Chapter 4

QUALITATIVE RISK SCREENING OF SELECTED MATERIALS

The scope of the DfE CDP, as presented in Chapter 1, was to first conduct an environmental life-cycle assessment (LCA) to evaluate a generic 17" CRT and 15" LCD desktop computer display, followed by a streamlined Cleaner Technologies Substitutes Assessment (CTSA), which would target specific materials or processes that warrant further evaluation. Traditionally, the DfE Program has conducted CTSAs that perform detailed risk characterizations of alternative chemical processes. The streamlined CTSA for the CDP takes a more detailed look than the LCA at the toxic effects of chemicals used in a process, without conducting a complete risk characterization typical of past CTSAs.

In order to provide meaningful and timely results, the CDP Core group agreed to select a few materials that are of interest to EPA and industry and conduct analyses concurrently with the LCA, instead of conducting a CTSA on selected materials or processes after the LCA results were presented. The LCA identifies material inputs and outputs and then characterizes them in a life-cycle impact assessment (LCIA). In the human and environmental health effects impact categories, these input and output amounts are used as surrogates for exposure. For the selected materials, the additional CTSA-related analyses are intended to better understand the potential exposures to selected materials, during any processes that use thee materials, in order to try to better understand potential chemical risks.

The materials that were selected for further analysis were lead, mercury, and liquid crystals. The justification for choosing these materials, and a brief description of the scope are provided below:

- **Lead**: Lead is a top priority toxic material at the U.S. EPA. Lead is found in glass components of CRTs, as well as in electronics components (printed wiring boards and their components) of both CRTs and LCDs. The electronics industry is also concerned with lead and continues to take steps to reduce the use of lead in electronics products. Lead has been extensively studied for its toxic effects and has been addressed elsewhere with regard to CRTs and electronics (ATSDR, 1999). Therefore, within the scope of the CDP, lead is recognized as a material of concern, but extensive evaluation beyond the LCA is not conducted. Some discussion of the potential for exposure is included in this chapter, but it references existing studies for further information.
- **Mercury**: Another top priority toxic material at the U.S. EPA is mercury. The fluorescent tubes that provide the source of light in the LCD contain mercury. Although very small amounts of mercury are found in the LCD backlights, EPA's concern with mercury and the potential for exposure during manufacturing and end-of-life processes are reasons why a more detailed analysis of mercury is warranted in the CDP. In addition, mercury is emitted from some fuel combustion processes, such as coal-fired electricity generation processes, and there is interest in the relative magnitude of mercury emissions from these sources as compared to the magnitude of mercury emissions from its intentional use in LCD backlights. Another reason for including mercury is to begin to do an improvement assessment, because there appear to be potential alternatives to backlights with mercury.

- **Liquid crystals**: The toxicity of the liquid crystals in LCDs has been alluded to in the literature and there is a need to better understand the toxicity of these materials as well as provide the appropriate context of potential exposure and any associated risk. For example, during normal use of a display, no exposure would be expected. Liquid crystals are generally organic materials in broad categories such as polycyclic aromatic hydrocarbons (e.g., phenylcyclohexanes, biphenyls) (EIAJ, 1996). By including liquid crystals in a more detailed analysis, this chapter attempts to better characterize any potential hazard and/or potential exposure of liquid crystals from the manufacturing, use, and disposal of LCD monitors.

Choosing these three materials as a priority does not presume that these are the only materials of importance and worthy of additional analyses. The results of the LCI and LCIA in Chapters 2 and 3 provide more information on where to focus additional analysis efforts or improvements. Chapter 5 also identifies some potential improvement opportunities.

Sections 4.1 through 4.3 present the qualitative risk screening of lead, mercury, and liquid crystals, respectively. Subsections in each section briefly describe the following:

- *The use of the materials in computer displays:* These subsections describe how the materials are used in computer displays and give information on the mass used in particular applications.
- *Life-cycle inputs and outputs of the materials from computer displays:* The life-cycle assessment approach not only focuses on the material contained within the product, but also emphasizes the environmental impacts of material inputs and outputs from every life-cycle stage. These subsections summarize the life-cycle inputs and outputs of the materials found in the CDP life-cycle inventories (LCIs).
- *Life-cycle impacts associated with the material inputs and outputs:* As discussed in Chapter 3, life-cycle impact assessment (LCIA) is a screening-level evaluation of potential impacts to any system (e.g., the environment) as a result of some action (e.g., a chemical release). In the LCIA, life-cycle inventory data were classified into various impact categories (e.g., greenhouse gases or ozone depletion) based on the characteristics of the inventory item. Characterization methods were then used to quantify the magnitude of the contribution the emission or consumption of the inventory item could have in producing the associated impact. The result is expressed as an impact score which has been calculated using specific impact assessment tools. These subsections summarize the CDP LCIA results for lead, mercury, and liquid crystal inputs and outputs.
- *Potential exposures to the material including occupational, public, and ecological exposures:* Toxic materials may pose a threat to human health anytime there is the potential for human exposure throughout the life cycle of a computer display. Exposure occurs anytime a chemical or physical agent comes into contact with an organism, be it human or ecological. The magnitude of exposure depends on the concentration of the chemical at the contact point, and the duration and frequency of the exposure. The concentration of the chemical at the contact point is influenced by several factors, including the type, quantity, and disposition (e.g., airborne, surface water) of the initial release, and the subsequent environmental fate of the chemical (the ultimate disposition of the chemical as it is transported through the environment). Note that exposure is often defined in terms of exposure pathways. An exposure pathway describes the route a

contaminant travels from its source to an individual. A complete exposure pathway consists of the source and mechanism of release, transport medium, point of potential human contact, and the exposure route (e.g., inhalation, ingestion, dermal contact). These subsections focus on identifying potential exposures for three groups: workers in facilities using the chemicals (occupational exposures), the general public, who may be exposed to releases of the chemicals into the ambient environment, and ecological populations. While a quantitative exposure assessment is beyond the scope of this study, a qualitative discussion of potential pathways of exposure is presented for each of the groups listed above.

- *Potential human health effects:* Human health effects can include acute effects from short-term exposure, as well as chronic effects from repeated, long-term exposure. To be consistent with the scope of the LCIA, these subsections focus on chronic effects, including noncancer and cancer effects, unless no chronic toxicity data are available.
- *U.S. environmental regulations for the material:* These subsections briefly summarize U.S. environmental regulations that may affect facilities that manufacture materials for the computer display or are otherwise affected by the life cycle of computer displays (e.g., disposal facilities). They do not summarize environmental regulations from other countries where displays or display components are manufactured, which may differ significantly from U.S. regulations.
- *Alternatives to reduce the use of the material in computer displays:* These subsections identify alternatives that can substitute for a material, or, in some cases, source reduction methods to reduce the use of a material. The discussion of alternatives presented here is not a rigorous evaluation of their performance, cost, and environmental attributes, but rather a summary of the current knowledge base that may be useful for manufacturers seeking to identify improvement opportunities.

In Section 4.4, summary information and conclusions are presented.

4.1 LEAD

Lead and/or lead compounds are present in both CRTs and LCDs. Because lead and lead-containing compounds have long been known to pose a threat to both human health and the environment, this section presents a more detailed look at the use of lead in computer displays and its effects on human health and the environment.

4.1.1 Lead in Computer Displays

Lead is a significant material in current CRTs, accounting for up to 8% of the overall composition of the CRT by weight (Menad, 1999), with a 17" monitor containing as much as 1.12 kg of lead (Monchamp *et. al.*, 2001). Lead is used in several parts of the CRT monitor, including the funnel and neck glass, the sealing frit, as solder on printed wiring boards (PWBs) within the monitor, and sometimes in the front panel glass of the CRT. Lead is not as prevalent in LCDs, only being found on PWBs.

Lead, in the form of lead oxide, lines the inner surface of both the neck and funnel glass of the CRT, or may in some cases be contained within the glass itself. The lead oxide layer acts as a shield, protecting users from x-ray emissions given off by the electron gun. The lead oxide layer can comprise as much as 28% by weight of the funnel (Lee *et al.*, 2000) and 32% of the neck (Menad, 1999).

