently not suitable for consumer applications, may eventually be developed sufficiently for such uses. These battery systems are discussed below in Section D.

C. Consumption of Cadmium in Nickel-cadmium Batteries

The amount of cadmium discarded in Ni-Cd batteries is presented in Table 30. As the table indicates, there has been an increase in total cadmium discards by a factor of 18 in the period 1970 to 1986. This is due in

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* Charge capacity is defined as the maximum charge that a battery will hold. The charge capacity decreases as the number of cycles through which the battery has passed increases (Moli Energy 1989).

Table 30. Discards of Cadmium in Nickel-cadmium Batteries in MSW

Year	Cadmium in Discards of Batteries in First Year[a] (tons)	Cadmium in Discards of Batteries in Fourth Year[b] (tons)	Total Cadmium Discarded (tons)
1970	17	34	51
1975	33	176	209
1980	79	917	996
1986	127	800	927

[a] Approximately half of all loose Ni-Cd batteries (20 percent of all Ni-Cd Batteries are loose) are assumed to be discarded the same year by the consumer.

[b] The remaining loose batteries and all batteries sealed within products (appliances, toys, etc.) are assumed to be discarded after four years. These constitute 90 percent of all Ni-Cd batteries.

Source: EPA 1989.

large part to the increase in demand for the use of Ni-Cd batteries in portable consumer electronic equipment and in rechargeable throw-away devices such as toys, hand-held power-vacuums, and other such items.

D. Potential Substitutes for Nickel-cadmium Batteries

There are a wide range of potential substitutes for nickel-cadmium batteries, including:

- lithium secondary batteries;
- silver-zinc batteries;
- nickel-zinc batteries;
- nickel-hydrogen batteries; and
- primary batteries.

With the exception of primary batteries, however, none of these potential substitutes has seen much, if any, commercial use in consumer products because of technical complications, reduced service life, and high cost.

1. Lithium Secondary Batteries

One of the more promising technologies is the rechargeable lithium cell, which is already used to a very limited extent in some consumer applications. Lithium cells are manufactured with a variety of materials, and include lithium-air batteries that allow air to circulate freely in the cell. According to one supplier, rechargeable lithium batteries have greater charge capacity than Ni-Cd batteries of a comparable size (SAFT 1989a). There are currently many limitations, however, to their use. Lithium batteries are currently much more expensive (at least twice the cost) of Ni-Cd batteries. Their cycle life is only 200-400 cycles, versus 1000 or more for Ni-Cd batteries, and in addition, they are less tolerant to abuse. Finally, large cells are not yet available, although there is work currently being funded to investigate and produce lithium cells for military applications such as communications equipment (Yardney 1989b). Although lithium cells cannot be used to power electric cars (normally powered by lead-acid batteries), there

is a possibility that lithium cells could be used for this application in the future (SAFT 1989c).

It is simple enough to add circuitry to the recharging equipment to prevent overcharge, although it would further increase the cost of using lithium batteries. Circuitry to prevent a deep discharge also is required in the equipment in which the batteries are used, which precludes their use in many applications in which Ni-Cds are currently found, and may make the cost of any product extremely high (SAFT 1989a). Because of these limitations, it is likely that lithium rechargeable batteries will be found only in applications where the higher cost of the batteries and controlling circuitry are not an obstacle, such as in computers. In such applications, the cost of the battery system and controlling circuitry is not large relative to the overall cost of the product (Yardney 1989b).

Advantages of lithium rechargeable batteries include their light weight, ability to provide energy in freezing temperatures, and very high efficiency (Chemical Business 1989, SAFT 1989c). Possible applications for lithium batteries include portable cellular phones, lap-top computers, portable radios, and military applications (Moli Energy 1989).

2. Silver-zinc Batteries

Another battery technology currently in use is the silver-zinc system, which is used primarily (90% of the time) for military and space applications and has a high energy density (Kirk-Othmer 1978, SAFT 1989c). However, there are many limitations which may restrict its use in consumer applications such as the high cost of such batteries. According to one supplier, silver-zinc batteries cost about five times more than similar nickel-cadmium batteries (Yardney 1989a). This high cost is due in part to the cost of the silver, a precious metal. Because of the value of silver,

expended batteries would probably be recycled to recover the metal. Recycling could allow for some recovery of the initial cost of purchase (Yardney 1989a).

Another obstacle to widespread use of silver-zinc batteries is their rather limited service life; silver-zinc batteries typically last 100-200 cycles and have about a 2-year wet life (the wet life is the amount of time it takes for the cell to degrade without cycling). Because of these limitations, it is highly unlikely that silver-zinc batteries could ever succeed as a substitute for the Ni-Cd system except in the very short term and for applications where cost is no object (Yardney 1989b).

3. Nickel-zinc Batteries

One battery system which generated a good deal of interest during the early and mid-1970s was the nickel-zinc cell. It potentially offers a charge density greater than that available from nickel-cadmium batteries but at a lower cost than silver-zinc. Some research into improving the performance of nickel-zinc batteries was funded by the U.S. government for use in electric vehicles. According to one company involved in that development effort, interest in electric vehicles waned; although attempts were made to continue the study, the funds were no longer available and the research was essentially stopped (Yardney 1989a). Although these previous studies focused on large batteries such as might be found in electric vehicles, future development might focus on smaller cells if such a demand arose.

A primary advantage of a nickel-zinc system over the silver-zinc battery is the cost. Although its performance is not as high as its silver-based counterpart, it is also not subject to the wide fluctuations in price resulting from speculation in markets for precious metals such as silver. In spite of this, the price is currently quite high due to the developmental nature of the Ni-Zn batteries produced thus far. Although nickel-zinc

batteries may be recycled, the metal recovery may not by worth the cost (SAFT 1989c). However, even if the cost of new cells is brought down, a major limitation in nickel-zinc cells is their short life. Capacity of the battery drops rapidly with multiple cycles. The cell can be periodically "conditioned" by fully discharging the zinc electrode, which restores some of the original capacity. After about 100 cycles, however, the cell can only reach about two-thirds of its original capacity, even after conditioning. Due to its initially higher charge density (relative to a nickel-cadmium cell), such a loss of capacity still might provide acceptable performance if the cell is conservatively rated. Further research in this area may alleviate some of these limitations and reduce production costs (Yardney 1989b).

4. Nickel-hydrogen Batteries

Another high technology battery system which currently is found only in very exotic applications is the nickel-hydrogen cell. Its gravimetric charge density* is slightly higher than that of a nickel-cadmium cell and the service life is somewhat longer (Kirk-Othmer 1978). The cycle life of the cell is also about double (1,500-2,000 cycles) that of a Ni-Cd system (Yardney 1989a). For these reasons, nickel-hydrogen cells were originally developed for satellite applications, where this combination of characteristics is advantageous. However, the hydrogen in the cell is in the gaseous form, and the operating pressure is much higher, ranging from 3-20 times atmospheric pressure, as compared to 0-3 atmospheres for a Ni-Cd cell. Because of these high operating pressures, construction is labor-intensive and very expensive. Unless significant breakthroughs are made in reducing the cost of

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* The gravimetric charge density is the charge density per unit of weight, as opposed to unit of volume.

construction, the nickel-hydrogen system is likely to be found only in very specialized applications (Yardney 1989a).

5. Primary Batteries

Primary batteries are available in a variety of configurations. The common carbon-zinc battery has been replaced by the alkaline battery as the dominant commercially available primary cell (Chemical Business 1989). Other types of primary batteries include lithium batteries and mercury batteries (Panasonic undated).

Primary lithium batteries last up to five times as long as carbon-zinc batteries (Chemical Business 1989). They have a very long life and are often used in watches and cameras. Primary mercury batteries have a compact size, long shelf life, and excellent voltage stability. Mercury batteries are often used in watches, calculators, cameras, and hearing aids (Panasonic undated).

While primary batteries do not contain cadmium, constant replacement may be expensive in applications involving high discharge rates.

E. Limitations on Substitution

The alternative secondary battery systems listed all have significant limitations when compared to the Ni-Cd system. In addition, many of these technologies are currently in an embryonic stage of development and their costs are quite high. As experimentation and development proceeds, the limitations as well as the costs of these potential substitute products may be reduced.

In general, nickel-cadmium batteries have performance characteristics which make them difficult to replace in consumer applications. These are as follows:

- A long cycle life that allows Ni-Cd batteries to be installed in products where the batteries are not readily accessible to the consumer. A cordless product can then be made that requires little attention on the part of the user.

- The charge density is comparable to that of many primary cells. The higher capacity of these products is an advantage in some applications.

- Ni-Cd batteries are relatively forgiving of misuse. Slight overcharging does not seriously damage their performance, and deep discharge is acceptable except when several batteries are arranged in series.

- Ni-Cd batteries cost significantly less than other rechargeable batteries currently available, with the exception of lead-acid systems which are not considered to be substitutes due to the scope of this report.

Some of the alternative battery technologies discussed in this chapter offer the potential for better performance than Ni-Cd batteries in one or more aspects (see Table 31). Unfortunately, cost information on possible substitute consumer products is not available at this time because of the experimental nature of potential substitute technologies. With sufficient research and development, however, it is not unreasonable to hope that some of these technologies (particularly lithium and nickel-zinc cells) can be improved sufficiently to eventually compare with nickel-cadmium batteries.

The solid performance and low cost of nickel-cadmium batteries make it unlikely that there will be replacements in the near future. In fact, according to one industry contact (SAFT 1989b), if both Ni-Cd and lead-acid batteries were eliminated immediately, substitute rechargeable batteries would not be available in the short run due to cost and performance limitations. This source expressed the belief, however, that there is enough interest in rechargeable batteries to develop alternate systems over time.

