Life-Cycle Assessment of Desktop Computer Displays:

Summary of Results

This summary document is based on information presented in the project report, *Desktop Computer Displays: A Life-Cycle Assessment*, written by University of Tennessee under a grant from EPA. Some information in the Life Cycle Assessment was provided by individual technology vendors and has not been independently corroborated by EPA. The identification of specific products or processes in this document is not intended to represent an endorsement by EPA or the U.S. Government. This summary document has not been through a formal exteneral peer review process.

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Contents

Introduction

This report summarizes the results of an analysis conducted by U.S. Environmental Protection Agency's Design for the Environment (DfE) Computer Display Project (CDP). The DfE Computer Display Project is a voluntary, cooperative partnership among the DfE Program, the University of Tennessee Center for Clean Products and Clean Technologies, the electronics industry, and other interested parties. The partnership assessed the life-cycle environmental impacts of two technologies that can be used for desktop computer displays. Specifically, it evaluated the traditional cathode ray tube (CRT) technology and the newer liquid crystal display (LCD) technology.

Purpose and Scope of the Project

The purpose of the Computer Display Project was twofold:

1) to assess the life-cycle environmental impacts of CRT and LCD technologies used in desktop computer displays; and
2) to develop a model that will expedite future environmental life-cycle analyses for computer display analyses.

To conduct this analysis, a life-cycle assessment (LCA) was used as the environmental evaluation tool. LCA looks at the full life cycle of the product being evaluated, from materials acquisition to manufacturing, use, and end-of-life (i.e., final disposition). While this project assesses CRT and LCD technologies specifically, the model in this study provides a baseline LCA upon which other technologies can be evaluated in the future.

Need for the Project

At present, CRT computer displays are used far more than any other display technology. CRT monitors are relatively inexpensive and provide a rich, high-resolution display well suited to a wide range of uses. CRT displays are bulky, however, and are associated with disposal problems with respect to with their leaded components. Newer technologies, collectively referred to as flat panel displays (FPDs), exhibit desirable qualities, such as reduced size and weight and greater portability, but currently are more expensive than CRT displays. CRTs currently dominate the desktop monitor market. At present, FPDs are used mainly in notebook computers, but their use in desktop monitors is increasing rapidly. Of the several types of FPD technologies, this study focused on active-matrix LCDs. Other FPD technologies were not included in the study because they make up a small fraction of the market and are not targeted for desktop applications. Market predictions indicate continued growth in LCD market share, as shown in the table below.

About EPA's Design for the Environment Program

EPA's Office of Pollution Prevention and Toxics established the DfE Program in 1992 to encourage businesses to incorporate environmental concerns into their business decisions. DfE industry projects are cooperative, joint partnerships with trade associations, businesses, public-interest groups, and academia to assist businesses in specific industries to identify and evaluate more environmentally sound products, processes, and technologies. The DfE Computer Display Project partnership consisted of members of electronics industry trade associations, computer monitor and component manufacturers, electronics industry suppliers, academic institutions, EPA, and a public interest group. The direction and focus of this project was chosen by the project partners.

Desktop display markets — actual for 1998 and projected for 2001

	Number of displays (thousands of units)	
Technology	**1998**	**2001**
CRT		
Worldwide	88,600	119,100
North America	33,801	42,609
LCD		
Worldwide	1,300	14,300
North America	229	3,787

Source: DisplaySearch 2001.

Given the expected market growth of LCDs, the various environmental concerns throughout the life cycle of computer displays, and the fact that the relative life-cycle environmental impacts of CRTs and LCDs had not been scientifically established to date, there was a need for an environmental life-cycle analysis of both desktop computer display technologies. As companies or consumers consider investing in certain displays, they can refer to the results of this study to assist them in making environmentally informed decisions. Although this study does not make recommendations or comparative assertions as to which display type is environmentally preferable, manufacturers can use its results to identify areas for improvement concerning the product's environmental burdens. With this information, the U.S. electronics industry may be more prepared to meet the global marketplace's growing demands of extended product responsibility, becoming better able to meet competitive challenges worldwide.

This booklet summarizes the key findings of the DfE Computer Display Project study. The information is presented in ten sections, or questions. The questions summarize:

- the study's life-cycle assessment methodology;
- the environmental impacts associated with the technologies evaluated;
- additional information on the health risks associated with lead, mercury, and liquid crystals;
- information on cost and performance; and
- guidance on where to find more information.

For more detailed information on any of these topics, the reader is encouraged to reference the full project report, *Desktop Computer Displays: A Life-Cycle Assessment* (EPA/744-R-01-004a and b). The document may be viewed at www.epa.gov/dfe.

Question 1:
What is a life-cycle assessment?

