Table 4-3. LCD lead-containing inputs by life-cycle stage

Life-cycle stage	Input	Quantity	Units	Type
Materials processing	Lead (Pb, ore)	2.47E-05	kg	Ancillary material
Manufacturing	Printed wiring board (PWB)	3.74E-01	kg	Primary material
Manufacturing	Solder (60% tin, 40% lead)	3.81E-02	kg	Primary material
Manufacturing	Solder (63% tin; 37% lead)	2.24E-02	kg	Primary material
Manufacturing	Solder, unspecified	7.35E-05	kg	Ancillary material

Material inputs can be raw materials such as lead ore, or output materials from a previous process or life-cycle stage. For example, small quantities of lead extracted from lead ore are sometimes used as additives in the production of several materials including ferrite, steel, and invar. Once extracted, lead is an input material to the manufacturing processes of several CRT components including CRT glass manufacturing and the manufacturing of the sealing frit paste, which then is an input for the CRT tube manufacturing process. Similarly, lead is used to produce solder which is then used to produce PWBs used in LCDs and CRTs.

Releases of lead and lead-based materials into the environment occur throughout the entire life cycle of the computer display. Environmental releases include airborne, waterborne, solid waste, and radioactive emissions of lead isotopes associated with nuclear fuel reprocessing. Similar to the inputs, emissions data were aggregated by the material released from individual processes and then reported by life-cycle stage. The lead or lead-based material released, the quantity of the release, the type of release (e.g., waterborne), and the ultimate disposition of the release all contribute to the environmental impacts.

The life-cycle outputs containing lead for both CRTs and LCDs are shown in Tables 4-4 and 4-5, respectively. More detailed data on lead and lead-based outputs for each process are presented in Appendix N.

Table 4-4. Life-cycle lead outputs to the environment from CRTs

Life-cycle stage	Output	Quantity	Units	Type	Disposition
Materials processing	Lead	1.66E-03	kg	Airborne	Air
Materials processing	Lead	2.29E-08	kg	Solid waste	Landfill
Materials processing	Lead compounds	1.59E-05	kg	Waterborne	Surface water
Materials processing	Lead-210 (isotope)	1.02E+00	Bq	Radioactivity	Air
Manufacturing	Broken CRT glass	1.88E-03	kg	Hazardous waste	Landfill
Manufacturing	Broken CRT glass	1.08E+00	kg	Solid waste	R/R
Manufacturing	Cinders from CRT glass mfg (70% PbO)	8.26E-03	kg	Hazardous waste	Landfill
Manufacturing	CRT glass faceplate EP dust (Pb) (D008 waste)	1.03E-03	kg	Hazardous waste	Landfill
Manufacturing	CRT glass funnel EP dust (Pb) (D008 waste)	5.01E-03	kg	Hazardous waste	R/R
Manufacturing	Frit	2.99E-03	kg	Hazardous waste	Landfill
Manufacturing	Hazardous sludge (Pb) (D008)	1.52E-03	kg	Hazardous waste	Landfill
Manufacturing	Lead	1.03E-06	kg	Waterborne	Treatment
Manufacturing	Lead	1.30E-05	kg	Airborne	Air
Manufacturing	Lead	4.64E-05	kg	Waterborne	Surface water
Manufacturing	Lead (Pb, ore)	4.41E-07	kg	Airborne	Air
Manufacturing	Lead compounds	1.62E-05	kg	Waterborne	Treatment
Manufacturing	Lead compounds	1.17E-09	kg	Waterborne	Surface water
Manufacturing	Lead contaminated grit (D008 waste)	3.46E-05	kg	Hazardous waste	Landfill
Manufacturing	Lead debris (D008 waste)	2.14E-04	kg	Hazardous waste	Landfill
Manufacturing	Lead sulfate cake	2.67E-05	kg	Hazardous waste	Landfill
Manufacturing	Printed wiring board (PWB)	3.70E-02	kg	Solid waste	R/R
Manufacturing	PWB-Solder dross	6.70E-02	kg	Hazardous waste	R/R
Manufacturing	Sludge from CRT glass mfg (1% PbO)	8.77E-04	kg	Hazardous waste	Landfill
Manufacturing	Waste batch (Ba, Pb) (D008 waste)	1.41E-03	kg	Hazardous waste	Landfill
Manufacturing	Waste finishing sludge (Pb) (D008 waste)	2.56E-04	kg	Hazardous waste	Landfill
Use	Lead	1.27E-05	kg	Airborne	Air
End-of-life	Lead	1.42E-05	kg	Airborne	Air
End-of-life	Lead compounds	1.60E-09	kg	Waterborne	Surface water
End-of-life	Printed wiring board (PWB)	1.46E-01	kg	Hazardous waste	R/R