The sealing frit, which is used to make a vacuum-tight connection between the funnel and the front panel, is comprised of as much as 80% lead oxide (Busio and Steigelmann, 2000). The lead oxide is mixed with boric oxide and zinc oxide, along with several other compounds, into a paste. The glass frit paste is applied as a bead around the top of edge of the funnel and allowed to dry. The front panel is then attached to the funnel and fired using a belt furnace for 30 to 60 minutes at typical temperatures of 450ºC (Busio and Steigelmann, 2000). The lead, boric, and zinc oxides devitrify to form large crystals which give strength to the frit seal (Techneglas, 2001). Recent research has been directed at either reducing the lead content of the frit or reducing the energy required to fuse the frit.

Printed wiring boards found in both LCDs and CRTs primarily use a lead-based solder as a surface finish and to attach electrical components to the circuit board. Solder is typically comprised of 37-40% lead. Depending on the type of component, parts can be applied using a solder paste which is subsequently melted, or by passing the boards over a wave of molten solder. Data collected for the life-cycle inventory indicates that a 17" monitor has approximately 51 grams of solder, or just under 19.8 grams of lead, while a 15" LCD panel contains nearly 22.4 grams of solder, or just about 8.5 grams of lead. Several lead-free solder alternatives are currently being tested and are in limited use. Solder is the only significant source of lead in LCDs.

The CRT panel glass itself may also contain a small percentage of lead oxide, typically ranging up to 4% by weight (Lee *et al.*, 2000). The lead acts as a stabilizer for the glass during its formation, and also serves to keep the glass from browning. Lead-free CRT panel glasses are currently being produced successfully.

A list of the lead-containing parts that make up a computer display, along with the quantity of lead and percentage of lead in each part, is presented in Table 4-1.

Table 4-1. Computer display parts that contain lead

Part	Display type	Quantity (Kg) [a]	% Lead content of part (by weight)
Funnel	CRT	0.91	22-28% [b, c]
Front panel	CRT	0.18	0-4 [b, c]
Neck	CRT	0.012	26-32 [b, c]
Frit	CRT	0.026	70-80 [b, c, d]
PWBs (total)	CRT	0.051	N/A
PWBs (total)	LCD	0.043	N/A

[a] Quantity of lead in a 17" monitor (Monchamp *et. al.*, 2001).
[b] Menad, 1999.
[c] Lee *et. al.*, 2000.
[d] Busio and Steigelmann, 2000.
N/A= Not applicable

4.1.2 Life-Cycle Inventory Inputs and Outputs of Lead for Computer Displays

Data on lead and lead-containing materials were collected and compiled as part of the life-cycle inventory. Material inputs containing lead included primary materials (e.g., lead-based solder) which end up as part of the product, as well as from ancillary materials (e.g., lead consumed during the production of steel used to make CRT parts) which are consumed as part of the manufacturing process or other supporting processes, such as energy production. The data were aggregated by material from individual processes and are presented by life-cycle stage for both CRTs and LCDs in Tables 4-2 and 4-3 below. More detailed material input data, which include the processes for each input and the quantity of lead released, are included in Appendix N.

Table 4-2. CRT lead-containing inputs by life-cycle stage

Life-cycle stage	Input	Quantity	Units	Type
Materials processing	Lead (Pb, ore)	6.50E-05	kg	Ancillary material
Materials processing	Lead (Pb, ore)	4.96E-01	kg	Primary material
Manufacturing	Frit	6.67E-02	kg	Primary material
Manufacturing	Lead	4.94E-01	kg	Primary material
Manufacturing	Printed wiring board (PWB)	8.47E-01	kg	Primary material
Manufacturing	Solder (63% tin; 37% lead)	5.08E-02	kg	Primary material
Manufacturing	Solder, unspecified - (CRT Assembly)	2.67E-02	kg	Primary material

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

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[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).

4.2 MERCURY

Mercury is not only used in the manufacturing of LCDs, but also is emitted from a number of processes over the life cycle of both LCDs and CRTs. Because of mercury's toxicity to both humans and the environment, this section presents a more detailed look at the uses and impacts of mercury, and its potential for causing harm as a result of the manufacture, use, and disposal of computer displays.

4.2.1 Mercury in Computer Displays

Mercury is an important material in the construction of cold cathode fluorescent lamps (CCFLs) that are used to backlight the LCD. A typical LCD utilizes a minimum of two CCFLs, and can use as many as eight in larger displays. The CCFL consists of a glass tube filled with a small amount of rare gas (typically argon) and a few drops of mercury. Metal electrodes built into the ends of the tube conduct electric current to the inside gas, vaporizing a portion of the mercury which then becomes excited, emitting light in the ultraviolet spectrum. Fluorescent phosphors, which coat the inside of the glass tube, convert the ultraviolet emissions from the mercury gas into visible white light. The phosphors are responsible for nearly all of the visible light from the lamp, with the visible mercury spectrum contributing only a little to the lamps output (Srivastava and Sommerer, 1998). No mercury is contained directly within the CRT.

Although a great deal of mercury is obtained by CCFLs, there also is a small source of mercury generated by the infrequent breakage of mercury lamps in the photolithographic exposure systems used to make both the CRT and LCD. Mercury filters are used in some water cooled exposure table equipment to catch the mercury from lamp explosions or trap it in water cooling baths. In air cooled lamp usage, the proximity of aluminum metal gives sites for amalgam formation and a number of clean-up procedures are used. Unbroken lamps are returned to the lamp manufacturer for recycling or disposal (Donofrio and Eckel, 1999).

Mercury may also be emitted from several processes required to manufacture, operate, and dispose of both CRTs and LCDs. For example, electricity generated from the combustion of coal results in the emission of mercury contained within the fuel. Other processes potentially responsible for mercury emissions include mercury ore processing, non-ferrous metal production, and the recycling of LCDs at the end of their useful life. The amount of mercury released through these incidental mercury emissions is comparable to the amount of mercury used as a direct material in the manufacture of LCD backlights.

4.2.2 Life-Cycle Inputs and Emissions of Mercury for Computer Displays

Data on mercury and mercury-containing materials were collected and compiled as part of the life-cycle inventory. Material inputs containing mercury include primary materials (e.g., CCFLs) which end up as part of the product, as well as ancillary materials (e.g., fossil fuels containing mercury) which are consumed as part of the manufacturing process or other supporting processes (e.g., energy production). The data were aggregated by material from individual processes and are presented by life-cycle stage for LCDs in Table 4-11. More detailed material input data, which include the processes that use each input and the quantity of mercury releases, are included in Appendix N.

Table 4-11. Life-cycle stage mercury inputs for LCDs

Life-cycle stage	Inputs	Quantity	Units	Type
Manufacturing	Mercury	3.99e-06	kg	Primary material
Manufacturing	Backlight lamp (CCFL)	1.94E-03[a]	kg	Product

[a] Quantity of release shown represents entire mass of input material. Mercury may only comprise a fraction of the total mass of material shown.

Mercury is not listed as an input in the life-cycle inventory for CRTs. However, mercury is contained in raw material inputs (e.g., mercury contaminants in fossil fuels burned to produce energy) into processes such as non-ferrous metal production and energy production for both LCDs and CRTs. Though mercury inputs exist, they occur in upstream manufacturing processes where input data did not contain detailed composition data for fuel inputs.

Releases of mercury and mercury-containing materials into the environment occur throughout the entire life cycle of the computer display. Environmental releases include airborne, waterborne, solid waste, and hazardous waste emissions. Similar to the inputs, emissions data were aggregated by the material released from individual processes and then reported by life-cycle stage. The mercury and mercury-containing material released, the quantity of the release, the type of release (e.g., waterborne), and the ultimate disposition of the release all affect the nature and type of environmental impacts.