Table 31. Advantages and Disadvantages of Substitutes
for Nickel-cadmium Batteries

Substitute Battery	Advantages	Disadvantages
Lithium Battery	• Very light weight • Provide energy in freezing temperatures • Very efficient	• Over twice the cost of nickel-cadmium batteries • Less than half the lifetime of a nickel-cadmium battery • Sensitive to abuse (overcharging and deep discharging)
Silver-zinc Battery	• Very high energy density	• Five times the cost of nickel-cadmium batteries • Less than one-fifth the lifetime of a nickel-cadmium battery
Nickel-zinc Battery	• Relatively high energy density	• High cost • Less than one-tenth the lifetime of a nickel-cadmium battery
Nickel-hydrogen Battery	• Twice the cycle life of a nickel-cadmium battery	• More expensive than a nickel-cadmium battery due to high atmospheric pressure required in the cell
Primary Battery (alkaline, lithium, and carbon-zinc)		• Replacement costs may be substantial in high discharge applications

Sources: Yardney 1989a, 1989b, SAFT 1989a, Chemical Business 1989.

- 93 -

F. References

Chemical Business. 1989 (July/August). "The Assault on Batteries," p. 35-36.

Kirk-Othmer. 1978. Encyclopedia of Chemical Technology. John Wiley and Sons Publishing Co., Inc. Vol. 3, pp. 569-639.

Moli Energy. 1989 (January). Product literature on Molicel Lithium batteries.

EPA. 1989 (January). U.S. Environmental Protection Agency. Characterization of Products Containing Lead and Cadmium in Municipal Solid Waste Facilities 1970 to 2000. Prepared by Franklin Associates Ltd., Prairie Village, KS.

Panasonic. Undated. "Batteries," a publication of Panasonic, Secaucus, NJ.

SAFT America. 1989a (July 14). G. Lupul. Maryland. Transcribed telephone conversation with Donald Yee, ICF Incorporated, Fairfax, VA.

SAFT America. 1989b (July 17). R. Vikmund. Valdosta, GA. Transcribed telephone conversation with Donald Yee, ICF Incorporated, Fairfax, VA.

SAFT America. 1989c (August 15). P. Scardaville, Director of Engineering. Valdosta, GA. Transcribed telephone conversation with Alex Greenwood, ICF Incorporated, Fairfax, VA.

Yardney Battery. 1989a (July 13). T. Aretakis. Connecticut. Transcribed telephone conversation with Donald Yee, ICF Incorporated, Fairfax, VA.

Yardney Battery. 1989b (July 20). D. Wissocker. Massachusetts. Transcribed telephone conversation with Donald Yee, ICF Incorporated, Fairfax, VA.

VII. GLASS AND CERAMIC PRODUCTS

A. Overview of Glass/Ceramic Products

Glass is an inorganic, brittle, transparent or translucent material that consists of a mixture of crystalline materials such as silicates, borates, or phosphates combined by melting at high temperatures and then cooling to a rigid condition. Silicates are the main constituent in glass. Silica by itself makes a good glass, but its high melting point (about 1700 C°) and its high viscosity in the liquid state make it difficult to melt and work.

Glass manufacturing begins by mixing and melting the raw materials, such as silicates and limestone. After melting, the molten glass, called metal, is refined, freed of bubbles, and then cooled. Heat treatment follows, and the glass is strengthened.

Ceramics are non-metallic materials such as clay, produced by firing at very high temperatures. Ceramics are usually hard, brittle, and are good electrical and thermal insulators. Ceramic products are often divided into two groups:

- pottery and brick are shaped or formed before high-temperature treatment; and

- glass and cement are shaped afterward.

Glazes and enamels are also used with glass/ceramic products. Enamel or porcelain enamel is a decorative or protective glassy coating which is applied to metal or glass. Glass color enamels are used to decorate and label glass objects. Glaze is a glassy coating applied on ceramics.

B. Uses of Lead and Cadmium in Glass/Ceramic Products

1. Use of Lead in Glass/Ceramic Products

Lead monoxide often is used as an intermediate or modifier in glass products. As an intermediate, lead monoxide adds to the brilliance of

the glass products, and as a modifier, it lowers the melting temperature, thereby simplifying glass processing. Alkali metal* oxides also are widely used and are inexpensive, but glass produced with these products may require modifications in the manufacturing processes when substituted for lead products and can not fully replace lead in the glass formulation (Nordyke 1984).

Lead-containing glass also can shield high energy radiation and the high refractive index of lead yields excellent properties for optics and for hand-formed art ware. The glass and ceramic use areas identified in the EPA 1989 report are discussed in the following section. In addition, Table 32 lists the special properties that are associated with lead-based glass/ceramic products and specific glass/ceramic products that require these properties.

a. Television and X-ray Shielding Parts

Leaded glass is used in three main parts of television picture tubes: in the neck surrounding the electron gun, in the funnel that provides structural integrity, and in the faceplate or panel used in the television screen. About 2.25, 22.5, and 28.4 percent lead monoxide is used in the faceplate, funnel, and neck, respectively. Lead is used because it absorbs radiation from the electron gun. Linear absorption (or attenuation) coefficients** that increase as lead oxide content increases and the thickness of the absorbing material (in this case, leaded glass) are useful indicators in determining the effectiveness of a compound for absorbing radiation. To achieve a low dosage rate of radiation, a material with a high

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* Alkali metals are metals in Group 1A of the Periodic Table (e.g., lithium, sodium, potassium, etc.).

** The linear absorption coefficient (u) is computed by multiplying the mass absorption coefficient of the compound (in this case, lead oxide) by the density of the absorbing material (Nordyke 1984, Corning 1989d).

Table 32. Properties Lead Imparts to Glass/Ceramic Products

Properties	Associated Glass/Ceramic Products
Low Melting Range	Enamels
Wide Softening Range (Processability)	Fluorescent lighting and neon sign tubing
High Index of Refraction	Optical Glass; Crystalware
Resonance	Crystalware
Radiation Absorption	Leaded glass in televisions and X-ray shielding
Good Electrical Properties	Glazes and Enamels; Neon sign tubing

Source: Nordyke 1984.

linear absorption coefficient, large thickness, or combinations of these factors can be used.

From a design standpoint, the thickness of these television parts tends to be fixed by the strength requirements of the pieces. The faceplate, funnel, and neck are 1.14, 0.25, and 0.25 cm thick, respectively (Nordyke 1984). The Joint Electron Device Engineering Council of the Electronics Industry Association has set the radiation standard at a dose rate of 0.5 mR/h (milliroentgen per hour) measured 5 cm from the tube face (Nordyke 1984). For this dose rate and these thicknesses, linear absorption coefficients are typically 28, 62, and 90, for the faceplate, funnel, and neck, respectively.

As televisions have increased in size, voltage requirements have also increased resulting in pressure on manufacturers to produce television parts with higher radiation absorption characteristics (Nordyke 1984). Manufacturers have typically met this demand by increasing the lead content in some cases by as much as two-fold.

Leaded X-ray shielding glass is found in areas other then televisions including hospitals, nuclear power plants, or any other place where radiation is prevalent; these sources of lead, however, are not expected to contribute to lead discarded in MSW. Lead content varies from 35 to 82 percent lead oxide in X-ray shielding glass in these applications.

b. Fluorescent Tubing and Light Bulbs

Lead is used in the outer envelope of fluorescent lighting and neon sign tubing because of its excellent electrical resistivity properties (high electrical resistance) and because its low melting temperature allows easy processability (Nordyke 1984). It is believed that the lead content in these envelopes is small -- less than 10 percent (Sylvania and Laxman 1989) while the lead content for neon sign tubing is about 30

percent lead oxide (Nordyke 1984). Light bulbs contain leaded glass at a concentration of 20 to 30 percent lead oxide in the flare and exhaust tube, both of which are part of the mount that is at the base of the bulb (EPA 1989). In addition to providing excellent insulation at the base of the bulb, lead is also used because of its ease of processability.

c. Optical and Ophthalmic Glass

Optical leaded glass is found in all types of concave and convex lenses principally because of its high index of refraction.[*] Optical glass can be classified into ophthalmic and non-ophthalmic uses. Ophthalmic glass is used to correct vision deficiencies. About 50 percent of ophthalmic glass is used in single-vision spectacles which have a moderate refraction index of 1.523 and use lime glass rather than leaded glass (Nordyke 1984). The remainder of ophthalmic glass is used in multifocal lenses. Lead oxide makes up 5 to 10 percent of the segment[**] used in multi-focal lenses (Corning 1990) and is used to achieve refraction indexes up to 1.7 (Nordyke 1984).

Non-ophthalmic optical glass includes camera and telescopic lenses, and fiber optics; lead oxide content in these uses ranges from 20 to 30 percent in cameras and telescopes and from 30 to 40 percent for fiber optics (Schotts 1989). Photochromatic glass or glass that changes color when exposed to light uses a marginal amount of lead oxide, typically less than three percent (Corning 1989d).

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[*] The index of refraction can be defined as the ratio of the velocity of light in air to the velocity of light in glass. Generally, as lead content increases so does the refractive index (Nordyke 1984).