R/R = recycling/reuse

Table 4-5. Life-cycle lead outputs to the environment from LCDs

Life-cycle stage	Outputs	Quantity	Units	Type	Disposition
Materials processing	Lead	3.13E-06	kg	Airborne	Air
Materials processing	Lead	5.42E-09	kg	Solid waste	Landfill
Materials processing	Lead compounds	3.68E-06	kg	Waterborne	Surface water
Materials processing	Lead-210 (isotope)	3.21E-01	Bq	Radioactivity	Air
Manufacturing	Lead	8.84E-06	kg	Airborne	Air
Manufacturing	Lead	8.33E-07	kg	Waterborne	Treatment
Manufacturing	Lead (Pb, ore)	1.48E-06	kg	Airborne	Air
Manufacturing	Lead compounds	5.67E-11	kg	Waterborne	Surface water
Manufacturing	Lead compounds	7.14E-06	kg	Waterborne	Treatment
Manufacturing	Printed wiring board (PWB)	7.50E-03	kg	Solid waste	Landfill
Manufacturing	PWB-Lead contaminated waste oil	5.14E-03	kg	Hazardous waste	Treatment
Manufacturing	PWB-Solder dross	2.96E-02	kg	Hazardous waste	Recycling/ reuse
Manufacturing	Waste batch (Ba, Pb) (D008 waste)	6.55E-05	kg	Hazardous waste	Landfill
Manufacturing	Waste CCFL, with lead	8.17E-08	kg	Hazardous waste	Treatment
Use	Lead	4.76E-06	kg	Airborne	Air
End-of-life	Lead	4.76E-06	kg	Airborne	Air
End-of-life	Lead compounds	4.98E-10	kg	Waterborne	Surface water

4.1.3 Computer Display Life-Cycle Impacts for Lead

The life-cycle impacts of lead, lead compounds, and materials containing lead (e.g., lead-based solder on printed wiring boards) calculated for CRTs and LCDs during the LCIA are summarized in Tables 4-6 and 4-7 respectively. Impact scores in the table are expressed in units specific to each impact category (see Chapter 3.1 for a discussion of impact category units and weighting). The total impact score for each category resulting from lead and lead-based materials is presented at the bottom of each table.

Table 4-6. Summary of Lead Impact Scores for CRTs

Life-cycle stage	Material	Impact Scores by Category							
		Non-renewable resource (kg)	Hazardous waste landfill use (m^3)	Solid waste landfill use (m^3)	Radio-activity (Bq)	Chronic health effects-public (tox-kg)	Chronic health effects-occupational (tox-kg)	Aquatic toxicity (tox-kg)	Terrestrial toxicity (tox-kg)
Materials processing	Lead	0	0	0	0	3.31e-03	0	0	1.66e-03
	Lead (Pb, ore)	4.96e-01	0	0	0	0	0	0	0
	Lead compounds	0	0	0	0	3.17E-05	0	3.10e-04	1.59E-05
	Lead-210 (isotope)	0	0	0	1.02E+00	0	0	0	0
Manufacturing	Broken CRT glass	0	6.22E-07	0	0	0	0	0	0
	Cinders from CRT glass mfg (70% PbO)	0	6.88E-06	0	0	0	0	0	0
	CRT glass faceplate EP dust (Pb) (D008 waste)	0	2.15E-06	0	0	0	0	0	0
	Frit	0	3.04E-06	0	0	0	0	0	0
	Hazardous sludge (Pb) (D008)	0	1.38E-06	0	0	0	0	0	0
	Lead	4.94e-01	0	0	0	1.19e-04	9.88e-01	9.3E-05	5.94E-05
	Lead compounds	0	0	0	0	2.35E-09	0	2.3E-08	1.17E-09
	Lead contaminated grit (D008 waste)	0	2.99E-09	0	0	0	0	0	0
	Lead debris (D008 waste)	0	1.85E-08	0	0	0	0	0	0
	Lead sulfate cake	0	3.03E-08	0	0	0	0	0	0
	Sludge from CRT glass mfg (1% PbO)	0	6.45E-07	0	0	0	0	0	0
	Waste Batch (Ba, Pb) (D008 waste)	0	1.22E-07	0	0	0	0	0	0
	Waste finishing sludge (Pb) (D008 waste)	0	2.32E-07	0	0	0	0	0	0
Use	Lead	0	0	0	0	2.55E-05	0	0	1.27E-05
End-of-life	Lead	0	0	0	0	2.85E-05	0	0	1.42E-05
	Lead compounds	0	0	0	0	3.19E-09	0	3.1E-08	1.6E-09
Total Impact Scores By Category		**9.89e-01**	**1.52E-05**	**0**	**1.02E+00**	**3.52e-03**	**9.88e-01**	**4.00e-04**	**1.80e-03**

Table 4-7. Summary of lead impact scores for LCDs

Life-cycle stage	Material	Impact scores by category							
		Non-renewable resource (kg)	Hazardous waste landfill use (m^3)	Solid waste landfill use (m^3)	Radio-activity (Bq)	Chronic health effects-public (tox-kg)	Chronic health effects-occupational (tox-kg)	Aquatic toxicity (tox-kg)	Terrestrial toxicity (tox-kg)
Materials processing	Lead	0	0	0	0	6.26E-06	0	0	3.13E-06
	Lead (Pb, ore)	2.47E-05	0	0	0	0	0	0	0
	Lead compounds	0	0	0	0	7.36E-06	0	7.25E-05	3.68E-06
	Lead-210 (isotope)	0	0	0	3.21E-01	0	0	0	0
Manufacturing	Lead	0	0	0	0	1.77E-05	0	1.64E-05	8.84E-06
	Lead compounds	0	0	0	0	1.13E-10	0	1.12E-09	5.67E-11
	Printed wiring board (PWB)	0	0	9.38E-06	0	0	0	0	0
	Waste Batch (Ba, Pb) (D008 waste)	0	5.67E-09	0	0	0	0	0	0
Use	Lead	0	0	0	0	9.52E-06	0	0	4.76E-06
End-of Life	Lead	0	0	0	0	9.52E-06	0	0	4.76E-06
	Lead compounds	0	0	0	0	9.95E-10	0	9.80E-09	4.98E-10
Total Impact Scores By Category		**2.47E-05**	**5.67E-09**	**9.38E-06**	**3.21e-01**	**5.03E-05**	**0**	**8.9E-05**	**2.52E-05**