The DfE Computer Display Project (CDP) conducted this analysis of computer displays using a life-cycle assessment (LCA) approach, which allows for a comprehensive analysis of the environmental consequences of a product system over its entire life. LCA, which is increasingly being used by industry, contains four major steps:

1. **Goal Definition and Scoping** lays out why the LCA is being conducted, its intended use, and the system or data categories to be studied.
2. **Life-Cycle Inventory (LCI)** involves quantifying inputs (e.g., raw materials and fuel) and outputs (e.g., emissions, effluents, and products).
3. **Life-Cycle Impact Assessment (LCIA)** involves characterizing the effects of the inputs and outputs (as identified in the life-cycle inventory step) on the environment and human and ecological health.
4. **Improvement Assessment or Life-Cycle Interpretation** uses findings from the analysis to identify and evaluate opportunities for reducing life-cycle environmental impacts or to reach conclusions and recommendations. This step is left to the electronics industry and others to complete, using the results of this study.

In the LCI and LCIA steps, the inputs and outputs and environmental impacts associated with the product throughout its life are quantified and characterized for each life-cycle stage: raw material extraction, materials processing, product manufacturing, product use, and end-of-life. Each of these major stages of the product life-cycle are described in Figure 1.1.

In addition to the LCA, the study incorporated some methodologies more typical of the EPA Design for the Environment (DfE) Program's Cleaner Technologies Substitutes Assessment (CTSA) approach. Such an approach includes a more detailed assessment of the impacts of specific chemicals, and an evaluation of comparative cost and performance of different displays. For this analysis, the DfE streamlined CTSA approach was incorporated by analyzing three specific chemicals found in computer displays (lead, mercury, and liquid crystals), and by including a consideration of product costs and performance.

Figure 1.1. Life-cycle stages of a computer display

Inputs		Life-cycle stages		Outputs
	→	**Raw materials extraction/acquisition** Activities related to the acquisition of natural resources, such as mining and transporting raw materials to processing facilities.	→	
Materials	→	**Materials processing** Processing natural resources by reaction, separation, purification, and alteration steps in preparation for the manufacturing stage; and transporting processed materials to product manufacturing facilities.	→	Wastes
Energy	→	**Product manufacture** Processing materials and assembling component parts to make a computer display.	→	
Resources	→	**Product use, maintenance, and repair** Displays are transported to and used by customers. Maintenance and repair may be conducted either at the customer's location or taken back to a service center or manufacturing facility.	→	Products
	→	**End-of-life** At the end of its useful life, the display is retired. If reuse and recycle of usable parts is feasible, the product can be transported to an appropriate facility and disassembled. Parts and materials that are not recoverable are then transported to appropriate facilities and treated (if required or necessary) and/or disposed of.	→	

Question 2:
Which computer displays were investigated during the project?

This study evaluated two types of computer display technologies: cathode ray tubes (CRTs) and liquid crystal displays (LCDs). In a life-cycle assessment (LCA), a "functional unit" is defined to delineate the functional characteristics of the products being evaluated and allow them to be evaluated on an equivalent basis. For this study, the functional unit was defined as one desktop computer display over its life. Data collected in this project were normalized to a display that meets the functional unit specifications presented in Table 2.1.

Table 2.1. Functional unit specifications

Specification	Measure
display size [a]	17" (CRT); 15" (LCD)
diagonal viewing area [a]	15.9" (CRT); 15" (LCD)
viewing area dimensions	12.8" x 9.5" (122 in^2) (CRT); 12" x 9" (108 in^2) (LCD)
resolution	1024 x 768 color pixels
brightness	200 cd/m^2
contrast ratio	100:1
color	262,000 colors

[a]An LCD is manufactured such that its nearest equivalent to the 17" CRT display is the 15" LCD. The viewing area of a 17" CRT is about 15.9 inches and the viewing area of a 15" LCD is 15 inches. LCDs are not manufactured to be exactly equivalent to the viewing area of the CRT.

In addition to LCDs, several other flat panel display technologies were considered for inclusion in the project; however, as these other technologies are not used for standard desktop computer displays (this study's functional unit), they were ultimately not included in the study. Each of the technologies included, CRTs and LCDs, is discussed in more detail below.

Cathode Ray Tube Display

CRT Technology

CRT monitors are a mature technology and are the current industry standard for desktop computer displays. The technology is the same as that for a television. CRT displays use high voltages to accelerate electrons toward a luminescent material (phosphor) that is deposited on a faceplate. The phosphor converts the kinetic energy of the electrons into light. The CRT must have excellent electrical insulating properties because the high voltages used to accelerate the electrons must be insulated from the external surfaces of the tube. The decelerating electrons produce X-rays, so the CRT must also be a good X-ray absorber. Leaded glass therefore surrounds the cathode ray tube to absorb the X-rays.