[**] The segment is the point of juncture of two lenses, typically making up less than 10 percent of the surface area of bifocal lenses (Schotts 1989).

d. Lead Crystalware

Lead crystal is defined by its lead oxide content but the term lead crystal is not always applied uniformly. Full lead crystal is defined as containing at least 32 percent lead oxide, but glassware with lower percentages of lead oxide, typically about 24 percent, is often sold as lead crystal (BCR 1990). The use of lead crystal can be traced back to ancient Russian glasses of the eleventh century. The chemical composition of modern lead crystalware has not changed appreciably, although improved refractories and melting furnaces, and purity of raw materials have helped to enhance its brilliance, smoothness, resonance, and temperature stability properties (Nordyke 1984).

e. Piezoelectric Ceramics

Combining lead zirconate and lead titanate form the piezoelectric family of ceramic products known as PZT (lead zirconate titanate). Piezoelectricity means "pressure electricity" and with ceramics, PZT can serve as a transducer for electrical and mechanical energy. The use of PZT is found mainly in small appliances such as watch alarms, automobile cigarette lighters, and measurement devices where a small mechanical displacement creates a low voltage. PZT contains about 68 percent lead oxide (Piezo Kinetics 1989). The family of materials designated PZLT for lead-lanthanum-zirconate-titanate is commonly used in electrooptic applications (Nordyke 1984). An electrooptic application such as maintaining memory in a calculator after turning it on and off is due to the piezoelectric characteristics of PZLT (Nordyke 1984).

2. Use of Cadmium in Glass/Ceramic Products

The uses of cadmium in glass and ceramic products are commonly as a pigment in a glaze, as a colorant in the glass itself, or as a phosphor[*] (EPA 1989). Except for its use in colorants and glazes, the use of cadmium associated with glass and ceramics is less than 5 percent of the total production of cadmium (Blythe 1990, Cadmium Council 1989). The use of cadmium in the production of colorants is discussed in Chapter II on plastics. Cadmium- and lead-based glazes and enamels used with glass/ceramic products are discussed in the following section.

3. Use of Lead in Enamels and Glazes

a. Applied to Metal

Lead compounds are used in enamel compositions as fluxing agents (i.e., to aid the softening or melting of the enamel). This allows the successful application of the enamel at relatively low temperatures. As fluxing compounds, lead compounds offer the advantage of increasing the brilliance and smoothness of the enamel even when used in large quantities. Lead also increases resistance to chipping, improves elasticity, and increases corrosion resistance. The amount of lead in an enamel will depend on the type of metal to which it is applied. Enamels used on cast iron contain only from 0 to 3 percent lead bisilicate.

Using lead enamels on steel broadens the types of steel that can be successfully enameled. When enamels are applied below the strain point of the steel, the strength and warpage characteristics are not damaged. The flux characteristics of lead allow enamels to be applied below this point. Lighter

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[*] A phosphor is a phosphorescent substance that emits light when excited by radiation. Common applications include mercury-vapor lamps and fluorescent tubes (EPA 1989).

gauge steel can be used as a result. Typical leaded enamels applied to steel contain between 2 and 7 percent lead.

Enamels used on the limited number of aluminum alloys that can be coated are all leaded. These enamels can contain between 30 and 45 percent lead oxide. The use of lead in the enamel is necessary because of the low maturing temperature of aluminum.

b. Applied to Glass

Glass color enamels are used to decorate and label glass objects. Lead enamels are used for glassware primarily as a flux. The lower melting points which can be achieved with lead are important in preventing the glassware from deforming during firing.

Four properties are important for glass enamels: stability of composition, chemical durability, coefficient of expansion, and melting temperature. Stability is necessary so that the enamel will not react to form compounds which will be harmful to the color or the item. Chemical resistance to acids and alkalies serves to protect enamels from damage in their contact with food, dishwasher detergents, or attack by weather. Enamels must expand slightly less when heated than the host to which they are applied or the enamel will craze, peel, or crack when fired. Glass enamels must have a melting temperature far enough below the softening point of the preformed glass to which they are applied so that the article will not be deformed.

Formulation of enamels for glassware is also similar to the formulation enamels used on metals. The requirement for lower firing temperatures generally increases the use of flux agents. Lead oxide is the primary flux in glass enamels. Due to concerns about the toxicity of lead, industry has put significant effort in reducing lead in enamels used to decorate glass. Most of the progress has resulted in enamels which prevent the lead from becoming

- 102 -

soluble in a range of acidities, thus preventing glassware from posing
toxicity concerns during use. Most enamels, however, are still based on lead
flux. These enamels contain 50 percent lead oxide.

c. Glazes

Lead also is used in glazes for ceramics as a flux or
softening agent. Lead glazes are generally more tolerant to application
variables than non-lead glazes. They can be fired at lower temperatures, and
resist crazing, cracking or splitting due to expansion and contraction during
firing, The lower temperatures attained allow the use of a broader range of
pigments (Nordyke 1984). Glazes can contain 50 to 60 percent lead oxide (EPA
1989).

4. Use of Cadmium in Enamels and Glazes

Cadmium is used in glazes and enamels as a pigment (e.g., cadmium
sulfoselenide red) and as a stabilizing agent of the cadmium pigment (cadmium
oxide). Without the stabilizer, the cadmium pigment would become black under
firing (Nordyke 1984). The use of cadmium as a pigment is discussed in the
chapter on plastics (Chapter II).

C. Consumption of Lead and Cadmium in Glass/Ceramics Products

Table 33 lists the discards of lead in glass/ceramic products from 1970
to 1986. Leaded glass used in televisions accounts for by far the largest
quantity of lead discards, representing 85 percent of the lead in
glass/ceramic products discarded in MSW in 1986. Discards of lead from glass
and ceramics in MSW are expected to steadily increase and are projected to
rise to 91,000 tons by the year 2000 (EPA 1989).

Table 34 presents the discards of cadmium in pigments for glass,
ceramics, and miscellaneous products. Use of cadmium in glass and ceramic
products accounts for a relatively minor portion of cadmium discards in MSW.

Table 33. Discards of Lead in Glass and Ceramics in MSW

Year	Discards of Lead from Glass in TV Sets[a] (tons)	Discards of Lead from Light Bulb Glass[b] (tons)	Discards of Lead from All Other Glass and Ceramics[c] (tons)	Total Lead Discards from Glass and Ceramics (tons)
1970	10,395	491	3,366	14,252
1975	17,969	506	3,934	22,409
1980	27,756	635	5,235	33,626
1986	52,247	672	7,795	60,714

[a] Includes adjustment for imports. TV's are assumed to have an 8 year life.

[b] Light bulbs are assumed to be discarded one year after manufacture.

[c] All other glass and ceramics are assumed to be discarded 3 years after manufacture.

Source: EPA 1989.

Table 34. Discards of Cadmium in Pigments for
Glass, Ceramics, and Miscellaneous Products in MSW

Year	Cadmium Discarded in Pigments for Glass and Ceramics[a] (tons)	Cadmium Discarded in Pigments for Miscellaneous Products[b] (tons)	Total Discards of Cadmium in Pigments for Glass, Ceramics and Miscellaneous Products[c] (tons)
1970	32	79	111
1975	27	65	92
1980	23	56	79
1986	29	70	99

[a] Half of the glass and ceramics with cadmium pigments is assumed to
end up in MSW. Discards are assumed to be in the year of manufacture
for the glass product. The cadmium used to stabilize cadmium pigments
in glass and ceramics is assumed to be included with the figures for
the cadmium in the pigments.

[b] Includes pigments in products other than plastics, rubbers, and
glass/ceramics. Products are assumed to be discarded in the year of
manufacture.

[c] Includes pigments other than those found in rubbers and plastics.

Source: EPA 1989.

- 105 -

In 1986, 29 tons of cadmium were discarded in glass/ceramic products. This quantity is less than 2 percent of the total cadmium discarded.

D. Potential Substitutes for Lead and Cadmium in Glass/Ceramic Products

Substitution for lead- and cadmium-based glass/ceramic products usually involves switching to alkaline earth metals* (primarily strontium and barium), and zirconium that are expensive in comparison to lead and cadmium. In the case of potential substitutes for lead-based glass/ceramic products, the performance properties of the substitutes lack the refractive indices, the radiation absorption characteristics, and the processability of lead-based glass/ceramic products. There are also reports of supply problems with strontium and zirconium (Corning 1989c). Table 35 presents the potential substitutes for lead and cadmium in glass and ceramic products.

1. Television and X-ray Shielding Parts

Zirconium is a potential substitute for lead in faceplates, but its use would increase the cost of the faceplate by six percent (Corning 1989c). Zirconium products would require higher processing temperatures necessitating possible changes in manufacturing equipment. Television manufacturers have already begun to use zirconium-based faceplates that provide better resistance to radiation darkening (browning) than lead-based faceplates (Corning 1989c).

Strontium and barium are potential substitutes for the funnel and neck portions of X-ray shielding substitution but as much as 50 percent more strontium carbonate than lead oxide would be required to achieve the same radiation protection at current thicknesses of funnels and necks. A similar percentage increase of barium carbonate would be required to substitute for

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* Alkaline earth metals include calcium, barium, strotium, and radium (i.e., Group IIA fo the Periodic Table).