Impact scores for some lead-based inputs and outputs shown in Tables 4-2 though 4-5 were not calculated if the type and disposition of the input or release was not expected to contribute to any of the impact categories. For example, a waterborne release of lead with a disposition going to treatment assumed that lead was not yet released to the environment where impacts could occur, and therefore no impacts were calculated. However, since inventory data for subsequent disposal processes could not be obtained, it was assumed the lead (or other inventory item) had been removed to a level such that the subsequent release of treated wastewater would not contribute significantly to the impact. Similarly, impact scores were not calculated for releases going to recycling/reuse or for product outputs.

Lead-based impacts from the CRT ranged from moderately to significantly greater than those from the LCD in every category, with the exception of solid waste landfill use. The most significant difference was in non-renewable resource consumption, where the CRT (989 grams) consumed over 40 thousand times the mass of non-renewable resources over the course of its life cycle than those consumed by the LCD (0.025 grams). Hazardous waste landfill use is another significant difference, with lead-based life-cycle outputs from CRTs using over 2,600 times the space of the lead-based outputs from LCDs. However, the absolute volume of waste from the CRT is still a relatively small volume (1.50 cm^3). Other categories where CRTs had notably greater impacts as a result of lead include the chronic public health effects and terrestrial toxicity impact categories.

Based on the CDP LCIA methodology, chronic occupational health effect impacts were only calculated for lead inputs (excluding lead ore) to processes in the computer display life cycle. Only the manufacturing life-cycle stage had lead inputs from which impacts were calculated as shown in Table 4-6. The overall impact scores (0.988 tox-kg for CRT, none for LCD) likely underestimate the chronic occupational impacts for lead because they do not consider chronic occupational impacts from other processes such as the mining, smelting, and refining of the lead, which are known to pose potential occupational exposures (see Section 4.1.4). For a more detailed discussion of how chronic occupational health effect impacts were calculated, refer to Section 3.1.2.12.

The contribution of lead-based impacts for each computer display technology to the overall impacts for each individual impact category is shown in Table 4-8. Values in the table are expressed in the percent contribution the material made to the overall impact score for all materials (e.g., mercury, fuel oil, glass) for each category. The percent contributions give an indication of the importance of lead-based impacts relative to the life-cycle impacts from other materials or outputs from the computer display.

Table 4-8. Summary of percent contributions from lead-based materials to individual impact categories

Impact category	CRT	LCD
Non-renewable resource	1.48E-01 %	6.78E-06 %
Hazardous waste landfill use	8.99E-02 %	1.57E-04 %
Solid waste landfill use	NA	1.73E-02 %
Radioactivity	2.70E-08 %	2.63E-06 %
Chronic health effects- public	1.80E-04 %	5.58E-06 %
Chronic health effects- occupational	1.10E-01 %	N/A
Aquatic toxicity	1.96E-01 %	1.71E-03 %
Terrestrial toxicity	8.90E-05 %	2.82E-06 %

N/A= Not applicable

It can be seen from Table 4-8 that the contributions of lead-based impacts are not significant relative to the total impacts from other materials (e.g., glass, copper wire, electronic components) in each category. Impacts from lead-based CRT outputs in the categories of nonrenewable resources, aquatic toxicity, and chronic public health effects are all range from 0.1-0.2% of the overall impact scores in each category.

4.1.4 Exposure Summary

Lead may pose a threat to human health anytime there is the potential for human exposure to the lead throughout the life cycle of a computer display. Exposure occurs anytime a chemical or physical agent, in this case lead or lead compounds, comes into contact with an organism, be it human or ecological. This section qualitatively identifies potential exposures for three groups: occupational workers in facilities using lead (occupational exposures), the general population living nearby these facilities which may be exposed to lead releases into the ambient environment, and ecological populations in the area surrounding a facility.

4.1.4.1 Occupational exposures

Workers are typically exposed to far greater concentrations of chemicals for longer periods of time than other populations. Worker exposures to lead can be especially serious given the overall toxicity of lead and lead compounds. As a result, both employers and government agencies have adopted recommendations or requirements for employers who wish to limit worker exposures.

Occupational exposures can occur anytime a worker comes into contact with lead, whether it be through dermal (skin) contact with a part containing lead (e.g., lead oxide coating on glass funnel), through the inhalation of lead particulates dispersed into the air, or through the inadvertent ingestion of lead. Many of the primary and support processes required to manufacture computer displays have lead in the workplace, and correspondingly, the potential for worker exposure. The processes associated with lead inputs and outputs throughout the computer displays' life cycles are presented in Tables N-1 through N-4 in Appendix N. It is important to note that while this list gives an indication of where likely lead exposures may occur, it is not exhaustive. Many processes and subprocesses may be contained within a process listed, each of which may pose its own potential for occupational lead exposures.