The total life-cycle outputs/emissions containing mercury for both CRTs and LCDs are organized by output type and shown in Tables 4-12 and 4-13, respectively. More detailed data on mercury and mercury-containing outputs for each process are presented in Appendix N.

Table 4-12. Life-cycle stage mercury outputs from CRTs

Life-cycle stage	Outputs	Quantity	Units	Type	Disposition
Materials processing	Mercury	3.00E-06	kg	Airborne	Air
Materials processing	Mercury	1.42E-10[a]	kg	Solid waste	Landfill
Materials processing	Mercury compounds	9.68E-07	kg	Waterborne	Surface Water
Manufacturing	Mercury	1.12E-06	kg	Airborne	Air
Manufacturing	Mercury compounds	1.35E-12	kg	Waterborne	Surface Water
Use	Mercury	7.51E-06	kg	Airborne	Air
End-of-life	Mercury	-1.15E-07	kg	Airborne	Air
End-of-life	Mercury compounds	4.33E-11	kg	Waterborne	Surface Water

[a] Quantity of release shown represents entire mass of waste disposed. Mercury may only comprise a fraction of the total mass of waste shown.

Table 4-13. Life-cycle stage mercury outputs from LCDs

Life-cycle stage	Outputs	Quantity	Units	Type	Disposition
Materials processing	Mercury	9.44E-07	kg	Airborne	Air
Materials processing	Mercury compounds	5.82E-07	kg	Waterborne	Surface Water
Manufacturing	Broken CCFL	2.69E-07[a]	kg	Solid waste	Landfill
Manufacturing	Mercury	2.64E-06	kg	Waterborne	Treatment
Manufacturing	Mercury compounds	6.52E-14	kg	Waterborne	Surface Water
Manufacturing	Waste CCFL, with mercury	8.17E-10[a]	kg	Hazardous waste	Treatment
Manufacturing	Waste glass, with mercury	1.05E-10[a]	kg	Hazardous waste	Landfill
Manufacturing	Wastewater stream, from CCFL mfg.	167	kg	Waterborne	Treatment
Use	Mercury	2.80E-06	kg	Airborne	Air
End-of-life	Mercury	-8.64E-08	kg	Airborne	Air
End-of-life	Mercury compounds	1.62E-11	kg	Waterborne	Surface Water

[a] Quantity of release shown for solid waste and hazardous waste represents entire mass of waste disposed. Mercury may only comprise a fraction of the total mass of waste shown.

Mercury is released into the environment in many forms, but is most typically an airborne release. The largest air emissions of mercury result from the generation of electricity from fossil fuel burning. For LCDs, there is nearly the same amount of mercury emitted to the air from energy production (3.22 mg) as the mass of mercury used in the fabrication of an LCD (3.99 mg). In fact, the amount of mercury emitted to the air from electricity generation for CRTs (7.75 mg) is greater than the entire amount of mercury from both the fabrication and energy production for an LCD. Other airborne releases include the processing of ores such as lead, and the production of several raw materials such as aluminum, polycarbonate, and steel.

4.2.3 Computer Display Life-Cycle Impacts for Mercury

The life-cycle impacts of mercury, mercury-based compounds, and materials containing mercury (e.g., waste glass from broken CCFLs) calculated for CRTs and LCDs during the LCIA are summarized in Tables 4-14 and 4-15, 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 mercury and mercury-based materials is presented at the bottom of each table.

Table 4-14. Summary of mercury-based impact scores by impact category for CRTs

Life-cycle stage	Material	Impact scores by category					
		Hazardous waste landfill use (m^3)	Solid waste landfill use (m^3)	Chronic health effects-public (tox-kg)	Chronic health effects-occupational (tox-kg)	Aquatic toxicity (tox-kg)	Terrestrial toxicity (tox-kg)
Materials processing	Mercury	0	0	3.00E-06	0	0	3.00E-06
Materials processing	Mercury compounds	0	0	5.11E-04	0	9.02E-04	5.10E-04
Manufacturing	Mercury	0	0	1.12E-06	0	0	1.12E-06
Manufacturing	Mercury compounds	0	0	7.13E-10	0	1.26E-09	7.11E-10
Use	Mercury	0	0	7.51E-06	0	0	7.51E-06
End-of-life	Mercury	0	0	-1.15E-07	0	0	-1.15E-07
End-of-life	Mercury compounds	0	0	2.29E-08	0	4.04E-08	2.28E-08
Total Impact Scores by Category		**0**	**0**	**5.22E-04**	**0**	**9.02E-04**	**5.21E-04**

Table 4-15. Summary of mercury-based impact scores by impact category for LCDs

Life-cycle stage	Material	Impact scores by category					
		Hazardous waste landfill use [a] (m^3)	Solid waste landfill use [a] (m^3)	Chronic health effects-public (tox-kg)	Chronic health effects-occupational (tox-kg)	Aquatic toxicity (tox-kg)	Terrestrial toxicity (tox-kg)
Materials processing	Mercury	0	0	9.44E-07	0	1.82E-07	9.44E-07
Materials processing	Mercury compounds	0	0	3.07E-04	0	5.42E-04	3.07E-04
Manufacturing	Broken CCFL	0	1.98E-11	0	0	0	0
Manufacturing	Mercury	0	0	5.54E-07	3.99E-06	1.9387E-07	5.54E-07
Manufacturing	Mercury compounds	0	0	3.44E-11	0	6.08E-11	3.44E-11
Manufacturing	Waste glass, with mercury	7.73E-15	0	0	0	0	0
Use	Mercury	0	0	2.80E-06	0	0	2.80E-06
End of Life	Mercury	0	0	-8.64E-08	0	0	-8.64E-08
End of Life	Mercury compounds	0	0	8.53E-09	0	1.51E-08	8.52E-09
Total Impact Scores by Category		**7.73E-15**	**1.98E-11**	**3.11E-04**	**3.99E-06**	**5.43E-04**	**3.11E-04**

[a] Percentages of impacts shown for solid and hazardous wastes are based on the entire mass of material disposed, not necessarily on the amount of mercury. As such, the percentage over-estimates the impact of mercury to either the solid or hazardous waste landfill use.

Impact scores for some mercury-based inputs and outputs shown in Tables 4-11 through 4-13 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 mercury with a disposition going to treatment assumes that the mercury was treated prior to being released to the environment. However, since inventory data for subsequent treatment/disposal processes could not be obtained, it was assumed the mercury (or other inventory item) had been removed to a level such that the subsequent release of treated wastewater would not contribute significantly to aquatic toxicity impacts. Similarly, impact scores were not calculated for releases going to recycling/reuse or for those designated as a product.

The life-cycle mercury-based outputs from LCDs had a broader affect on the environment than those from CRTs, impacting a wider group of impact categories. Impacts to both solid and hazardous waste landfill use, as well as to the chronic health effects of workers, all directly result from the use of mercury in the LCD backlights. No mercury is required for the fabrication of a CRT. Although the quantities are not large (see Tables 4-11 through 4-13), they cannot be discounted, given the toxicity of mercury to both human health and the environment.

Chronic occupational toxicity impacts were only calculated for mercury inputs to processes in the CDP. The overall impact scores (3.99E-06 tox-kg for LCD, none for CRT) likely underestimate the chronic occupational impacts for mercury, because they are based on inputs only and do not consider chronic occupational impacts from outputs in other processes such as aluminum production or fluorescent lamp recycling, which may result in emissions of mercury that originate within the workplace.

The contribution of mercury-based impacts for each computer display technology to the overall impacts for each individual impact category is shown in Table 4-16. Values in the table are expressed in the percent contribution the material made to the overall impact score for all materials (e.g., liquid crystals, fuel oil, glass) for each category. The percent contributions give an indication of the importance of mercury-based impacts relative to the life-cycle impacts from other materials or outputs from the computer display.