Table 35. Potential Substitutes for Lead and Cadmium in Glass and Ceramics

Use	Potential Substitute	Comments on Potential Substitutes
GLASSES		
Television Parts: Neck and Funnel (28 and 22 percent PbO respectively)	● Strontium ● Barium	● Processing problems, lower durability, larger quantity required
Faceplate (panel) (2 percent PbO)	● Zirconium	● Supply problem, marginal cost difference (6 percent higher)
Leaded Glass: X-ray shielding	● Thicker glass	● Increased space requirements and decreased visual clarity ● Expensive
Neon/Fluoroescent Tubing	● Strontium/Barium	● Processing problems
Light Bulb	● Cerium/Alkaline Earth Metals	● Under development; processing problems
Optical Glass	● Barium/zinc oxides ● Zinc, lithium and barium oxides	● Lower index of refraction achievable than with lead ● Commercially available

Table 35.   Potential Substitutes for Lead and Cadmium in Glass and Ceramics
(Continued)

Use	Potential Substitute	Comments on Potential Substitutes
CERAMICS Glazes/Enamels PZT/PZLT (68 percent PbO)	●Zirconium dioxide ●Chrome tin salt ●Barium Lead Titanate (10 percent lead) ●Quartz ●Rochelle Salts	● Satisfactory brilliance and alkali resistance; some application problems ● Color instability ● Not as piezoelectrically efficient; less expensive; can't be used in temperatures over 100°C; 25 percent less expensive ● Not as piezoelectrically efficient ● 3-4 times more expensive ● Not effective in humid environment; more efficient

Sources: Blanche 1989; Corning 1989a, 1989b, 1989c, 1989d; Degussa 1989; Piezo Kinetics 1989; Sylvania 1989.

lead oxide (Corning 1989d). Significant processability and durability problems exist with strontium and barium glass products and reformulation costs could be substantial. The costs of strontium and barium are higher than lead (Corning 1989d). To achieve the required density associated with proper x-ray shielding, a 50 percent weight increase would be necessary. This increase would raise the costs of substitute funnels and necks even more as well as increasing the technical processing problems (Corning 1989d).

2. Fluorescent Tubing and Light Bulbs

Bismuth alloys containing smaller amounts of lead oxide are potential substitutes for neon sign tubing (Piezo Kinetics 1989). Cerium and other alkaline earth metals have been suggested as potential substitutes for outer envelopes used in fluorescent lighting and for the flare and exhaust tube used in light bulbs. These potential substitutes lack the processability and durability of lead based products (Sylvania 1985).

3. Optical and Ophthalmic Glass

Based on refraction indices, substitution to barium and zinc oxides is possible in optical glass requiring refractive indices below approximately 1.6 (Nordyke 1984). Lanthanum is a potential substitute for ophthalmic and non-ophthalmic optical glass requiring high indices of refraction (above 1.6); however, research is still preliminary (Schotts 1989). One industry contact noted that in addition to the technical feasibility of lanthanum substitution being unknown, the cost of this substitution would be very high (Corning 1990).

4. Lead Crystalware

By definition, substitute glassware that does not contain at least the specified percentage of lead oxide would not be considered lead crystalware. Although the functional aspects of leaded crystalware could be

replaced many of the quality aspects could not. For example, the smoothness and temperature stability of lead crystalware is hard to replace with other compounds (ProChem Tech 1989); unleaded glass such as lime glass could be considered a substitute, but many of the properties of leaded glass (e.g., brilliance, strength, and clarity) could not be maintained.

5. Piezoelectric Ceramics

Three potential substitutes for lead-based PZT and PZLT ceramics have been mentioned by industry sources. A reduction in lead content from about 68 percent lead oxide to about 10 percent lead oxide can be achieved by switching to barium titanate products (Piezo Kinetics 1989). Barium titanate was the first commercially available ceramic and is still widely used in sonar detection and ultrasonic cleaning devices. Barium titanate is about 50 percent as efficient as PZT (i.e, less voltage produced for a given mechanical displacement) and barium titanate cannot be used at temperatures above 100°C (Piezo Kinetics 1989). PZT can be used at temperatures up to 300°C. The cost of barium titanate piezoelectric ceramics is about 25 percent less than PZT (Piezo Kinetics 1989).

The temperature limitation makes barium titanate unsuitable for use as an igniter in glass appliances and cigarette lighters. In general, due to the lower cost of barium titanate it has already been substituted for PZT where feasible. Some additional substitution may be possible, but with a sacrifice in performance in other consumer electronic applications.

Quartz is also piezoelectric and is used in applications such as radio tuners that require a high degree of frequency control. Quartz costs 3 to 4 times more than PZT and is 10 to 20 percent less efficient (Piezo Kinetics 1989).

The final potential substitute is Rochelle salts. Although they are 25 to 30 percent more efficient than PZT, they do not work well in humid conditions, including most ambient air, making them unsuitable for most applications (Piezo Kinetics 1989).

6. Glazes and Enamels

a. Lead-Free Glazes and Enamels

Lead free enamels were introduced in the early 1980s and have found application on lighting fixtures and liquor and cosmetic containers. Because their chemical resistance is much lower than that of standard lead-based enamels, they are finding a relatively limited use. According to Nordyke (1984), no lead-free systems are available for use on cookware, tableware, and other areas that demand excellent chemical resistance. In a typical glass enamel, lead oxide accounts for 56 percent of the formulation. The lead oxide can be replaced by using a formulation with up to 40 percent zinc oxide (ZnO), lithium oxide (Li_2O), calcium oxide (CaO), barium oxide (BaO), and antimony oxide (SbO), and the remaining 16 percent can be allocated to other ingredients of the formulation.

In addition, an enamel system free of lead and cadmium consisting of zirconium dioxide (ZrO_2) has been recently developed (Gillier 1989). Used for glass decorating, the enamel has high brilliancy and alkali and dishwasher resistance. The enamel system can be colored with pigments to 13 shades. The range of colors available is specifically intended for the decoration of dinnerware, glass-ceramics, and borosilicate and opal glass but does not include red or bright yellow without the use of cadmium.

With the absence of lead, lack of brilliance is a problem. Lithium is added to improve brilliance, but this can have a negative effect on the glass to which it is applied due to ion exchange, thereby weakening the glass. In

- 111 -

addition, these enamels have higher and narrower firing temperatures than leaded enamels (Degussa 1989).

Potential substitutes for lead in glazes appear to be scarce because of the number of excellent properties currently available from lead-based glazes. As discussed earlier, these properties include fusibility, smoothness, brilliancy, and mechanical and chemical resistance. A potential substitute consisting of a chrome-tin salt has been identified for pink glazes (Blanche 1989). More development work is required on this compound because of color instability in lead-free glass. Lead-free decorative glazes are also being developed, but they are experiencing difficulty because the lead-free glazes actually encourage greater release of lead from the leaded glazes over which they might be applied (Degussa 1989).

The cost of these unleaded glazes and enamels is not significantly different than leaded versions, but they may add to the cost of the final product due to higher firing temperatures and more precise processing conditions that would be required (Degussa 1989).

b. Cadmium

As mentioned earlier, cadmium is used in glazes and enamels as a color stabilizer for cadmium pigments (bright reds and yellows). Cadmium pigments are discussed in the plastics chapter and Chapter II.

E. <u>References</u>

Blanche, S.T. 1989. "Chrome-Tin Pink Glazes," <u>Ceramic Engineering Scientific Proceedings</u>, Vol. 10, pp. 65-68.

Blythe Colours. 1990 (March 27). G.R. Streatfield, Technical Director, Cresswell Stoke-on-Trent, England. Comments on draft of " Use and Substitutes Analysis For Lead and Cadmium Products in Municipal Solid Waste.

BCR 1990 (March 5). British Ceramic Research Limited. D.W.F. James, Chief Executive. Penhull Stoke-on-Trent, England. Comments on draft of "Use and Substitutes Analysis For Lead and Cadmium Products in Municipal Solid Waste."

Cadmium Council. 1989 (May 25). H. Morrow. Transcribed telephone conversation with Peter Weisberg, ICF Incorporated, Fairfax, VA.

Corning Glass. 1989a (July 21). T. Seward. Transcribed telephone conversation with Peter Weisberg, ICF Incorporated, Fairfax, VA.

Corning Optics. 1989b (July 21). R. Thompson. Transcribed telephone conversation with Peter Weisberg, ICF Incorporated, Fairfax, VA.

Corning Glass. 1989c (May 30). D. Lopata. Transcribed telephone conversation with Peter Weisberg, ICF Incorporated, Fairfax, VA.

Corning Glass. 1989d (July 26). J. Connelly. Transcribed telephone conversation with Peter Weisberg, ICF Incorporated, Fairfax, VA.

Corning Glass. 1990 (October 3). C. McCarthy. Letter to Gary Cole, U.S. Environmental Protection Agency, Washington, DC.

Degussa Corporation. 1989 (August 14). D. Gillier. Transcribed telephone conversation with Louis Gardner, ICF Incorporated, Fairfax, VA.

EPA. 1989 (January). U.S. Environmental Protection Agency. Characteristics of Products Containing Lead and Cadmium in Municipal Solid Waste Facilities 1970 to 2000. Prepared by Franklin Associates Ltd., Prairie Village, KS.

Gillier, D. 1989 (February). "Beauty and the Beast: Colors Shine Without Lead," <u>Ceramic Industry</u>, pp. 21-22.

Nordyke, J.. 1984. <u>Lead in the World of Ceramics.</u> The American Ceramic Society. Westerville, OH.

Piezo Kinetics Inc. 1989 (May 30 and July 27). R. Turner. Transcribed telephone conversation with Peter Weisberg, ICF Incorporated, Fairfax, VA.

Pro Chem Tech. 1989 (May 31). T. Keister. Transcribed telephone conversation with Peter Weisberg, ICF Incorporated, Fairfax, VA.

Schotts Glasswerke. 1989 (July 27). R. Scheller. Transcribed telephone conversation with Peter Weisberg, ICF Incorporated, Fairfax, VA.

Sylvania and Laxman Ltd. 1989 (June 1). R. Marlor. Transcribed telephone conversation with Peter Weisberg, ICF Incorporated, Fairfax, VA.