Exposures to lead are more likely to occur during the extraction, manufacturing, and disposal life-cycle stages of a computer display. During the use of the computer display, potential exposures to lead are unlikely as the components containing the lead are contained within the outside shell of the computer display, limiting the opportunity for contact with consumers. Table 4-9 presents some typical pathways leading to the occupational exposure of workers to lead over the life cycle of a computer display.

Table 4-9. Potential occupational exposure pathways for lead over the life cycle of a computer display

Exposure route	Transport media	Example mechanisms of exposure
Inhalation	Air	Lead fumes resulting from the vaporization of lead during smelting
	Air	Lead oxide dust released to the air during lead frit manufacturing
	Air	Lead aerosols created during the aeration of tin/lead solder plating baths during PWB production
Dermal	Direct contact	Handling of leaded CRT glass funnels prior to assembly
Ingestion	Direct contact	Consumption of food eaten with lead-contaminated hands (or drinking, smoking, etc)
	Air	Ingestion of lead contaminated soil particles which become airborne during lead mining

Workers may be exposed to airborne lead concentrations through the release of lead dust, fumes, or aerosols into the workplace. The lead is transported by the air, where it is inhaled into the lungs and then absorbed into the bloodstream. The greatest potential for high-level occupational exposure is during lead smelting and refining, where lead is vaporized during high temperature heating resulting in the release of lead fumes and small respirable particles of lead (EPA, 1986). Lead concentrations in air at three primary lead smelters were found to range from 80-2,900 $\mu g/m^3$, peaking at a level 58 times the OSHA recommended guidance level of 50 $\mu g/m^3$ (HSDB, 2001). Another study found that during the smelting and refining of lead, mean concentrations of lead in air reached as high as 4,470 $\mu g/m^3$, nearly 90 times the OSHA guidance level (Fu and Bofetta, 1995). Exposures to lead dust may also occur during lead mining, frit manufacturing, CRT glass manufacturing, or processes in which metallic lead is heated in the presence of air. Exposures to lead fumes are only possible during high temperature operations (above 500°C), such as welding or spray coating of metals with molten lead (Sittig, 1985).

Dermal exposures can take place anytime lead or materials containing lead are physically handled by workers. Opportunities for dermal exposures to lead are numerous in processes throughout the computer display life-cycle, as many processes involve lead or parts containing lead, especially in CRT manufacturing. Lead can be transferred to the skin of workers through contact with lead-containing materials and parts. Dermal exposures may also occur during cleaning and maintenance of equipment used to smelt, refine, or apply lead in a molten state (e.g., solder wave machinery for PWBs) or in areas with large airborne lead concentrations that may settle out onto work surfaces directly contacted by workers.

The contribution of dermal exposures to the overall lead body burden is uncertain. It is believed that most forms of lead are unable to readily penetrate the skin, allowing only a small amount of lead to enter the bloodstream. (ATSDR, 1999). Alkyl lead compounds, which are the known exception, are primarily used as additives in gasoline and are not used directly in computer display manufacturing (Bress and Bidanset, 1991; ATSDR, 1999). Therefore, dermal exposures to inorganic lead compounds are not expected to be as significant as the inhalation or ingestion routes of exposure (EPA, 1986).

Along with inhalation, ingestion of lead-bearing dust and fumes is a major route of exposure in lead smelting and refining industries (EPA, 1986). Airborne dust particles of lead can eventually settle onto skin, equipment, clothing, and work surfaces, where they may be subsequently transferred to the mouth and become ingested. Airborne particles may also be inhaled and swallowed, directly when greater than 5 micrometers in size (ATSDR, 1999). Once ingested, the amount of lead that reaches the bloodstream through the stomach depends on a number of factors, such as the age of the subject, length of time since last meal, and how well the lead was able to dissolve in the stomach. Studies have found that roughly 6% of the lead ingested will absorb into the blood stream of an adult who has recently eaten (within the last day), while upwards of 60-80% was absorbed in adults who had not recently eaten (ATSDR, 1999).

Lead exposures of workers are frequently measured by biological testing (e.g., blood lead levels, urinary lead levels) rather than monitoring the workplace for lead concentrations, making occupational data on lead exposures often not readily available (EPA, 1986). For a discussion of blood lead levels, corresponding effects, and recommended exposure guidelines, refer to Section 4.1.5 of this chapter.

Blood-lead levels have been reported in studies of workers for several industries relevant to computer display manufacturing. For example, workers occupationally exposed to lead during glass production were tested to determine their blood lead levels. Workers were divided into groups based on work activities and blood samples were collected at the end of each shift. Concentrations of lead in the blood ranged from 70 to 680 µg/l, with median values ranging from 170 to 340 $\mu g/m^3$, depending on the worker group. Data on types and rates of exposure were not identified (Ludersdorf *et al.,* 1987). Another study found that workers producing ceramic coated capacitors and resistors using leaded glass were exposed to occupational lead levels ranging from 61 to 1,700 $\mu g/m^3$. Blood lead levels ranged from 16 to 135 µg/dL in these same workers, greatly exceeding the OSHA recommended level of 50 $\mu g/m^3$ (Kaye *et al.*, 1987).