Table 4-16. Summary of percent contributions from mercury-based materials to individual impact categories

Impact category	CRT	LCD
Hazardous waste landfill use	N/A	NA
Solid waste landfill use	N/A	3.65E-08
Chronic health effects- public	2.64E-05	3.45E-05
Chronic health effects- occupational	N/A	5.80E-07
Aquatic toxicity	4.01E-01	1.05E-02
Terrestrial toxicity	2.64E-05	3.48E-05

N/A = Not applicable

The results from Table 4-14 and 4-15 indicate that the mercury impacts from a CRT exceed the impacts from an LCD in categories common to both technologies. This was not expected, because mercury is used intentionally in an LCD, but not in a CRT. However, the results are not surprising because 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. In fact, the mercury emitted from the generation of power consumed by the CRT exceeds the entire amount of mercury emissions from the LCD, including both the mercury used in LCD backlights and the mercury emissions from electricity generation in the use stage that can be attributed to the LCD.

The impacts resulting from mercury and mercury-based materials do not appear to be significant relative to the total impacts of all of the computer display materials (e.g., liquid crystals, lead solder), as shown in Table 4-16. The largest contribution is 0.4% of the total aquatic toxicity impacts for CRTs, and 0.01% of the total aquatic toxicity impacts for LCDs. Impacts to other categories from both LCDs and CRTs were minimal.

4.2.4 Exposure Summary

Mercury may pose a threat to human health anytime there is the potential for human exposure throughout the life cycle of a computer display. Exposure occurs anytime a chemical or physical agent, in this case mercury or mercury compounds, come into contact with an organism, be it human or ecological. This section qualitatively identifies potential exposures for workers in facilities using mercury (occupational exposures), the general public, who may be exposed to mercury releases into the ambient environment, and the ecological population.

4.2.4.1 Occupational exposures

About 4 mg of elemental mercury (combined total of all mercury contained within the backlights) is used to manufacture the fluorescent backlight for the LCD backlight unit assembly. Workers manufacturing the backlights may be exposed to the mercury used for these lights. This study found no information on the specific manufacturing processes that are used to make CCFLs or the specific worker exposures that could occur, but did find manufacturing information for generic fluorescent lamps. We assume the processes are similar and have included a brief discussion of the fluorescent lamp manufacturing process and potential sources of worker exposure, below.

In fluorescent lamp manufacturing, pre-cut bulbs are washed, dried, and coated with a liquid phosphor emulsion that deposits a film on the inside of the bulb. Mount assemblies are then fused to each end of the bulb and the bulb is transferred to an exhaust machine. The bulb is then exhausted and mercury is injected into the bulb. Some of the mercury combines with the emulsion on the interior of the bulb where it remains over the life of the bulb. The glass bulb is then filled with an inert gas and sealed (EPA, 1997).

During the lamp manufacturing process, emissions of mercury can occur from transfer and parts repair during mercury handling, by the mercury injection operation, and from broken lamps, spills, and waste materials. Workers can be exposed to mercury from any of these sources, but mercury air levels can be reduced by process modifications, containment, ventilated inclosures, local exhaust ventilation, and temperature control (EPA, 1997).

There were no other inputs of mercury reported in the LCD life-cycle inventory, and none were reported in the CRT life cycle. Workers may also be exposed to inorganic mercury in the fluorescent backlights when processing LCDs at the end-of-life. Family members of workers may be exposed as well, from a worker's clothing or shoes if they are contaminated with mercury and brought home.

The processes associated with LCI mercury inputs and releases are presented in supplemental tables in Appendix N. It is important to note that while this list gives an indication of where likely mercury 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 mercury exposures.

4.2.4.2 General population exposures

Mercury is a persistent biaccumulative toxic (PBT) chemical, as designated by EPA (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. The general public may be exposed to metallic mercury that is not safely contained (although it is unlikely that the backlight would break to release mercury during normal LCD use) or to methylmercury-contaminated foods. Mercury also can be passed from a pregnant woman to developing child through the placenta, and from a mother to nursing infant through breast milk.

Most of the mercury released to the environment throughout the CRT and LCD life cycles results from electricity generation required for use, manufacturing, and materials processing life-cycle stages. A total of approximately 4 mg of mercury and mercury compounds are released to air for an LCD, and approximately 12 mg are released to air for a CRT. Mercury is naturally present in coal and becomes airborne when coal is burned to generate electricity. Airborne mercury can stay in the atmosphere for up to a year, and can travel thousands of miles (EPA, 2001a). EPA modeling suggests that "a substantial fraction" of the mercury released to air by utilities is dispersed "well beyond the local area" due to the fine particulate nature of the emissions and tall stacks (EPA, 1998). Mercury in the atmosphere moves to land and water by settling out with particles and being washed out by rain (dry and wet deposition). It may be deposited directly to water or be carried by runoff to a lake, stream, or ocean. In the LCIs, in addition to the air releases of mercury, 0.6 mg of mercury and mercury compounds are released directly to surface water in the LCD life cycle, and 1 mg in the life cycle of the CRT. Ultimately, at the end of life, the 4 mg of mercury in the LCD backlight will most likely be released to the environment during LCD recycling or disposal processes.

Surface water is the environmental medium of most concern for mercury. In a surface water environment, inorganic mercury can be transformed into methylmercury, a form which readily bioaccumulates in fish (inorganic mercury does not tend to bioaccumulate). An EPA study of mercury supports a "plausible link" between releases of mercury from industrial and combustion sources and methylmercury found in fish[3] (EPA, 2001c). Methylmercury

[3] The mercury released to the environment from the CRT and LCD life cycles are only part of the overall burden of mercury released to the environment from coal-fired power plants for all uses of electricity. The proportion of mercury in fish that is due to coal-fired power generation is not known. In addition, there are other natural and anthropogenic sources of mercury to the environment.

concentrations at the top of the food chain (such as in predatory fish or fish-eating animals) can be thousands or even millions of times greater than that in the surface water itself (EPA, 2000a).

The most important mercury exposures to the general public result from eating fish that are contaminated with methylmercury. The populations of most concern are children and women of child-bearing age (the developing fetus may be the most sensitive to the effects of methylmercury). Also of concern are people whose diet largely depends on fish, such as with some native cultures. The overall amount of exposure to mercury from eating fish depends on both the concentration of mercury in the fish, and on the amount of fish a person regularly eats. Fish advisories due to methylmercury contamination have been issued by EPA[4], 39 states, and some tribes, providing consumption limits for certain species of fish (EPA, 2000a, 2001c).

Freshwater fish are most affected, but some saltwater fish have also been found to be contaminated with methylmercury. The Food and Drug Administration (FDA) has issued a fish consumption advisory for pregnant women, nursing mothers, and small children to avoid eating certain large saltwater fish (shark, swordfish, king mackerel, and tilefish), and to limit overall weekly fish consumption, due to methylmercury contamination (FDA, 2001).

4.2.4.3 Exposure and effects to ecological populations

In addition to the fish themselves being contaminated, wildlife that eat fish also may be at risk from exposure to methylmercury. Species of concern include loons, eagles, mink, otter, wood stork, and the endangered Florida panther. Adverse effects of mercury to wildlife include death, reproduced reproductive success, impaired growth and development, and behavioral abnormalities. Levels have been measured in some individual wild animals that are comparable to those levels seen to cause harmful effects in laboratory tests with the same species (EPA, 2001c). Ambient water criteria have been developed by EPA under the CWA. Criteria for the protection of aquatic life for mercury are presented in Table 4-17.