VIII. BRASS AND BRONZE PRODUCTS

A. Overview of the Copper Alloys Industry

Copper is combined with varying amounts of other metals to produce, among other alloys, brass and bronze. The properties of these alloys are varied by incorporating certain materials to fit a wide range of uses. Copper alloys generally have good mechanical properties, corrosion resistance, workability, and conductivity. Lead is included in some forms of brass and bronze to improve workability (Copper Development Association 1989).

Brass is generally an alloy of copper and zinc with small additions of other metals. Brass products may be cast or formed by rolling, extrusion, forging or other processes. The varieties of brass are defined by their content: red-gold brass is 75-85 percent copper, yellow brass consists of 60 to 70 percent copper, naval brass contains 2 percent tin, and leaded brasses contain lead in quantities greater than 2 percent (EPA 1989). Typically 3 percent lead is found in free machining brass (Kirk-Othmer 1978).

Lead is generally added to brass to improve the free machining characteristics of the alloy (Copper Development Association 1989, Wolfenden and Wright 1979). Lead also may be present as an impurity in some brass products due to the lead content of scrap materials used in the manufacture of brass materials. Lead is present, therefore, in virtually all kinds of brass to a small degree (Kirk-Othmer 1978).

Traditionally, bronze has been defined as an alloy of copper and tin, but currently is described as containing any of a variety of metals including aluminum, manganese, silicon, or tin in combination with copper, which is always the principle ingredient. Leaded bronze may contain up to 30 percent lead (EPA 1989) which is included because it improves workability and conformability (Kirk-Othmer 1978). In general, bronzes can be grouped into

- 115 -

leaded, tinned, and high strength bronzes with the latter groups being successively harder and stronger (Kirk-Othmer 1978, Glaeser 1983).

1. Use of Lead in Brass

Because lead is insoluble in copper it remains as free lead globules distributed throughout the alloy. The lead globules lend the alloys the properties associated with softness such as improved lubrication characteristics, decreased fatigue strength, and improved conformability (Concast Metal Products 1989, Glaeser 1983). The improved machinability that lead adds to leaded brass has led to its use in the manufacture of screw machine parts and plumbing goods (Copper Development Association 1989). Leaded brasses are not used in the majority of copper alloy applications because these properties are not needed and the increased lead reduces other important properties such as light weight, conductivity and strength (Copper Development Association 1989).

2. The Use of Lead in Bronze

Leaded bronze is used mainly in machine parts such as bushings and bearings where the lead adds to the natural lubricity of the parts and decreases the likelihood of mechanical seizures due to interruption or loss of lubricant (Concast Metal Products 1989). The conformability of leaded bronze allows parts to wear into best fit through use (Glaeser 1983). Highly leaded bronzes are not used where impact or heavy, oscillating loads may be encountered as a consequence of their lower strength and hardness. Lead also produces hot shortness (brittleness under red-heat), and therefore exceeding the maximum frictional temperature is of concern (Glaeser 1983).

B. Consumption of Lead in Brass and Bronze

Due to the narrow scope of applications, the majority of end products made from leaded brass and bronze are not disposed in MSW, but rather in

industrial waste facilities. Table 36 shows lead in brass and bronze discarded at MSW for the period from 1970-1986.

C. Potential Substitutes for Lead in Brass and Bronze

Two methods can be used to substitute for lead in brass and bronze. Alternative metals can be incorporated with copper to produce alloys with similar properties to lead-containing products or alternative materials (e.g., plastics or other materials) can be used in the final products. It is easiest to consider potential substitutes by use since leaded brass and bronze share many functions.

Bearings and fittings made from unleaded tin bronze and aluminum bronze are already used for heavier load applications for which leaded bronze is not hard enough. These products could be used for the softer leaded bronze, but would lack the natural lubricity of leaded bronze. A lubricant such as grease or silicon would be required to prevent equipment seizure when fabricating certain items made from these harder materials (Concast Metal Products 1989, Kirk-Othmer 1978). The hardness of these replacements would also necessitate that other parts with which they come in contact during use be made from equally hard materials. Engineering and design of machinery would also need to be more precise due to the loss of wear-in properties associated with leaded brasses and bronzes (Concast Metal Products 1989, Glaeser 1983).

Machinable leaded brass and bronze used for screw parts and plumbing fixtures can be substituted for by other copper alloys to a large degree. The addition of tellurium, selenium, or sulfur offers the possibility of improving the machining characteristics of copper and its alloys without the use of lead. These materials affect the metallurgy of copper in ways analogous to the effect provided by lead. Selenium, tellurium and sulfur also are insoluble in copper and thus remain as free globules which provide points in

- 117 -

Table 36.   Discards of Lead in Brass and Bronze in MSW

Year	Domestic Lead Discards[a] (tons)	Lead in Imports/Exports[b] (tons)	Gross Discards (tons)	Net Discards into MSW[c] (tons)
1970	20,485	N/A	20,485	410
1975	23,699	N/A	23,699	474
1980	20,044	165	20,209	404
1986	15,660	405	16,065	321

N/A - Not Available.

[a] Assumes 10 year product life. Quantities are amounts of lead consumed in brass/bronze production ten years earlier.

[b] Data not available some years. Negative numbers denote net exports.

[c] Assumed to be 2 percent of all discards.

Source: EPA 1989.

the microstructure for breaks to form. They do not provide, however, machinability at the same level as lead and increasing the consumption has a rapidly diminishing effect. Compared to free-cutting brass (61 percent Cu, 3 percent Pb, 36 percent Zn) as a standard of 100, copper has a machinability rating of 20, and sulfur copper (99.7 percent Cu, 0.3 percent S) and tellurium copper (99.5 percent Cu, 0.5 percent Te) both have a machinability rating in the range of 85-90. The effect of adding these materials is the same for many other brass alloys and for the tin bronzes (Kirk-Othmer 1978, Copper Development Association 1989).

The choice of a potential substitute depends to a large extent on the properties that the consumer requires most. Different substitutes will be chosen if hardness, color, strength, or another property is critical or must remain constant. The costs of potential substitute alloys depend on the costs of their components which are subject to the influence of world markets. Table 37 presents substitute products and some of their disadvantages. Table 38 presents costs for some representative lead-containing and potential substitute alloys.

Other potential substitutes for leaded brass can replace specific end products. For example, some plumbing fixtures and valves currently manufactured with brass or bronze may be replaced by PVC or other plastic materials (Cohen 1987), but these materials are not suitable for the bulk of brass and bronze applications. Machined screws may be replaced by steel screws or another machinable metal depending on the importance of corrosion resistance (Concast Metal Products 1989).

Table 37. Potential Substitutes for Lead-based Brass
and Bronze Products

Use	Potential Substitute	Disadvantages
Machined Products		
Plumbing Fixtures, Machine screw parts	Steel	Poor corrosion resistance
	PVC	Not able to handle all applications; poor shear resistance
	Tellurium bronze	Not commercially available; marginal difference in machinability
	Selenium bronze	Not commercially available; marginal difference in machinability
	Sulfur bronze	Not commercially available; marginal difference in machinability
Bushing/Bearing Products	Tin bronze	Harder, requires lubrication
	Aluminum bronze	Harder, requires lubrication
	Manganese bronze	Harder, requires lubrication

Sources: Copper Development Association 1989, Nielsen Undated,
Kirk-Othmer 1978.

Table 38. Cost: Lead-based Brass and Bronze Products
and Their Potential Substitutes

Product	Cost ($/lb)
Machined Products	
Leaded brass	$1.10
Leaded bronze	$1.40
Steel	$0.45
PVC[a]	$1.24
Tellurium bronze[b]	$3.00
Selenium bronze[b]	$3.00
Sulfur bronze[b]	$3.00
Bushing/Bearing Products	
Leaded bronze	$1.40
Tin bronze	$2.00
Aluminum bronze	$0.70
Manganese bronze	$0.70

[a] Costs presented for PVC are based
on a comparison of new products (e.g.,
PVC products cost an average of 13
percent more than equivalent brass
parts).

[b] Not widely available so costs are
rough estimates based on inputs
(Copper Development Association).

Sources: Nielsen undated, Copper
Development Association
1989, Wall Street
Journal 1989, Channel 1989.

D. References

Channel Hardware Store. 1989 (August 14). Fairfax, VA. Survey of merchandise prices performed by Louis Gardner, ICF Incorporated.

Cohen, Arthur. 1987 (September). Copper and Copper Alloy Tube and Pipe. ASTM Standardization News. pp. 54-59.

Concast Metal Products. 1989 (July 20). M. Barber. Pittsburgh, PA. Transcribed telephone conversation with Louis Gardner, ICF Incorporated, Fairfax, VA.

Copper Development Association. 1989 (July 21). A Cohen. Greenwich, CT. Transcribed telephone conversation with Louis Gardner, ICF Incorporated, Fairfax, VA.

EPA. 1989 (January). U.S. Environmental Protection Agency. Characterization of Products Containing Lead and Cadmium in Municipal Solid Waste Facilities 1970 to 2000. Prepared by Franklin Associates Ltd., Prairie Village, KS.

Glaeser, WA. 1983 (October). Wear Properties of Heavy Loaded Copper Base Bearing Alloys. Journal of Metals. pp. 50-55.

Kirk-Othmer. 1978. Encyclopedia of Chemical Technology. John Wiley and Sons Publishing Co. Inc. Volume 3, pp. 674-77. Volume 7, p. 45.

Nielsen, WD. Undated. Metallurgy of Copper Base Alloys. Casting Engineering & Foundry World. Reprint.