The presence of lead in the workplace does not mean that occupational exposures are unavoidable. Worker exposures to lead can be reduced or even eliminated through the use of personal protective equipment, sound operating practices, or through advanced machinery that protects workers from exposure (e.g., an enclosed and vented wave solder machine). To determine actual worker exposures to lead, a complete exposure assessment specific to each manufacturing process would be required.

4.1.4.2 General population

The general population living nearby a manufacturing facility using lead may potentially be exposed to lead emissions from the facility into the surrounding ambient environment. The likelihood and quantity of the potential exposure is dependent on the type and quantity of release, the receiving media, the local environmental conditions, and the fate and transport characteristics of the release. General population exposure to lead is most likely to occur through ingestion of lead contaminated food, water, and soil, as well as through inhalation of lead particulates in the ambient air (EPA, 1986).

Lead released into the ambient air will typically be in the form of lead particulate matter, which is eventually removed from ambient air through washout by precipitation (rain or snow) or through gravitational settling. Estimates indicate that the majority of lead released into the environment is dispersed into the atmosphere (EPA, 1980). With a relatively small mass mean diameter of 0.55 µm (HSDB, 2001), lead-containing particles can stay aloft for up to 64 hours and travel 1600 km, though they are more likely to be deposited within 10 km of the emission source (HSDB, 2001). General populations living near a source of lead emissions may encounter the lead while it is still airborne, leading to potential inhalation exposure. The direct inhalation of lead accounts for only a small part of the overall lead exposure to nearby populations, although the reentrainment of lead-contaminated soil is a common route of exposure (ATSDR, 1999).

Ingestion of lead is the most significant route of exposure for general populations (ATSDR, 1999). Particulates removed from the air are deposited into the soil, surface water, and onto local vegetation, where they may be ingested by nearby residents. Grains, vegetables, and fruits grown in close proximity to a source of lead emissions may contain lead which has been absorbed from contaminated soil through the root system. Lead also has the ability to bioaccumulate in the soft tissues of fish and wildlife, which are then consumed by sportsmen and their families.

Incidental ingestion of soil, which may occur while eating or smoking with soil-coated hands or when soil becomes reentrained and swallowed directly, often results in the largest lead exposures to residents living near emission sources. Lead-contaminated soil can also enter the home by being tracked into the house or carried home from the workplace on clothing, where it can come into contact with eating surfaces or food and become ingested. A study measuring lead in the home found mean lead levels as high as 22,191 µg/g in homes located within 1.6 km of a lead smelting facility, and mean levels of 2,687 µg/g in homes of workers at the smelting facility, irrespective of distance from the plant (ATSDR, 1999). One study found that once lead is swallowed, up to 50% of the lead is released from the contaminated soil into the stomach after only 10 minutes (HSDB, 2001).

Lead may also be released directly to surface water or indirectly to groundwater through the leaching of lead from landfills. Life-cycle inventory releases to surface water include 464 grams of lead and 159 grams of lead compounds per CRT. Surface water may also become contaminated through soil deposition or through surface water run-off from contaminated soil. Groundwater lead contamination from the leaching of lead-contaminated debris from solid- or hazardous waste disposal sites is unlikely to be significant due to the relative insolubility of lead (HSDB, 2001). Lead released to both surface waters and groundwater will typically remain insoluble, forming precipitates and settling into the sediment of the lake or stream. However, very little lead is typically found in U.S. waters which are used to supply the public with drinking water, due to strict governmental regulations (0.005 ppm lead) (ATSDR, 1999).

4.1.4.3 Ecological populations

Inorganic lead typically does not pose a significant health threat to fish and wildlife populations, except at extremely high concentrations. Once introduced into surface waters, the levels of soluble lead depend on the pH of the water and the dissolved salt content. At neutral pH, inorganic lead typically does not remain soluble in water at high concentrations, forming a precipitate that ultimately deposits in the sediment. However, as the alkalinity and pH decrease, the relative soluble concentrations of lead may become higher.

Toxic substances such as lead are capable of concentrating in the tissues of fish and wildlife. The bioconcentration of lead in fish is low-to-moderate in most species, with a bioconcentration factor (BCF) of 42 an 45 being reported for two fresh water fish species[1]. However, BCFs for certain other species, such as blue mussles (4,985), eastern oysters (1,000+) and 4 types of fresh water invertebrate species (range of 499 to 1,700), were much higher (EPA, 1999).

4.1.5 Human Health Effects

Lead has been classified by EPA as a persistent biaccumulative toxic (PBT) chemical (EPA, 2001b). PBT pollutants are highly toxic, long-lasting substances that can build up in the food chain to levels that are harmful to human and ecosystem health. Lead's ability to persist in the environment without breaking down, along with its tendency to bioaccumulate, poses adverse health effects to birds and mammals at the top of the food chain, along with anyone who consumes them for food. Lead and lead-based compounds have been associated with a range of adverse human health effects, including effects on the nervous system, reproductive and developmental problems, and cancer.