[4] "EPA is issuing a national advisory concerning risks associated with mercury in freshwater fish caught by friends and family. The groups most vulnerable to the effects of mercury pollution include: women who are pregnant or may become pregnant, nursing mothers, and young children. To protect against the risks of mercury in fish caught in fresh waters, EPA is recommending that these groups limit fish consumption to one meal per week for adults (6 ounces of cooked fish, 8 ounces of uncooked fish) and one meal per week for young children (2 ounces cooked fish or 3 ounces of uncooked fish)." – EPA Office of Water, January 2001

Table 4-17. EPA water quality criteria for mercury

Type of criteria	Criteria value (µg/L)	Notes
For protection of aquatic life		
Freshwater Criteria Maximum Concentration (CMC)	1.4 [a]	the acute limit for the priority pollutant in freshwater
Freshwater Criterion Continuous Concentration (CCC)	0.77 [a]	the chronic limit for the priority pollutant in freshwater
Saltwater Criteria Maximum Concentration (CMC)	1.8 [a]	the acute limit for the priority pollutant in saltwater
Saltwater Criterion Continuous Concentration (CCC)	0.94 [a]	the chronic limit for the priority pollutant in saltwater

Source: Water Quality Criteria and Standards, EPA Office of Water. Revised: 06/21/2001
http://oaspub.epa.gov/wqsdatabase/epa.rep_parameter; report for mercury

[a] Criteria for metals are expressed in terms of the dissolved metal in the water column. This recommended water quality criterion was derived from data for inorganic mercury (II), but is applied here to total mercury. If a substantial portion of the mercury in the water column is methylmercury, this criterion will probably be under-protective (EPA is updating the ambient water quality criteria on methylmercury.) In addition, even though inorganic mercury is converted to methylmercury and methylmercury bioaccumulates to a great extent, this criterion does not account for uptake via the food chain because sufficient data were not available when the criterion was derived.

4.2.5 Human Health Effects

Mercury affects the nervous system, brain, and kidneys. Effects on the nervous system vary depending on the form of mercury. Inorganic mercury salts, for instance, do not enter the brain as readily as elemental mercury or methylmercury. Symptoms of mercury effecting the brain and nervous system include personality changes, tremors, changes in vision such as narrowing of the visual field, deafness, loss of muscle coordination, loss of sensation, and problems with memory (ATSDR, 1999).

The fetus, infants, and young children are especially susceptible to the effects of mercury on the nervous system. As mentioned above, mercury (especially methylmercury in food) can be passed from a pregnant woman to the unborn developing child, and from a mother to a nursing infant through breast milk. The developmental effects of mercury vary in severity depending on the amount of exposure. Children exposed in this way may show small decreases in IQ or may be slower to walk and talk. More severe effects might include brain damage with mental retardation, blindness, muscle weakness or seizures, and inability to speak (ATSDR, 1999).

Mercury accumulates in the kidneys and all forms of mercury can cause kidney damage at higher exposures (ATSDR, 1999). Short term exposure (hours) to high levels of mercury vapor, as might occur through an accidental spill in the workplace, include damage to the lining of the mouth, irritated lungs and airways, nausea, vomiting, diarrhea, increased blood pressure or heart rate, skin rashes, and eye irritation. Skin contact may cause an allergic reaction (skin rashes) in some people (ATSDR, 1999).

4.2.5.1 Chronic effects (noncancer)

A reference dose (RfD) is an estimate (with uncertainty spanning perhaps an order of magnitude) of the daily exposure through ingestion to the human population (including sensitive subgroups) that is likely to be without an appreciable risk of deleterious noncancer effects during a lifetime (in mg/kg-day). Similarly, a reference concentration (RfC) is an estimate (with uncertainty spanning perhaps an order of magnitude) of the daily inhalation exposure to the human population (including sensitive subgroups) that is likely to be without an appreciable risk of deleterious noncancer effects during a lifetime (in mg/m^3) (Barnes and Dourson, 1988). RfDs and RfCs established by EPA for mercury and mercury compounds are presented in Table 4-18.

Table 4-18. Chronic toxicity reference values for mercury and mercury compounds

Form of mercury[a]	**Ingestion: reference dose (RfD) (mg/kg-day)**[b]	**Inhalation: reference concentration (RfC) (mg/m^3)**[c]	**Notes, Source**
Elemental mercury (Hg)	not available	0.0003	Based on hand tremor, memory disturbances, and other effects seen in human occupational inhalation studies (IRIS, 2001).
Methylmercury (CH_3Hg^+)	0.0001	not available	Based on developmental neuropsychological impairment seen in human epidemiological studies (IRIS, 2001).
Mercuric chloride (HgCl)	0.0003	not available	Based on autoimmune effects in rats (IRIS, 2001).

[a] Forms of mercury for which EPA has established an RfD or RfC
[b] milligrams per kilogram of body weight per day for oral exposure (ingestion)
[c] milligrams per cubic meter of air, assuming continuous inhalation exposure for a 70-kg adult

4.2.5.2 Carcinogenicity

EPA has determined that mercury chloride and methylmercury are Possible Human Carcinogens (cancer weight of evidence [WOE] classification C) based on limited evidence of carcinogenicity in animals and inadequate or lack of human data. Elemental mercury is classified by EPA as Not Classifiable as to Human Carcinogenicity (WOE class D) based on inadequate or no evidence of carcinogenicity (IRIS, 2001).

4.2.6 Environmental Regulations for Mercury

This section presents a brief summary of the U.S. regulations for mercury and mercury compounds that may affect facilities that manufacture materials for the computer display or are otherwise affected by the life cycle of computer displays. It should be noted that many of the parts that go into the computer display are manufactured in other countries with their own regulations which may differ significantly from those presented below.

Air emissions of mercury are regulated under the CAA of 1970 and the amendments of 1977 and 1990. Under the CAA, mercury is regulated as a hazardous air pollutant (HAP), which is by definition a chemical that is either known or is suspected to cause serious health problems for humans. EPA established National Emission Standards for HAPs (NESHAPs) for mercury emissions based on risk under the pre-1990 version of the Clean Air Act. These NESHAPS [40 CFR 61 Subpart E] cover three source categories: ore processing facilities, mercury cell chlor-alkali plants, and sewage sludge driers. Specific source requirements are specified for, among other things, municipal waste combusters, hazardous waste combusters, and mercury ore processing facilities. These source requirements could take the form of either a NESHAP or a maximum achievable control technology (MACT) requirement.

OSHA has established standards for protecting worker health through the maintenance of a safe working environment. The OSHA permissible exposure limit (PEL) for workplace exposure to mercury is 0.1 mg/m^3 (8-hour time weighted average). NIOSH has also established recommended exposure limits (RELs) for several mercury compounds including a REL of 0.05 mg/m^3 for mercury vapor.

Mercury emissions to surface water are regulated under the CWA, which lists mercury as a priority pollutant [40CFR 401.15], requiring the limitation of mercury in point source discharges. For mercury discharges, CWA regulations specify technology-based effluent limits for classes and categories of industries (see 40 CFR 401, 403, Appendix B), and describe the rights of states to establish effluent limits more stringent than technology-based standards. Technology-based standards are listed for the following specific industries and point sources involved in computer display manufacturing: nonferrous metals production, including primary precious metals and mercury (40 CFR 250); secondary mercury (40 CFR 421.200); steam electric power generation (40 CFR 423- Appendix A); and mercury ore mining (40 CFR 440.40). The CWA also requires that new and existing points sources of mercury obtain a NPDES permit, which will establish effluent limits for mercury discharges to surface waters.

To protect human health and preserve the nations drinking water supply, EPA has been tasked by the SDWA to establish safe drinking water standards for toxic chemicals. In accordance with the SDWA, EPA has established a safe drinking water standard for mercury of 2 μg/L.

The release or disposal of solid or hazardous waste containing mercury is regulated under RCRA, which outlines specific classification and disposal requirements for products and wastes that contain mercury. Mercury is both a characteristic and a listed waste under RCRA. A solid waste containing mercury may be considered a D009 characteristic hazardous waste if, when subjected to a TCLP test, the extract exceeds 0.2 mg/L [40 CFR 261.24] for mercury. Other mercury-contaminated wastes may be considered hazardous if they are specifically listed in 40 CFR 261.30-33, unless they are specifically excluded. Listed wastes for mercury include leachate resulting from the disposal of more than one restricted waste classified as hazardous (F039), and wastewater treatment sludge and brine purification muds resulting from the mercury cell process in chlorine production (K106 and K071 respectively). Hazardous wastes are subject to land disposal restrictions requiring that wastes be treated to below regulatory threshold levels before they may be land-disposed.