Wall Street Journal. 1989 (July 27). Commodity Prices.

Wolfenden, A. and Wright, PK. 1979 (August). Role of Lead in Free-Machining Brass. Metals Technology. pp. 297-301.

IX. CADMIUM-PLATED PRODUCTS

   A. Overview of the Plating Industry

   Plating can be defined as the application of metallic coatings to

various items in order to provide the base material to which they are applied

with surface properties of the metal that is used as a coating. Coatings

provide protection to plated materials by one of five methods: by protecting

the substrate by setting up a favorable electrochemical potential, by forming

a protective, passive film in aqueous media, by coating the substrate with a

slow oxidizer that protects the substrate at high temperatures, by acting as a

barrier to corrosive agents (e.g., noble metals), and finally, by providing

wear resistance by forming compounds that are much harder than the unplated

substrate (Kirk-Othmer 1978).

   1. Plating Technologies

   Several technologies are used to apply metallic coatings. The

particular process that is used depends on the properties of the substrate and

coating material. Electroplated coatings are formed by electrodeposition of

the coating material on the substrate, usually in an aqueous solution in which

ions of the coating material are dispersed. The ions are applied to the

substrate material by providing electrical current to the solution (Kirk-

Othmer 1978). Another process, diffusion coating, places the coating material

(in the liquid, solid, or vapor phase) in physical contact with the substrate

at an elevated temperature, thereby creating interdiffusion of the two

materials at the surface (Kirk-Othmer 1978).

   Sprayed coatings are applied to materials which cannot be easily coated

by other means due to the size, shape, or susceptibility to damage by heat.

In addition, some coatings can be applied by mechanical methods or liquid

metal cladding where the materials are brought into physical contact by force

to disrupt oxide films on the surface of each, thereby allowing a metallurgical bond to form (Kirk-Othmer 1978).

Chemical coating is an electroless plating technique which involves a catalytic chemical reaction reducing a species to a metallic or compound material which forms the coating. These reactions are temperature dependent and can require temperatures from 500 to 1500°C. Future development may allow these reactions to take place at lower temperatures. Finally, vacuum coatings transfer the coating metal in the vapor phase through heat or a ballistic process to the substrate. The use of vacuum allows this process to take place without interference from contaminating materials (Kirk-Othmer 1978).

2. Cadmium Plating

Cadmium plating is used on fabricated steel and cast iron parts and can be electroplated on plastics or metal in some appliance and consumer applications. Cadmium is used because it has a combination of properties: natural lubricity, corrosion resistance to salt water and alkalis, high deposition rate in application, good solderability and ductility, and a long-lasting silvery-white luster (Kirk-Othmer 1978, Humphreys 1989).

Cadmium plating is used to protect bolts and screws used in marine applications from corrosion due to prolonged exposure to moisture and salt. In general, cadmium plated products have a longer service life due to their corrosion resistance and natural lubricity which helps in applications where mechanical seizures would impair function. Automotive uses such as seat belt fasteners and brake linings are examples of applications for which these features are important (Cadmium Council 1989). Cadmium plated fasteners also are used because their natural lubricity reduces the torque experienced during fastening which could cause fatigue (Humphreys 1989).

B. Consumption of Cadmium in Electroplating

General use of cadmium plating has declined for two reasons: 1) the toxicity of cadmium itself and 2) cadmium traditionally has been plated on surfaces using a cyanide bath which manufacturers also avoid because of health and disposal problems. However, newer solutions involving trivalent chromium are being developed and have helped to revive to a certain extent cadmium's use in plating (Humphreys 1989).

The disposal of cadmium plated products in MSW will continue to decline over the next few years because users have substituted for these products (EPA 1989). The bulk of the remaining applications for cadmium plating are in the automotive, aerospace, and military markets that are disposed in solid waste facilities other than MSW. In general, there has been a decrease in the disposal of cadmium plated articles including dishwashers, washing machines, radios, and televisions in MSW because substitutes are currently in place for cadmium-plated parts in these applications. Table 39 shows the discards of cadmium in plated parts for home appliances and electronics for the period between 1970 and 1986. Due to the changes in materials that have already occurred the total discards to MSW of cadmium in plated products in the year 2000 are anticipated to be only 29 tons (EPA 1989).

C. Potential Substitutes for Cadmium in Metallic Coatings

Potential substitutes for cadmium in plating operations can be classified into two groups: alternative materials and technologies which do not require the properties imparted by cadmium plating and alternative coatings with similar properties that can be used in place of cadmium.

The substitution which has already taken place in the majority of household applications has used alternative materials. Cadmium in washing

Table 39. Discards of Cadmium in Plated Parts for
Home Appliances and Electronics in MSW

Year	Discards in Major Appliances[a] (tons)	Discards in Consumer Electronics[b] (tons)	Total Discards in MSW (tons)
1970	47	571	618
1975	39	330	369
1980	32	176	208
1986	24	161	185

Note: Total discards of cadmium plated parts in MSW are expected to be
       29 tons in year 2000.

[a] Assumes 8 year lifetime for appliances and includes adjustment for
cadmium recovered with ferrous parts.

[b] Assumes 8 year lifetime for products and includes an adjustment
for imports and exports.

Source: EPA 1989.

machines and dishwashers has been largely replaced by the increased use of plastics which do not require cadmium plated bolts to hold the frames together. Similarly, the technology that used cadmium plated chassis in radios and televisions is obsolete. Steel chassis that were plated with cadmium have been replaced by printed circuit boards made of resinous materials (EPA 1989).

Additional substitution for cadmium plating may use similar technology changes or alternative coatings. The choice of replacement plating will depend upon which properties of cadmium coating are most important. Although inferior in terms of solderability and lubrication, zinc is already used whenever possible because of reduced health and environmental concerns (Ajax Metal Processing 1989). Electroplated tin and gold are readily solderable, although gold is very expensive. Tin is not effective in corrosion resistance, but the development of tin-zinc alloys and a zinc-nickel alloy as possible substitutes for cadmium is progressing (AESF 1989, Kirk-Othmer 1978). Chromizing also is an economical process to improve corrosion resistance of steel where appearance is not important. Chrome offers the advantage of a low friction surface and good wearability (Kirk-Othmer 1978), but does not offer the same corrosion resistance as cadmium. Table 40 identifies the characteristics of potential substitute plating technologies and alternate products that can or have replaced cadmium plated parts in many applications. Table 41 provides representative costs for these potential substitutes.

As the tables indicate, there is a trade-off between cost, processability, and corrosion resistance for plating technologies that replace cadmium plating. For most applications that enter MSW, however, a workable substitute is available or can be developed. In cases when alternate materials (e.g., plastics) offer superior performance or wear characteristics

Table 40. Characteristics of Potential Substitutes for Cadmium Plating

Use	Potential Substitute	Advantages	Disadvantages
Electronics (Chassis)	• Resinous printed circuit boards	• Already occurred; superior technology	
Fasteners (Nuts, Bolts)	• Plastic construction	• Already occurred in consumer household appliances	• Not possible in most cases
	• Zinc plating	• Already preferred option where possible	• Lower corrosion resistance • Loss of lubricity • Loss of solder-ability
	• Tin plating	• Good solder-ability	• Poor corrosion resistance
	• Gold plating	• Good corrosion resistance	• Very expensive • Poor wear resistance
	• Chrome plating	• Good wear properties • Better corrosion resistance for acids	• Lower corrosion resistance for salts and neutral pH

Sources: AESF 1989, Cadmium Council 1989, Iron Age 1980, Kirk-Othmer 1978.

Table 41. Costs of Cadmium Plating and Potential Substitutes

	Cost/lb. of Plating Material[a]	Relative Cost of Plating Compared to Cadmium[b]
Cadmium	$ 4.50	1.00
Zinc	$ 0.80	0.50
Tin	$ 5.60	1.05
Gold	$6,552.00	1,500.00
Chrome	$ 7.50	1.12

[a] Weights are all for standard avoirdupois pounds.

[b] Relative cost are different from ratio of metal costs due to overhead and different thickness requirements.

Source: Cadmium Council 1989, Ajax Metal Processing 1989, Kirk-Othmer 1978, Wall Street Journal 1989.

to cadmium plating, substitution has already occurred to a large extent. It is also conceivable that these alternative materials can replace other cadmium-based products that are still in use (e.g., plastic bolts in marine applications that do not require high shear strength are possible).

D. References

Ajax Metal Processing. 1989 (July 27). F. Buono. Detroit, MI. Transcribed telephone conversation with Louis Gardner, ICF Incorporated, Fairfax, VA.

AESF. 1989 (July 31). American Electroplaters and Surface Finishers Society. W. Safranek. Orlando, FL. Transcribed telephone conversation with Louis Gardner, ICF Incorporated, Fairfax, VA.

Cadmium Council. 1989 (July 27). H. Murrow. New York, NY. Transcribed telephone conversation with Louis Gardner, ICF Incorporated Fairfax, VA.

EPA. 1989 (January). U.S. Environmental Protection Agency. Characterization of Products Containing Lead and Cadmium in Municipal Solid Waste Facilities 1970 to 2000. Prepared by Franklin Associates Ltd., Prairie Village, KS.

Humphreys, PG. 1989 (May). New Line Plates Non-Cyanide Cadmium. Products Finishing. pp. 80-90.

Iron Age. 1980 (January 14). Cadmium's Plight Opens Field to Alternative Coatings. p. 50.