4.1.5.1 Chronic effects (noncancer)

Lead is toxic to human health regardless of the form (Gosselin, 1984). It is one of the most hazardous of the toxic compounds because the dose of lead is cumulative over a lifetime, and the health effects are many and severe. Lead has been known to cause hematological, gastrointestinal, and neurological dysfunction in adults and children. Chronic exposures have also caused hypertension and reproductive impairment in both men and women, as well as slowed development in children (Sittig, 1985).

Adverse effects, other than cancer or mutations, are generally assumed to have a dose or exposure threshold. A reference dose (RfD) is an estimate of the daily exposure through ingestion to the human population that is likely to be without an appreciable risk of noncancer detrimental effects during a lifetime. Likewise, a reference concentration (RfC) represents an estimate of the daily inhalation exposure to the human population that is likely to be without an appreciable risk of noncancer detrimental effects during a lifetime.

Because of the relative toxicity of lead and the cumulative nature of lead doses, a safe level of human exposure has yet to be identified by researchers, preventing EPA from

[1] Bioconcentration is defined by EPA as the non-dietary accumulation of chemicals in aquatic organisms (U.S. EPA, 1999).

establishing a RfD or RfC for inorganic lead (ATSDR, 1999). Instead, lead exposure is determined by using exposure biokinetic models that relate exposure levels to an estimated blood lead level, which is then compared to actual blood lead levels where adverse effects are known to occur[2]. For example, increased blood pressure has been observed in adults with a blood-lead level as low as 7 µg/dL (ACGIH, 1991). Lead concentrations in excess of 60 µg/100g blood have been associated with neuropathy, gastrointestinal disturbances, and anemia, while workers with blood-lead levels between 50-70 µg/100 g to have shown decreased neural response (ACGIH, 1991).

As a guideline, a blood-lead level of concern for adult workers of 30 µg/dL has been established by both the Occupational Safety and Health Administration (OSHA) and ACGIH. A guideline of 10 µg/m^3 (for a child) has been set by the Center for Disease Control (CDC) for general population exposures to lead in the ambient environment. A summary of human health effect guidelines for lead is presented in Table 4-10.

Table 4-10. Human health effect regulations and guidelines for lead

Type	Agency/Category	Regulatory level
Workplace exposures to lead		
Worker blood-lead target/action levels	OSHA, Adults who “wish to bear children”	30 µg/dL
	OSHA, Blood-lead level of concern	40 µg/dL
	OSHA, Medical removal	50 µg/dL
	ACGIH, Biological Exposure Index (BEI) Blood-lead level of concern (ACGIH, 1998)	30 µg/dL
	NIOSH, level to be maintained through air concentrations	60 µg/100 g
Pregnant worker: fetal blood-lead target/action levels	OSHA	30 µg/100 g
	CDC	10 µg/dL[a]
Workplace air exposure limit	OSHA Permissible exposure limit (PEL)	50 µg/m^3
	NIOSH Recommended exposure limit (REL) (NIOSH, 1997)	100 µg/m^3
	ACGIH TLV TWA (ACGIH, 1998)	50 µg/m^3
Ambient environment exposures to lead		
Blood-lead target/action levels for child	CDC	10 µg/m^3 [a]
	OSHA	30 µg/100 g
	World Health Organization blood-lead level of concern	20 µg/dL

[a] CDC considers children to have an elevated level of lead if the amount of lead in the blood is at least 10 µg/dL. Medical evaluation and environmental remediation should be done for all children with blood-lead levels greater than 20 µg/dL. Medical treatment may be necessary for children with a blood-lead concentration above 45 µg/dL (RTI, 1999).

Notes: ACGIH: American Conference of Governmental Industrial Hygienists; NIOSH: National Institute for Occupational Safety and Health; TWA: Time weighted average; TLV: Threshold limit value

[2] In order to estimate blood-lead levels, worker exposure levels based on releases reported in the inventory would be required. However, without information pertaining to the exposure conditions (which is unavailable to this study) and fate and transport of the releases, worker exposure cannot be calculated.

4.1.5.2 Carcinogenicity

The potential for a chemical to cause cancer is evaluated by weight-of-evidence classifications, specific to the rating organization, which are typically determined by laboratory or epidemiological studies. Lead and inorganic lead-based compounds have been classified by the International Agency for Research on Cancer (IARC) as possible human carcinogens (Group 2B), based on sufficient evidence of carcinogenicity in animals (IARC, 1987). Lead has also been classified as an A3 carcinogen (confirmed animal carcinogen with unknown relevance to humans) by the American Conference of Governmental Industrial Hygienists (ACGIH, 1998). The U.S. EPA has given lead a weight-of-evidence classification of B2, indicating lead is a probable human carcinogen and a confirmed animal carcinogen (IRIS, 1999). There is currently no established cancer slope factor for lead, which could be used to estimate cancer risk from an exposure amount.

4.1.6 Environmental Regulations for Lead

Apart from the regulations and recommendations regarding worker safety presented in the previous section, lead is regulated in a number of ways. This section presents a brief summary of the U.S. regulations for lead and lead compounds expected to impact facilities that manufacture materials for the computer display. It should be noted that many of the parts and materials which go into the manufacture of computer displays are manufactured in countries outside the U.S., with their own lead regulations which may differ significantly from those discussed below.