In order to reduce the amount of hazardous waste in a landfill, EPA established the Universal Waste Rule (UWR) in 1995. The rule was intended to encourage the recycling and proper disposal of common hazardous waste components found in municipal waste streams, and reduce the regulatory burden on businesses who produce these wastes. The rule allows for less stringent standards for storing, transporting, and collecting wastes. However, the waste must comply with full hazardous waste requirements for final recycling, treatment, or disposal. Batteries and fluorescent lamps are included in the rule.

EPA also has regulated the air emissions of mercury from hazardous waste combustion and from industrial boilers and furnaces under RCRA. EPA has issued new standards for mercury emissions from these sources.

In December 2000, EPA announced plans to require coal-fired power plants to cut their emissions of mercury. EPA plans to propose the regulations by 2003, with final rules in place by 2004 (EPA, 2000a). More recently, in April 2001 the Bush administration sought to dismiss an electric industry lawsuit that would stop the EPA from regulating mercury and other toxic air pollutants (Doggett, 2001).

Manufacturer's who emit mercury are required to report the quantity of the emissions under the Emergency Planning and Community Right-to Know-Act (EPCRA). EPA has established a reportable quantity threshold of 10 pounds for a facility that manufactures, processes, or otherwise uses mercury. A similar threshold of 10 pounds exists for facilities that manufacture, process, or otherwise use mercury compounds. Data that has been reported by facilities for mercury is made available to the public through the publication of the Toxics Release Inventory (TRI).

4.2.7 Alternatives to Mercury Use in LCDs

In an effort to minimize or even eliminate the quantity of mercury used during the fabrication of LCDs, manufacturers have begun to develop mercury-free alternatives to mercury vapor backlights. One such alternative is a flat lamp which is filled with inert gas xenon in place of the typical mercury vapor lamps. The lamp has the appearance of a large white tile about one centimeter in thickness. Its dimensions are the exact same as the screen itself, illuminating the image evenly, hence eliminating the need for complex optical systems to distribute the light. The new lamp is capable of emitting enough light to make the monitor twice as bright, making it possible to use the screen during daylight, while also extending the viewing angle (OSRAM, 1998).

The new lamps generate light in a fashion similar to conventional backlight lamps. An electrical current passed through a gas discharge produces ultra-violet light which is then converted to visible light by phosphors. Unlike mercury gas which causes 'greying' in the phosphors over time, the xenon gas does not affect the phosphors, extending the life of the lamp. The lights have an average lifetime of up to 50,000 hours compared to only about 20,000 hours for the conventional mercury backlights, extending the life of computer LCD displays before they have to be replaced (OSRAM, 1998).

A drawback of the lamps, and the current subject of research is the reduced energy efficiency of the new mercury-free lamps. The luminous efficiency of the new mercury-free lamp is only about half of the efficiency of a conventional backlight, due to less efficient conversion of the UV light to visible light by the phosphors (OSRAM, 1998).

4.3 LIQUID CRYSTALS

One of the most significant differences between the two computer displays is the use of liquid crystals in the LCD to generate an image. The toxicity of liquid crystals in LCDs has been alluded to in literature indicating the potential for human health concerns. Because of relative lack of information about these compounds, this section provides a more detailed look a liquid crystals to better understand their potential impacts on human and ecological populations,

4.3.1 Liquid Crystals in Computer Displays

Liquid crystals (LCs) are organic compounds with the optical and structural properties of crystals, but with the mechanical features of fluids. There are hundreds of LC compounds that may be used in an LCD, each with different physical and optical characteristics. They are typically classified by molecular weight, with low molecular weight LCs typically used for LCD computer displays. LCs are not required for the fabrication of CRTs.

LCs are responsible for forming and transmitting the image produced by an LCD. The LC portion of an LCD typically consists of as many as 20 different LC substances, mixed together to form a white, opaque liquid that flows easily (Merck, 1999). The mixture consists of elongated molecules that are held together at their ends by polar forces and aligned in the same direction. The molecules move together in a series of flexible molecular chains, with each chain influencing the alignment of other chains. By exposing the molecular chains to electric fields, the alignment of the chains, and by extension their ability to transmit light, can be manipulated (SEMI, 1995).

LCDs are fabricated using a complex multi-step process in a clean room (refer to Chapter 1 for a more detailed description of the fabrication process). Once the front and back layers have been manufactured and assembled into a display cell, the LC is ready to be added. The assembled display cells are placed into a vacuum chamber containing a reservoir of the LC mixture, and the chamber is evacuated. A corner of the empty display cell is lowered into the LC mixture using a remote control. Nitrogen gas is then introduced into the evacuated chamber to bring the pressure up to approximately 1 atmosphere, exerting pressure on the surface of the LC mixture, forcing it up into the display cell (SEMI, 1995). Approximately 0.6 mg of LC is required for every square centimeter of panel surface (Merck, 1999). The display cell is sealed once the LC fully penetrates the cell.

4.3.2 Life-Cycle Inputs and Outputs of Liquid Crystals for Computer Displays

Data on LC compounds were collected and compiled as part of the life-cycle inventory. The data were aggregated by material from individual processes and presented by life-cycle stage for LCDs in Table 4-19**.**

The individual LC compounds identified in Table 4-19 formed the ingredients of the liquid crystal mixture used in the LCD. These compounds, used in varying quantities, are mixed together in a liquid crystal manufacturing process to develop a mixture with the desired optical characteristics for the LCD. While the above inputs illustrate the quantities of individual LC compounds found in the LCD evaluated in this LCA, LC mixtures found in other LCDs could be comprised of up to 20 or more liquid crystal compounds selected from the hundreds of compounds currently available for use in LCDs. A small quantity of the liquid crystal mixture (1.2 grams) is then used in the fabrication of the LCD.

Table 4-19. Life-cycle stage liquid crystal inputs

Life-cycle stage	Inputs [a]	Quantity	Units	Type
Manufacturing	Liquid crystal A	0.26	g	Primary material
Manufacturing	Liquid crystal B	0.37	g	Primary material
Manufacturing	Liquid crystal C	0.22	g	Primary material
Manufacturing	Liquid crystal D	0.33	g	Primary material
Manufacturing	Liquid crystal E	0.070	g	Primary material
Manufacturing	Liquid crystal F	0.34	g	Primary material
Manufacturing	Liquid crystal G	0.19	g	Primary material
Manufacturing	Liquid crystal mixture, for 15" LCD	1.2	g	Primary material

[a] Identities of liquid crystal compounds have been masked to protect the confidentiality of the compound names.

Life-cycle inventory data indicate that LCs are primarily released at the time of the product's final disposition. Although other outputs of liquid crystals surely exist, they are likely minimal and were not identified in the life-cycle inventory collected for LCDs. Evaporative LC emissions during the manufacturing and mixture formulation processes are minimal due to the typically low vapor pressures of LC compounds (Becker, 2001). Releases resulting from broken or defective LCDs during manufacture are also likely to be small because of the strong adhesives forces between LCs and the polymer film covering the outer layer of the displays (Becker, 2001). However, small amounts of LC compounds were observed to present in the waste of one LCD manufacturing facility during data collection (Overly, 2001). Because data were not provided from manufacturers on manufacturing releases, and no data were available for releases at end-of-life, it is difficult to definitively quantify the releases or their significance to the environment.

4.3.3 LCD Life-Cycle Impacts of Liquid Crystals

The life-cycle impacts of LC compounds calculated for LCDs during the LCIA are summarized in Tables 4-20. Impact values 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 from LCs is presented at the bottom of the table.