Kirk-Othmer. 1978. Encyclopedia of Chemical Technology. John Wiley and Sons Publishing Co., Inc. Volume 6, p. 166; Volume 8, pp. 827-869. 1981. Volume 15, pp. 241-274.

Wall Street Journal. 1989 (July 27). Commodity Prices.

X. COLLAPSIBLE TUBES

A. Overview of the Tube Industry

Collapsible tubes are used to dispense a number of products from medicines to epoxy resin adhesives. While tubes are manufactured from a variety of materials, lead tubes are used to dispense corrosive products (lead is difficult to corrode) or to satisfy customer packaging preferences (Teledyne 1989).

B. Use of Lead Tubes

Only a few companies still make lead tubes, including Teledyne Packaging in Pennsylvania and Atlantic in New Jersey. Lead tubes represent a very small fraction (less than one percent) of the tube market (TCNA 1989a, 1989b). Of the lead tubes currently manufactured, most are used for artists colors and the remainder for corrosive glues. Market surveys show that artists tend to prefer the relatively heavy lead tubes because of the heft and quality feel that is added to the paint product (Teledyne 1989).

C. Consumption of Lead in Tubes

The consumption of lead in collapsible tubes reached a peak in 1969 and has since declined (see Table 42). The decline is attributable to the increasing use of aluminum for this purpose (EPA 1989). The total discards of lead in tubes in MSW has dropped from over 9,000 tons in 1970 to about 600 tons in 1985 (EPA 1989).

D. Potential Substitutes for Lead Tubes

The possible substitutes for lead tubes and their performance characteristics and relative price compared to lead are provided in Table 43. One of the possible substitutes for lead tubes identified in the table is aluminum tubes with phenolic epoxy lining. This aluminum technology does not differ in cost and offers similar performance to the lead tubes.

- 132 -

Table 42. Discards of Lead in Collapsible Tubes in MSW

Year	Discards of Lead in Collapsible Tubes[a] (tons)
1970	9,310
1975	2,860
1980	1,477
1986	639

[a] The lifetime of lead collapsible tubes before discard is assumed to be 2 years.

Source: EPA 1989.

Table 43. Potential Substitutes for Collapsible Lead Tubes

Lead Technology	Substitutes	Comments
Lead Tubes	● Aluminum tubes with phenolic epoxy lining	● Similar in cost and performance to lead tubes
	● Laminate tubes of plastic and aluminum	● Similar in cost and performance to lead tubes

Source: Teledyne 1989.

The other substitute technology, laminate tubes manufactured with alternating layers of plastic and aluminum also can replace lead tubes. Unlike plain plastic tubes that have memory and return to their original shape, laminate tubes will flatten during use. Laminate tubes and lead tubes are similar in cost (Teledyne 1989).

E. References

EPA. 1989 (January). U.S. Environmental Protection Agency. Characterization of Products Containing Led and Cadmium in Municipal Solid Waste Facilities 1970 to 2000. Prepared by Franklin Associates Ltd., Prairie Village, KS.

TCNA. 1989a (May 31). Klein, T. Executive Secretary, Tube Council of North America. New York, NY. Transcribed telephone conversation with Thomas Hok, ICF Incorporated, Fairfax, VA.

TCNA. 1989b (August 15). McCoy. Assistant to the Executive Secretary, Tube Council of North America. New York, NY. Transcribed telephone conversation with Thomas Hok, ICF Incorporated, Fairfax, VA.

Teledyne Packaging. 1989 (May 31). K. Barry . New Jersey. Transcribed telephone conversation with Thomas Hok, ICF Incorporated, Fairfax, VA.

XI. OTHER PRODUCTS

There are a variety of other products that contain lead and/or cadmium and are disposed in MSW facilities. These products account for a very small percent of the total amount disposed, but are discussed in this chapter for completeness. The products are:

- Foil wine wrappers;
- Used oil;
- Rubber (elastomers); and
- Electric blankets/heating pads.

A. Foil Wine Wrappers

The capsule used to enclose the cork in a wine bottle contains a tin-lead alloy. The Wine Institute (1989) reports that a tin-lead capsule has traditionally been used for market recognition and that plastic would be a viable substitute (EPA 1989). In addition, some liquor products use aluminum foil as wrappers. Lead wrappers are easily substituted because the cost of substitute plastic and aluminum foil wrappers are comparable to that of lead wrappers, and wrappers do not constitute a significant portion of the cost of a bottle of wine, but consumers seem to prefer the lead wrappers because of the appearance of quality that the lead wrapper imparts to the bottle (Wine Institute 1989). The discards of lead for this use are presented in Table 44.

B. Used Oil

The used oil generated by the do-it-yourself (DIY) automobile sector is the main source of oil waste entering the MSW. Although the sources of lead, and, to a lesser extent, cadmium in used oil include the particles of metal from engine wear and derivatives of gasoline combustion, this analysis is concerned with the amount of lead contained in the oil before it is used

Table 44. Discards of Lead in Foil Wine Wrappers in MSW

Year	Lead Foil on Domestic Wine Bottles[a] (tons)	Lead Foil on Imported Wines[b] (tons)	Total Foil Discarded[c] (tons)
1970	552	39	591
1975	321	35	356
1980	311	72	383
1986	181	22	202

[a] Assumes to be 10 percent of total domestic lead foil consumption.

[b] Estimate based on the ratio of domestic to imported wine purchases for the given year, assuming that all imported wines use lead foil wrap.

[c] Assumes all foil discarded in the year of production.

Source: EPA 1989.

because it would not be feasible to address the lead and cadmium that is deposited in oil from other sources given the scope of this analysis.

Organic leaded compounds are used in oil and lubricant additives as antiwear agents. Antiwear agents produce a surface film to minimize friction and wear under boundary-lubrication conditions. The role of cadmium in lubricant additives in used oil is very small compared to that of lead. Cadmium discards are, therefore, not discussed in this report.

The disposal in MSW of lead in oil and gasoline additives dropped dramatically over the period 1970 to 1986: from over 1,600 tons in 1970 to just under 200 tons in 1986. Recycling of used oil and reduction of lead content have been responsible for this decline. Table 45 presents the consumption of lead in used oil that is disposed of in MSW.

A large number of formulations are available that can perform the role of anti-knock agents and improve lubrication in oil products. Potential substitutes include iron and zinc organo-phosphates, iron and zinc chlorides, and iron sulfides. These products are comparable in price to the lead-based compounds and have essentially the same performance characteristics. Table 46 presents the information on potential substitutes for alkyl lead compounds used in oil products.

C. Rubber (Elastomer) Products

Rubber products are usually modified by processing with vulcanizing agents and other additives before they can be used in most applications. Lead and cadmium compounds are found in a number of these rubber compounding chemicals including: pigments, fillers, activators, vulcanizers or curing agents, stabilizers, and plasticizers. Lead metal may also be integrated into a rubber product such as lead-sheathed hose (EPA 1989).

Table 45. Discards of Lead in Used Oil in MSW

Year	Estimated Used Oil in MSW (tons)	Average Lead in Used Oil (ppm)	Net MSW Discards of Lead (tons)
1970	556,257	2,889	1,636
1975	661,900	1,606	1,261
1980	673,935	1,265	853
1986	708,772	268	190[a]

Note: Less than 1 ton of cadmium is expected to be disposed
      annually in municipal solid waste. This is based on a
      median concentration of 1.4 ppm cadmium (EPA 1989).

[a] Discards were expected to be about 74 tons in 1988.

Source: EPA 1989.

Table 46.   Potential Substitutes for Alkyl Lead Anti-Knock
Agents Used as Oil Lubricants

Lead Products	Potential Substitute Products
Alkyl Lead Compounds	● Iron and zinc organophosphates
	● Iron and zinc chlorides
	● Iron sulfides

Source: Kirk-Othmer 1983.

These products can be broken down into three main types of ingredients used for rubber compounding: cure systems, protective systems, and pigments. Cure systems include activators, vulcanizers or curing agents, stabilizers, and platicizers. Protective systems include fillers and other chemical additives.

Pigments may be used in elastomers for color identification of two similar objects, to improve aesthetic appeal, or to match two parts of different composition with the same color. Examples of these uses include coloring white walls on tires, backing on carpeting, sporting goods such as basketballs, rubber bands, rubber-based floor tile, housewares, and clothing and footwear (Pigment Handbook 1973).

Lead compounds used as activators and vulcanizers in rubber include litharge (lead oxide), lead peroxide, and lead stearate. Accelerators and activators may employ inorganic compounds such as lead oxide, red oxide, and white lead (EPA 1978). Lead dimethyl dithiocarbamate, a vulcanizing agent, is used in the base compound for V-belt* manufacture.

Discards in MSW of lead and cadmium in rubber products are presented in Tables 47 and 48. The total input to MSW identified in the EPA (1989) report for rubber products is considered to be the lead and cadmium pigments used in rubber. The other lead- and cadmium-containing products in rubber are assumed not to enter MSW (EPA 1989).

Lead and cadmium are among the least common chemicals used during rubber formulation, but both metals may be used in dithiocarbamate compounds as vulcanizers or curing agents. Cadmium acts as an accelerator during the

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* V-belts and other shaped belts are used in automobile and other engines to transfer energy from one moving part to another. "V" refers to the trapezoidal cross section shape which makes the belt hold in place better.

Table 47. Discards of Lead in Pigments Used in Rubber Products in MSW

Year	Discards of Lead in Tire Pigments (tons)	Discards of Lead in Fabricated Rubber Products (tons)	Total Discards of Lead in Rubber Pigments[a] (tons)
1970	45	16	52
1975	44	15	53
1980	83	33	104
1986	56	21	70

[a] Ten to fifteen percent of tires and other rubber products are diverted or recovered annually.