Air emissions of lead are regulated under the Clean Air Act (CAA) of 1970 and the amendments to the CAA of 1977 and 1990. Under the CAA, lead is regulated as a hazardous air pollutant (HAP), which is by definition a chemical that is generally known or suspected to cause serious health problems. Stationary source categories involved in the life cycle of a computer display that must meet new source performance standards include primary and secondary lead smelters, glass manufacturing plants, and metallic mineral processing plants (EPA, 1977; EPA, 1980a; ATSDR, 1999). A National Ambient Air Quality Standard (NAAQS) was also established for lead, requiring that the concentration of lead in air that the public breathes be no higher than 1.5 $\mu g/m^3$ averaged over 3 months [40 CFR 50.12].

Lead releases to surface water are regulated under the Clean Water and Effluent Guidelines and Standards promulgated under the Clean Water Act of 1977. Lead is identified as a priority pollutant [40 CFR 401.15], requiring the limitation of lead concentrations in pollutant discharges from point sources. The regulations also set standards of performance for new point sources, as well as pretreatment standards for both new and established sources. Regulated point source categories include lead smelters, steam electric power generation, glass manufacturers, and aluminum production and others, all of which contribute to the life-cycle impacts of a computer display. New point sources of lead contamination must also apply for National Pollution Discharge Elimination System (NPDES) permits which will establish effluent limits for sources of lead discharge.

To protect the population from a contaminated water supply, toxic substances in drinking water are regulated under the Safe Drinking Water Act of 1986. A federal drinking water standard of 15 ug/L has been established for lead.

EPA also regulates lead content in hazardous and solid wastes under the Resource Conservation and Recovery Act (RCRA). A solid waste containing lead or lead compounds may be considered a D008 characteristic hazardous waste if, when subjected to a Toxicity Characteristic Leachate Procedure (TCLP) test, the extract exceeds 5.0 mg/L [40 CFR 261.24] for lead. Other lead-contaminated wastes may be considered hazardous if specifically listed in 40 CFR 261.30-33, unless specifically excluded. Listed wastes from specific sources which contribute to the manufacture of computer displays include emission control dust from steel production and from lead smelting (K061 and K069 respectively), waste leaching solution of control dust from secondary lead smelting (K100), and spent baths and residues from electroplating operations containing cyanide (F006), which are sometimes used in PWB manufacturing. Specific sources of hazardous wastes, whether characteristic or listed wastes, are subject to handling, storage, and disposal restrictions detailed in the code of federal regulations.

Manufacturers who emit lead are required to report the quantity of the emissions under the Community Right-to-Know Act. EPA has recently reduced the reportable quantity threshold for lead from 10,000 lbs per year to 100 lbs per year of lead.

4.1.7 Alternatives to Lead Use in Computer Displays

Because of increasing pressure through regulation and market forces, attempts to reduce or eliminate lead in electronics have become popular. Several countries are considering or have already passed restrictions on the use and disposal of lead, prompting many companies to establish aggressive timelines for reducing or eliminating lead in their products. Several opportunities to eliminate or reduce the amount of lead used in a computer display are being aggressively researched. Two options being researched extensively are the development of a reduced lead frit, and lead-free solders for PWB manufacturing and assembly.

Although not large in mass in a monitor, frit glass is 70 to 80% lead by weight. Lead is one component of a mixture that crystalizes under intense heat, providing strength to the vacuum-tight frit seal. An alternative lead-free frit glass has been developed that is based on tin and zinc oxides, along with phosphate (Busio and Steigelmann, 2000). The lead-free glass is inherently mechanically weak, requiring large amounts of ceramic fillers (Al2O3) to be added to improve the mechanical strength of the seal. It also requires the addition of vitreous silica particles to match the thermal expansion requirements of the CRT glass. The resulting mixture requires a firing cycle approaching 450ºC, which is typical of frit glasses. A drawback is that the frit glasses stay vitreous during the typical 30-60 minute furnace dwell time. However, initial evidence suggests that the fired frit seal remains rigid during the pumping step, which occurs at 350ºC. Although comprehensive test results are not yet available, the high-temperature stability and rigidity of the lead-free frit glass is currently being tested under vacuum (Busio and Steigelmann, 2000).

Lead-free solders have been the subject of industry research for some time. Driven by renewed regulatory attention and by recent corporate commitments to reduce or eliminate lead from their product lines, alternatives to lead-based solder are garnering increased attention. Alternative lead-free solders include tin in combination with one or more of the following metals: silver, copper, bismuth, germanium, and antimony. Several companies, including Sony, Toshiba, Hitachi, and Ford Motor Company, have either already begun to implement electronics production using a lead-free solder alternative, or have announced plans to do so. Though still a relatively new and untested technology, initial testing has shown that alternatives are capable of producing quality component connections, though they have a narrower operating window and require higher temperatures to apply (Keenan and Kellett, 2001).

workers clothing or on shoes. Studies have discovered potentially high concentrations of lead in households within close proximity to certain facilities that use lead.