The major parts of the CRT display are a faceplate (glass panel), a shadow mask (also referred to as the aperture mask), a leaded glass funnel, and an electron gun with a deflection yoke. Various connectors, wiring, an implosion band, printed wiring boards, and the casing comprise most of the rest of the display. The overall project report, *Desktop Computer Displays: A Life-Cycle Assessment*, provides a detailed list of each part in the CRT assembly, the subassemblies that make up that part, and the materials in the manufacture of each component. To illustrate the level of detail examined, an example of this detailed materials list is presented in Table 2.2 for the tube -- just one component of the CRT display.

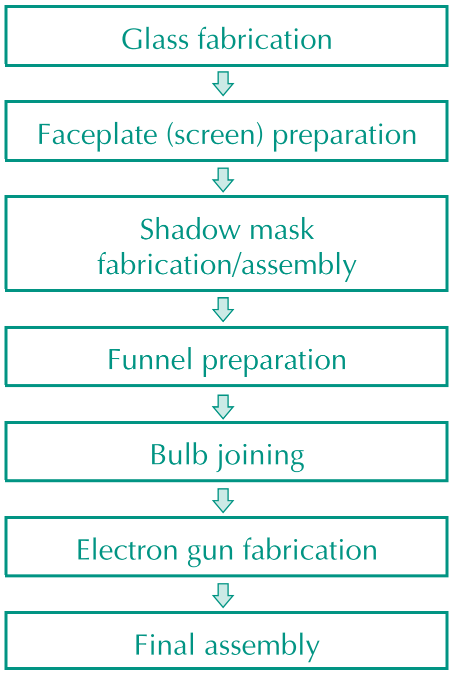
Table 2.2. CRT display components and materials (excerpt)

Component parts				Materials
Tube	Faceplate assembly	Phosphor-coated faceplate	Glass faceplate	Glass (1-2.5% PbO alkali/ alkaline earth aluminosilicate)
			Phosphors	ZnS, Y_2O_2S (powders): Sn, Si, K, Cd
			Photoresist	Polyvinyl alcohol
			Black matrix coating	Aquadag
			Lacquer coating	Mixture of alcohol and plastics
			Aluminum coating	Aluminum
		Internal electron shield		Aluminum
		Shadow mask assembly		Steel, Ni
	Frit (lead solder glass)			Lead oxide, zinc borate (- 70% PbO)
	Conductively coated funnel	Glass funnel		Leaded glass (- 24% PbO)
		Conductive coating		Aquadag (may also add iron oxide)
		Frit		PbO, zinc oxide, boron oxide
		Binder		Nitrocellulose binder, amyl acetate
	Neck	Neck glass		Leaded glass (30% PbO alkali/alkaline earth silicate)
		Deflection yoke		Cu, ferrite
		Base & top neck, rings		Polystyrene
		Brass ring, brackets		Brass
		Rubber gaskets		Rubber
		Screws, washers		Zn-plated steel
		Neck clamp		Steel
		Insulating rings		Polysulphone
		Neck printed wiring board		Misc. electronics and resin board
	Implosion band			Steel

CRT Manufacturing

The traditional CRT manufacturing process is generally composed of the steps shown in Figure 2.1.

Figure 2.1. CRT manufacturing process



Glass fabrication. The manufacturing process of the CRT monitor involves first preparing the glass. In glass manufacturing, raw materials (e.g., sand, soda ash, limestone, boron) are converted to a homogeneous melt at high temperatures and then formed into the panel (the faceplate on the front of the CRT) and the funnel (the back half of the CRT vacuum shell).

Faceplate preparation. The faceplate, also referred to as a screen or panel, is coated with a conductive material known as aquadag. The aquadag acts as an anode, attracting the electrons emitted from the electron guns. Luminescent phosphor materials are also applied to the inside surface of the faceplate. Using photolithography, the phosphor is applied in a pattern of dots or stripes where red, green, and blue phosphors are deposited in subsequent steps. The result is a patterned luminescent screen with the emissive elements separated by non-reflecting material. A lacquer coating is applied to the phosphor-coated glass to smooth and seal the inside surface of the screen, and an aluminum coating is added to enhance brightness.

Shadow mask fabrication and assembly. The shadow mask makes color images possible as electrons pass through the mask before hitting the precisely located colored regions of the faceplate. The shadow mask is a thin steel panel with a mask pattern of either round or slotted openings applied through photolithography. The flat mask is fitted to the contour of the faceplate and supported in the faceplate on a heavy frame. Alignment fixtures and an internal magnetic shield are added to complete the faceplate assembly.

Funnel preparation. The funnel provides the back half of the vacuum shell and electrically connects the electron gun and the faceplate to the anode button (a metal connector button in the funnel provided for attachment of the power supply). A conductive coating similar to the type used on the faceplate is applied to the inner surface of the glass funnel. Frit (solder glass) is applied to the edge of the funnel to be joined with the faceplate.