Table 4-20. Summary of LCD liquid crystal impacts

Life-cycle stage	Material	Chronic health effects- occupational (tox-kg)
Manufacturing	Liquid crystal A	5.29E-04
Manufacturing	Liquid crystal B	4.35E-04
Manufacturing	Liquid crystal C	3.89E-04
Manufacturing	Liquid crystal D	1.40E-04
Manufacturing	Liquid crystal E	6.84E-04
Manufacturing	Liquid crystal F	6.53E-04
Manufacturing	Liquid crystal G	7.31E-04
Total category impact score		**3.56E-03**

Impact scores have been calculated based on the inventory item, release type, and its reported disposition. Occupational impacts to workers as a result of LC inputs are shown in the Table 4-20. Impacts were not calculated for LCs which end up as part of the product because users of the product are not expected to become exposed to the LC compounds during the typical operation of the LCD. In addition, because releases of LCs to the environment were not provided by the manufacturers in the LCI, potential impacts resulting from these releases were also not assessed in this project. LCs are not used to fabricate CRTs and so have no environmental impacts in the CRT life cycle.

LCs do not appear to contribute significantly to any of the impact categories defined for this study. The total score for occupational impacts based on potential worker exposure to LCs of 4.18 tox-grams 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.

4.3.4 Exposure Summary

Like any materials classified as potentially toxic, LCs have the potential to pose a threat to human health anytime there is the potential for human or ecological exposure throughout the life cycle of a LCD. Exposure occurs anytime a chemical or physical agent, in this case LC compounds, come into contact with an organism, be it human or ecological. This section qualitatively identifies potential exposures for workers in facilities using LCs (occupational exposures), the general public, who may be exposed to LC releases into the ambient environment, and the ecological population.

4.3.4.1 Occupational exposures

Occupational exposures to LCs during the fabrication of the LCD panels are not expected to be significant. LCD panels are fabricated in a clean room environment. The previously assembled but empty display cells are placed into a vacuum chamber containing a reservoir of the LC mixture, and lowered into the LC mixture using a remote control. Approximately 1.2 grams of LC compounds are used to develop the LCD panel. The enclosed nature of the chamber combined with the equipment (e.g., gloves, aprons) worn by workers in a clean room environment may both act to minimize exposures.

However, the potential for other occupational exposures still exist. Workers could become exposed to LCs during other manufacturing process steps, such as during the formulation of the LC mixture (approximately 1.8 grams from Table 4-31), the handling and disposal of broken or defective panels, or during the recycling or disposal of an LCD at the end of its useful life. Because of the physical nature of the LCs (e.g., they are not volatile), typical worker exposures are likely to be through dermal or ingestion (e.g., accidentally ingesting LC present on a workers hands) routes. Worker exposure to LCs via dermal exposure is expected to be minimal for workers who wear gloves while handling LCs.

4.3.4.2 General population

Because of the enclosed nature of the LCD panel, it is unlikely that consumers could become exposed to LC compounds contained within the display through normal usage. LCs may be released into the environment should the panel become fractured, either through accident or through final disposal. No other releases of LC compounds into the environment were identified by the LCI data collected for the LCD, making it difficult to assess any possible exposures to nearby populations.

4.3.4.3 Ecological populations

Potential exposure to ecological populations could typically only occur through the migration of LCs through the environment after being released during manufacturing or disposal (either at LCD end-of-life, during disposal of broken or damaged panels during manufacturing, or during disposal of containers or equipment contaminated with LCs). The potential for transport of the LC through the environment is dependent on the identity of the chemical compound. The number of choices of LC compounds along with the unavailability of data on disposal quantities make it difficult to accurately assess the potential exposures which might result.

4.3.5 Human Health Effects

There are at least ten meaningful groups of liquid crystal compounds representing several hundred LC substances. Each of these substances is chemically unique, each having the potential to affect human health. Because of the number of LC compounds potentially present in the LCD, it is not possible to provide a comprehensive review of the human health effects of the universe of liquid crystal substances. However, a review of a small sample of LC compounds, those which appeared in the project LCI collected for the LCD, was conducted by EPA and the results presented below.

Toxicological testing of LC substances and mixtures was conducted by three manufacturers responsible for roughly 90% of LC production. Testing of their chemical products included testing for acute toxicity effects, and effects on skin and eyes. Results of the testing indicated that of 588 LC substances tested, only twenty-five LC compounds had an LD_{50}[5] less

[5] LD_{50} represents the dose of chemical which is lethal to 50% of the test population. By comparison, the LD_{50} for sodium chloride (table salt) is 3,000 mg/kg of body weight.

than 2,000 mg/kg of body weight (classified as exhibiting harmful effects to humans by the European Union), and only one had a LD_{50} of less than 200 (classified as toxic by the European Union). The remaining 562 LC substances did not have any acute toxic potential. Of the twenty-five harmful LCs, only twenty-two substances are produced and all are present at less than 10% concentration by weight, meaning that the resulting LC mixtures are not expected to exhibit harmful properties to humans (Becker, 2000). The remaining three harmful chemicals along with the lone toxic chemical were discontinued and excluded from further development. Several compounds, but still a minority, were found to be skin or eye irritants (Merck, 1999).

4.3.5.1 Chronic effects (noncancer)

EPA conducted a review of existing toxicological data for the LC substances listed in Table 4-31. The review failed to identify a RFD, RFC, NOAEL, or LOAEL for any of the LC substances shown. This typically indicates that insufficient testing of these chemical compounds has been performed to accurately determine their potential for chronic human effects.

4.3.5.2 Carcinogenicity and mutagenicity

An EPA review of toxicological studies for the liquid crystals identified in the life-cycle inventory for LCDs failed to identify an existing slope factor for any of the LC compounds. A lack of carcinogenicity data usually does not indicate that a compound is not carcinogenic, but only that sufficient testing to ascertain carcinogenicity has yet to be performed.

Toxicological testing of LC substances for mutagenic effects was conducted by three manufacturers responsible for roughly 90% of LC production. In a bacterial mutagenicity test of 615 LC substances, one LC compound showed mutagenic potential, with the remaining compounds displaying no mutagenic effects. The lone chemical that failed the test was excluded from further development and was never marketed (Becker, 2000). Additionally, 10 LC compounds representing each of the significant groups of LCs, underwent mutagenicity testing using mammalian cells. None of the tests indicated mutagenic activity. Based on both sets of data, the manufacturer concluded that there does not appear to be a suspicion of mutagenic potential in the liquid crystals it produces (Merck, 1999).

4.3.6 Environmental Regulations for Liquid Crystals

No regulations exist specifically for liquid crystals compounds. However, regulations may exist for individual liquid crystal compounds. Because of the number of possible LC compounds available for use in a LCD, a comprehensive review of U.S. regulations could not be provided.

4.4 CONCLUSIONS

The purpose of this chapter was to provide a more detailed analysis of a few select materials of interest to EPA and industry that was intended to better understand the potential exposures and chemical risks to both human and ecological populations. The materials selected for further analysis included lead, mercury, and liquid crystals, each selected for its known or suspected toxicity to humans and the environment, or because they are of particular interest to indsutry or the U.S. EPA. The analysis of each material summarized or evaluated the following key areas:

- Use of the materials in computer displays;
- Life-cycle inputs and outputs of the materials from computer displays;
- Life-cycle impacts associated with the material inputs and outputs;
- Potential exposures to the material including occupational, public, and ecological exposures;
- Potential human health effects;
- U.S. environmental regulations for the material; and
- Alternatives to reduce the use of the material in computer displays.

The following are the conclusions drawn from the analyses of lead, mercury, and liquid crystal use in the life cycle of both CRTs and LCDs.

4.4.1 Lead

Lead is found in glass components of CRTs, as well as in electronics components (printed wiring boards and their components) of both CRTs and LCDs. It is also a top priority toxic material at the U.S. EPA and the subject of electronics industry efforts to reduce or eliminate its use. The following conclusions were drawn from a focused look at lead's role in the life cycle of the computer display, and its effects on human health and the environment:

- Due to the much greater quantity of lead in the CRT than the LCD, lead-based life-cycle 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 consumed over 40 thousand times the mass of non-renewable resources over the course of its life cycle than those consumed by the LCD. Other categories where CRTs had notably greater differences in impacts occurred in hazardous waste landfill use, chronic public health effects, and terrestrial toxicity.
- Contributions of lead-based impacts are small relative to the total life-cycle impacts from other materials in the CRT (e.g., glass, copper wire), with the greatest impacts from lead-based CRT outputs occurring in the categories of non-renewable resources, aquatic toxicity, and chronic public health effects (ranging from 0.1 to 0.2% of the overall impact scores in each category).
- For workers, inhalation is the most likely route of exposure to lead which may result in health concerns. General population exposure to lead is most likely to come from incidental ingestion of lead in the soil, or ingestion of lead brought into the household on

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.