- Significant worker exposures to lead have been documented by existing studies of several processes which contribute to the life-cycle of the computer displays (e.g., lead smelting). These exposures have been as high as 90 times the OSHA recommended safety levels for exposure to workers at lead smelters. The resulting occupational chronic health effects to workers from lead exposure likely have been underestimated by the CDP LCIA methodology, which uses material inputs, and not outputs, as surrogates for exposure.
- Lead and lead compounds pose serious chronic health hazards to humans who may become over-exposed either in the workplace, or through the ambient environment. Lead exposure is associated with a range of adverse human health effects, including effects on the nervous system, reproductive and developmental problems, and cancer. Lead persists in the environment, but is relatively immobile in water under most surface and groundwater conditions.
- Alternatives are being developed, such as lead-free solders and glass components, that will potentially minimize the future lead content in both CRTs and LCDs.

4.4.2 Mercury

Mercury is contained within the fluorescent tubes that provide the source of light in the LCD. Mercury is also emitted from some fuel combustion processes, such as coal-fired electricity generation processes, which contribute to the life-cycle impacts of both CRTs and LCDs. EPA's concern with mercury and the potential for exposure during manufacturing and end-of-life processes warranted a more detailed analysis of mercury in the CDP. The following conclusions were drawn from a focused look at mercury's role in the life cycle of the computer display, and its effects on human health and the environment:

- The mercury emitted from the generation of power consumed by the CRT (7.75 mg) exceeds the entire amount of mercury emissions from the LCD, including both the mercury used in LCD backlights (3.99 mg) and the mercury emissions from electricity generation (3.22 mg). Although this was not expected because mercury is used intentionally in an LCD, but not in a CRT, the results are not surprising since mercury emissions from coal-fired power plants are known to be one of the largest anthropogenic sources of mercury in the United States. Because the CRT consumes significantly more electricity in the use stage than the LCD, its use stage emissions of mercury are proportionately higher than those of the LCD.
- Contributions from mercury-based impacts are not significant relative to the total life-cycle impacts from other materials (e.g., glass, copper wire) in the CRT or LCD, with the greatest impacts from mercury-based outputs occurring in the aquatic toxicity category (0.4% for CRTs, 0.01% for LCDs)
- Possible pathways of worker exposure during backlight fabrication include inhalation of mercury vapors, and dermal exposure or ingestion of mercury on skin. The most likely pathway for general population exposure is inhalation of mercury released into the air.
- Exposure data relevant to the manufacturing of mercury backlights were not available, therefore specific conclusions about the potential magnitude of worker exposures could not be made. Occupational chronic health effects to workers from mercury exposures

calculated during the impact assessment (3.99e-06 tox-kg for LCD, none for CRT) likely have been underestimated by the CDP LCIA methodology, which uses material inputs as surrogates for exposure.

- Mercury and mercury compounds pose serious chronic health hazards to humans who are exposed. EPA has determined that mercury chloride and methylmercury are possible human carcinogens. Mercury poses serious chronic health hazards to humans, affecting the nervous system, brain, and kidneys.
- Alternative backlights have been developed that not only eliminate mercury from the light, but also improve on many of the optical characteristics of the displays. Current development is focused on improving the energy efficiency of the alternative lights.

4.4.3 Liquid Crystals

Liquid crystals are organic compounds responsible for generating the image in an LCD. LCs are not present in CRTs. The toxicity of the LCs in LCDs has been alluded to in the literature, yet there is very little known about the toxicity of these materials. By including LCs in a more detailed analysis, this section attempted to better characterize any potential hazard and/or potential exposure of LCs from the manufacturing, use, and disposal of LCD monitors. The following conclusions were drawn from a focused look at LCs role in the life cycle of the computer display, and its effects on human health and the environment.

- LCs are combined into mixtures of as many as 20 or more compounds selected from hundreds of potential liquid crystal compounds. Because of the possible variations in mixtures and the sheer number of compounds available, a select number of liquid crystals were used to assess potential human health hazards.
- LCs do not appear to contribute significantly to any of the impact categories defined for this study. The total score for LCD occupational impacts based on potential worker exposure to LCs of 4.18 tox-grams, calculated using default toxicity values, represents less than 0.01% of the total overall chronic occupational health effects impact score of 898 tox-kg for the functional unit of one LCD.
- Impacts were not calculated for LC releases in the CDP LCIA because data regarding LC outputs were not available to the project. LCs are not used to fabricate CRTs and so have no environmental impacts in the CRT life cycle.
- Occupational exposures to LCs during the fabrication of the LCD panels are not expected to be significant. The enclosed nature of the chamber in which the LCDs are assembled, combined with the equipment (e.g., gloves, aprons) worn by workers in a clean room environment, are both expected to act to minimize exposures. Other occupational exposures may exist that have not been identified.
- Toxicological testing by a manufacturer of LC substances and mixtures showed that 95.6% (562 of 588) of the liquid crystals tested displayed no acute toxic potential to humans. Twenty-five of the remaining twenty-six chemicals had the potential to exhibit harmful effects to humans, while the remaining crystal was classified as toxic (EU classification) and thus was discontinued. An EPA review of toxicity data for the confidential LC compounds was unable to identify any relevant toxicity information. Insufficient toxicity data exist to assess the toxicity of specific LC compounds.

- Testing for mutagenic and carcinogenic effects by the supplier showed that 99.9% (614 out of 615) of the liquid crystal compounds tested displayed no mutagenic effects. The remaining chemical that showed mutagenic potential was excluded from further development. Additionally, mutagenicity testing of ten LC substances using mammalian cells showed no suspicion of mutagenic potential.

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