Source: EPA 1989.

Table 48. Discards of Cadmium Pigments
Used in Rubber Products in MSW

Year	Cadmium in Pigments for Rubber Products[a] (tons)
1970	10
1975	13
1980	8
1986	6

[a] Consumption of cadmium pigments in rubber was assumed to be one percent of total consumption of cadmium pigments.

Source: EPA 1989.

curing process, decreasing energy requirements (Gates Rubber 1989). While other compounds in the dithiocarbamate family may be substituted for lead and cadmium dithiocarbamate compounds, some changes in the performance of the final rubber products may occur (Polysar 1989). The use of cadmium in rubber products improves aging resistance by decreasing the likelihood of hardening at high temperatures, but neither cadmium nor lead vulcanizing agents are required for rubber formulation. Zinc dithiocarbamates not only provide an acceptable chemical substitute for cadmium and lead dithiocarbamates, but zinc compounds are also less costly.* Table 49 presents potential substitutes for lead and cadmium vulcanizing agents; discussion of potential substitutes for pigments can be found in the chapter on plastics (Chapter II).

Lead and cadmium also may be considered part of the protective system of a rubber compound. Cadmium accelerators tend to improve the aging resistance of rubber, and lead increases the density and strength of rubber used for hydraulic lines (Gates Rubber 1989). Lead lubricants also help the rubber release from commonly used lead molds. However, lead and cadmium are not essential to protective systems in rubber compounding (Polysar 1989).

D.   Printing Inks

Printing inks that are disposed in MSW primarily are used for printing newspapers, magazines, and packaging for a variety of consumer products. These inks consist of a dissolved dye or pigment in a vehicle to produce a fluid or paste that can be transferred to paper, film, foil, or metal. The solvent then evaporates, leaving the ink on the surface.

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* Although their use is not essential, lead and cadmium may still be used in rubber compounds because of compatibility, customer preference, or price considerations.

Table 49. Potential Substitutes for Representative Lead- and
Cadmium-based Vulcanizing Agents

Lead and Cadmium Compounds	Substitute Dithiocarbamates	Other Compounds
Lead dithiocarbamate	Bismuth	Aldehyde-amine reaction products
Cadmium dithiocarbamate	Copper	Benzothiazoles
	Selenium	
	Tellurium	Benzothiazolesul- fenamides
	Zinc	Dithiophosphates
	Piperidinium	Guanidines
	Thiazoles	Thioureas
		Thiurams
		Thiocarbamyl sulfenamides
		Other curing agents[a]

Note: These potential substitutes are presented for completeness even though
this analysis assumes that the total lead and cadmium contribution to
MSW from rubber products is attributable to pigments (EPA 1989).

[a] Other curing agents include alkylphenol-formaldehyde resin, alkylphenol
disulfides, N,N'-caprolactam disulfide, p-quinonebis(benzoyloxime), 4,4'-
dithiobismorpholine, hexamethylene diamine carbamate, p-quinone dioxime,
sulfur, and insoluble sulfur.

Sources: Kirk-Othmer 1983.

Printing inks may be classified as organic or inorganic. While both categories of ink may contain trace elements, inorganic inks contain the highest levels of lead or cadmium. Organic inks may contain trace amounts of lead and cadmium as impurities (BASF 1989, EPA 1989). Cadmium is not widely used for inorganic printing inks; cadmium pigments are very lightfast and tend to be used in automobile manufacturing* or for printing applications that demand the pigment withstand chemicals (e.g., a label for an acid bottle) (ICI 1989, ANPA 1989b). Cadmium inks are heavy and do not tend to flow well (ANPA 1989b). Printing inks that contain lead are inorganic and include lead chromate (yellow and orange) and molybdate orange (ANPA 1989b). Neither lead nor cadmium are used to make black ink, or in lithographic printing (used to produce magazines) (ANPA 1989a, 1989b, 1989c).

Relatively little lead is currently used in printing inks. As shown in Table 50, discards of lead in printing ink has declined steadily and substantially since 1970. The amount of ink discarded in 1970 is over 72 times the amount discarded in 1986. This decline in lead use reflects the general trend away from inorganic pigments toward organic pigments. While some printing applications (e.g., covering a dark background with a light color and clear films used in packaging) may demand the use of inorganic pigments for their excellent opacity (hiding power) and brightness, recently developed organic pigments also have very good opacity, color, and brightness (BASF 1989, ANPA 1989b).

Dialyrid yellow and dialyrid orange are the major substitutes for lead-containing printing inks. These substitute inks are used in newspapers, magazines, and packaging. Table 51 shows the advantages and disadvantages of

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* BASF, a major U.S. ink manufacturer, does not use cadmium in any of its inks (Wagner 1989).

Table 50. Discards of Lead in Printing Inks in MSW

Year	Lead Discards in Printing Inks[a] (tons)
1970	19,192
1975	13,819
1980	8,222
1986	265

[a] Lead in ink is assumed to enter MSW in the same year as it is consumed. Adjustments were made to reflect the industrial disposal of ink that is removed from recycled paper. Manufacturing losses were estimated to be 5 percent.

Source: EPA 1989.

Table 51. Advantages and Disadvantages of Potential Substitute Ink Pigments
for Lead-containing Printing Ink Pigments

Lead-Containing Ink Pigment	Potential Substitute Pigment	Advantages	Disadvantages
Lead Chromate (yellow or orange)	Dialyrid Yellow	● Does not contain lead	● More expensive than lead chromate and lead sulfo-chromate ● Less lightfast and opaque than lead chromate and lead sulfo-chromate
Molybdate Orange	Dialyrid Orange	● Does not contain lead	● More expensive than lead chromate and lead sulfo-chromate ● Less lightfast and opaque than lead chromate and lead sulfo-chromate

Sources: BASF 1989, ANPA 1989a, 1989b.

the potential substitute inks. While lead-containing inks have better lightfastness and opacity, the organic substitutes perform well and are constantly improved through research.*

The opacity of the potential substitute inks can be increased by either adding titanium dioxide to thicken the ink, or by "sizing" the printing surface.** The addition of titanium oxide tends to wash out the color of an ink if enough titanium oxide is added to create good opacity. Dialyrid yellow and dialyrid orange are more expensive than lead chromate and molybdate orange (BASF 1989, ICI 1989, ANPA 1989b).

E. Electric Blankets and Heating Pads

Cadmium-containing copper wire has been used in electric blankets and heating pads. This use has not been characterized and potential substitutes have not been evaluated because of the extremely low discard volume. It is likely, however, that other copper alloy wires will be able to fully supplant the cadmium-containing wires. Table 52 presents the discards in MSW of cadmium wire for electric blankets and heating pads.

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* The American Newspaper Publishers Association (ANPA) produces lead-free ink (trace amounts of lead and cadmium impurities are found in all ink formulations as a processing by-product); 97 percent of all newspapers published in the U.S. use ANPA inks (BASF 1989).

** "Sizing" a surface means precoating it before the application of ink such that the ink will provide more even and opaque coverage of the surface.

Table 52. Discards of Cadmium in Electric Blankets in MSW

Year	Cadmium Discards (tons)
1970	1
1975	1
1980	1
1986	1

ª Assumes a product lifetime
of 8 years.

Source: EPA 1989.

F. References

ANPA. 1989a (August 14). G. Cashau, Director of Technical Research, American Newspaper Publishers Association, Reston, VA. Transcribed telephone conversation with Thomas R. Hok, ICF Incorporated, Fairfax, VA.

ANPA. 1989b (August 14). P. Volpe, Technical Coordinator, National Association of Printing Ink Manufacturers, Westchester, NY. Transcribed telephone conversation with Thomas Hok, ICF Incorporated, Fairfax, VA.

ANPA. 1989c (August 30). G. Cashau, Director of Technical Research, American Newspaper Publishers Association, Reston, VA. Transcribed telephone conversation with Louis Gardner, ICF Incorporated, Fairfax, VA.

BASF. 1989 (August 14). R. Wagner, Manager in Charge of Product Compliance, BASF, Clifton, NJ. Transcribed telephone conversation with Thomas Hok, ICF Incorporated, Fairfax, VA.

EPA. 1978. U.S. Environmental Protection Agency. Assessment of Industrial Hazardous Waste Practices -- Rubber and Plastics Industry, Rubber Products Industry.

EPA. 1989 (January). U.S. Environmental Protection Agency. Characterization of Products Containing Lead and Cadmium in Municipal Solid Waste Facilities 1970 to 2000. Prepared by Franklin Associates Ltd., Prairie Village, KS.

Gates Rubber. 1989 (June 1). E. Karger. Denver, CO. Transcribed telephone conversation with Thomas Hok, ICF Incorporated, Fairfax, VA.

ICI. 1989 (August 3). J. Klein, Lab Manager, ICI Americas Incorporated, Wilmington, DE. Transcribed telephone conversation with Thomas Hok, ICF Incorporated, Fairfax, VA.

Kirk-Othmer. 1983. Encyclopedia of Chemical Technology. John Wiley and Sons Publishing Co. Vol. 14, pp. 493-496; Vol. 20, p. 338.

Pigment Handbook. 1973. Volume 3; First Edition.

Polysar. 1989 (June 1). J. Dunn. Polysar, Canada. Transcribed telephone conversation with Thomas Hok, ICF Incorporated, Fairfax, VA.12

Wine Institute. 1989 (June 1). W. Lee. San Francisco, CA. Transcribed telephone conversation with Peter Weisberg, ICF Incorporated, Fairfax, VA.