REFERENCES

ACGIH (American Conference of Governmental Industrial Hygienists). 1991. *Documentation of the Threshold Limit Values and Biological Exposure Indices*. Sixth edition. ACGIH, Cincinnati, OH.

ACGIH. 1998. *Threshold Limit Values for Chemical Substances and Physical Agents Biological Exposure Indices*. ACGIH, Cincinnati, OH.

ATSDR (Agency for Toxic Substances and Disease Registry). 1999. Toxicological Profile for Mercury. U.S. Department of Health and Human Services. Web site available at http://www.atsdr.cdc.gov/toxprofiles/tp46.html. March.

ATSDR. 1999. Toxicological Profile for Lead. U.S. Department of Health and Human Services. Web site available at: http://www.atsdr.cdc.gov/toxprofiles/tp46.html. March

Barnes, D.G., and M. Dourson. 1988. "Reference Dose (RfD): Descriptions and Uses in Health Risk Assessments." *Regulatory Toxicology and Pharmacology*. **8**: 471-486.

Bress, W.C., and Bidanset, J.H. 1991. "Percutaneous *in vivo* and *in vitro* absorption of lead." *Veterinary and Human Toxicology.* **33**: 212-214.

Becker, W. 2000. "Results of the Toxicological Testing of Liquid Crystal Compounds." Presented at International Display Works Conference, Kobe, Japan. December.

Becker, W. 2001. Personal communication by e-mail with W. Becker, Merck, Liquid Crystals Division, and M. Socolof, University of Tennessee, Center for Clean Products and Clean Technologies. December 6.

Busio, M. and Steigelmann, O. 2000. "New Frit Glasses for Displays." *Glasstech*. Berlin Glass Science and Technology. **73**(10): 319-325.

Doggett, T. 2001. "EPA Seeks to Dismiss Utility Lawsuit over Mercury." Reuters press release dated April 12, 2001 accessed at http://www.planetark.org/dailynewsstory.cfm?newsid=10496&newsdate=12-Apr-2001. September 2.

Donofrio, R. and Eckel, R. 1999. "Arc Lamps for Microelectronics." Presented at Vehicle Displays and Microsensors '99 SID Symposium, pp.103-111.

EIAJ (Electronic Industries Association of Japan). 1996. *1996 Update to: Research Report on the Visions of the Electronic Display Industry to the Year 2000.* Translated and published in English by InterLingus.

EPA (Environmental Protection Agency). 1986. *EPA Air Quality Criteria for Lead.* Publication No. EPA 600/8-83-028af. U.S. EPA, Office of Research and Development, Office of Health and Environmental Assessment. Research Triangle Park, NC.

EPA. 1998. Fact Sheet: "Utility Air Toxics Report to Congress." U.S. EPA, Office of Air Quality, Planning, and Standards. Web site available at: http://www.epa.gov/ttn/oarpg/utilfs.html. February 25.

EPA. 1999. "Proposed Rule Change; Lead and Lead Compounds, Lowering of Reporting Thresholds, Community Right-to-Know Toxic Chemical Release Reporting." Federal Register: Volume 64, Number 148. U.S. EPA, Office of Pollution Prevention and Toxics, Washington, D.C. August.

EPA. 2000a. "Mercury Study Report to Congress: White Paper." U.S. EPA Office of Air and Radiation. Web site available at http://www.epa.gov/oar/merwhite.html. (The full eight-volume 1997 *Mercury Report to Congress* is available online at: http://www.epa.gov/airprogm/oar/mercury.html). September 26

EPA. 2000b. "EPA Decides Mercury Emissions from Power Plants Must be Reduced." U.S. EPA Headquarters Press Release. December 14.

EPA. 2001a. "Mercury Study Report to Congress: Overview." EPA Office of Air and Radiation. Web site available at: http://www.epa.gov/oar/mercover.html. (The full eight-volume 1997 *Mercury Report to Congress* is available online at: http://www.epa.gov/airprogm/oar/mercury.html). February 8.

EPA. 2001b. "Persistent and Bioaccumulative Toxic Chemical Program's Chemical List." U.S. EPA, Office of Pollution Prevention and Toxics. Web site available at: http://www.epa.gov/opptintr/pbt/cheminfo.htm. March 8.

EPA. 2001c. "National Advisory on Mercury in Fish Caught by Family and Friends: for Women Who Are Pregnant or May Become Pregnant, Nursing Mothers, and Young Children." U.S. EPA, Office of Water, EPA-823-F-01-004. January, 2001.

FDA (U.S. Food and Drug Administration.). 2001. "Consumer Advisory: an Important Message for Pregnant Women and Women of Childbearing Age Who May Become Pregnant about the Risks of Mercury in Fish." U.S. Food and Drug Administration, Center for Food Safety and Applied Nutrition. March.

Gosselin, R.E., R.P. Smith, and H.C. Hodge. 1984. *Clinical Toxicology of Commercial Products*. 5^{th} ed. Williams and Wilkins, Baltimore, MD.

HSDB (Hazardous Substance Data Base). 2001. MEDLARS Online Information Retrieval System. National Library of Medicine, National Toxicology Program (via TOXNET). Bethesda, MD.

IARC (International Agency for Research on Cancer). 1987. IARC Monographs on the Evaluation of the Carcinogenic Risk of Chemicals to Humans: Overall Evaluations of Carcinogenicity. Supplement 7. World Health Organization, Lyon, France.

IRIS (Integrated Risk Management System). 1999. U.S. Environmental Protection Agency. National Center of Environmental Assessment. Office of Research and Development. Cincinnati, OH.

Keenan, C. and Kellett, T. 2001. Personal communication with C. Keenan and T. Kellett, Abt Associates Incorporated, and K. Hart, U.S. EPA. Background Research on Lead-Free Solder Alternatives.

Lee, C., Chang, S., Wang, K., and Wen, L. 2000. "Management of Scrap Computer Recycling in Taiwan." *Journal of Hazardous Materials*. **A73**: 209-220.

Menad, N. 1999. "Cathode Ray Tube Recycling." *Resources, Conservation, and Recycling*. **26**: 143-154.

MERCK. 1999. "Toxicological Investigations of Liquid Crystals." Presented at 28th Freiburger Arbeitstagung. March 24-26.

Monchamp, A., Evans, H., Nardone, J., Wood, S., Proch, E., Wagner, T. 2001. "Cathode Ray Tube Manufacturing and Recycling: Analysis of Industry Survey." *Electronic Industries Alliance.* Spring.

Musson, S., Jang, Y., Townsend, T., and Chung, I.. 2000. "Characterization of Lead Leachability from Cathode Ray Tubes Using the Toxicity Characteristic Leachate Procedure." *Environmental Science and Technology*. **34**: 4376-4381.

NIOSH (National Institute for Occupational Safety and Health). 1997. *NIOSH Pocket Guide to Chemical Hazards*. Publication No. 97-140. U.S. Government Printing Office. Washington D.C.

OSRAM. 1998. "The World's First Mercury-Free Flat Lamp." Web site available at: http://www.osram.com/txt/aktuell/planone.htm. July 13.

Sittig, M. 1985. *Handbook of Toxic and Hazardous Chemicals and Carcinogens.* 2nd ed. Noyes Data Corporation, Park Ridge, NJ.

Srivastava, A.M. and Sommerer, T.J. 1998. "Fluorescent Lamp Phosphers." *Electrochemical Society Interface.* Summer.

Techneglas, Incorporated. "Frit Facts: A Brief Technological Summary of Televison Solder Glass for CRT Technicians, Engineers, and Managers", downloadable fact sheet. http://www.techneglas.com.