Bulb joining. The faceplate assembly is placed on the fritted edge of the funnel in a fixture that carries the two halves in precise alignment through a high temperature oven, where the frit is cured. The resulting assembly is a vacuum tight bulb, ready to receive the electron gun and to be evacuated to become a finished CRT.

Electron gun fabrication. The electron gun is an assembly of glass and a number of electrostatic electrodes made of steel. The electrodes, along with cathodes, ribbon conductors, and electrical feed-through pins are heated to embed the metal parts in the glass.

Final assembly. The frit-sealed bulb assembly and the electron gun assembly are joined by fusing a glass stem on the electron gun with the neck tubing in a machine that melts the two glasses together in precise alignment. Final steps are conducted to remove the air from the CRT to form a vacuum, before the entire monitor is assembled with other necessary parts (e.g., printed wiring boards, power cord, casing).

Liquid Crystal Display

LCD Technology

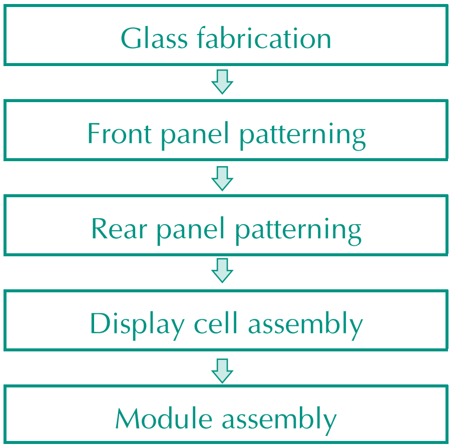
The two most common types of LCDs are passive matrix (PMLCD) and active matrix (AMLCD). This project focused on AMLCDs because PMLCDs are used primarily for low-end products (e.g., products that cannot perform video applications) and are forecasted to decline to less than one percent of the LCD desktop display market by 2002. The most common type of AMLCD, and the one that meets the functional unit specifications of this project, is called an amorphous silicon thin-film transistor active matrix LCD.

In general, an LCD is composed of two glass plates surrounding a liquid crystal material that filters external light. LCDs control the color and brightness of each pixel (picture element) individually, rather than from one source, such as the electron gun in the CRT. The orientation of the liquid crystal molecules either allows or does not allow light from a backlight source to pass through the display cell. When no electrical current is present, the liquid crystals align themselves parallel to an alignment layer on the glass. When a current is applied, the liquid crystals turn perpendicular to the glass. The combination of the alignment layer, electrical charge, and polarizers that are laminated to the glass panels determine the on or off state of the LCD cell. The backlight supplies the light source for the display and generally has fluorescent tubes that contain small amounts of mercury vapor. Because the LCD technology essentially regulates passage of a backlight through the display, LCDs are considered non-emitting display technologies. CRTs, on the other hand, emit electrons to illuminate appropriate phosphors and are considered to be emitting displays.

LCD Manufacturing

The LCD manufacturing process is more complex than the CRT process in terms of the types of materials used and how the process steps are completed. A general overview of the manufacturing process is shown in Figure 2.2 and described below.

Figure 2.2. LCD manufacturing process



Glass fabrication. Molten glass (e.g., soda lime or borosilicate glass) is prepared into flat substrates. The glass sheets are trimmed to the required size and cleaned, which is a critical step in reliable manufacturing.

Front panel patterning. The front panel electrode is created by sputtering indium tin oxide onto the glass. Next, a black matrix and red, green, and blue color filters is deposited and patterned (using a photolithography process) onto the panel. The black matrix creates a border around the color filters for contrast. The color filter process results in a non-uniform surface, so a layer of polyimide is added to create a planar surface. The last material added to the front panel is an alignment layer, which is a polyimide applied by roll coating and then rubbed to the desired molecular orientation.

Rear panel patterning. The rear panel is where the transistors are created, requiring more complex steps than the front panel. In the case of LCDs, the fast response speed required for computer displays is achieved by having a switch at each pixel, which is the basis for active-matrix addressing. This switch is a transistor that basically consists of a gate, source and drain, and channel. Electrons flow through the channel between the source and drain when voltage is applied to the gate. There is an insulating layer between the gate the source/drain region, referred to as a dielectric. The gate metal is applied first to the glass substrate and patterned. Next, a silicon-based dielectric, channel, and a doped silicon layer are applied and patterned as needed. The pixel electrode is formed by sputtering indium tin oxide (also used to create the front panel electrode). The source/drain metal is sputtered and patterned, and a contact is formed between this layer and the doped silicon layer. The substrate is cleaned and a thin polymer alignment layer is deposited onto the surface. This layer is then rubbed in the direction desired for the liquid crystal orientation.

Display cell assembly. At this stage of the process, the color filter substrate (front glass) and the transistor substrate (rear glass) are joined with an adhesive seal material. Before sealing the two substrates, spacers are deposited to maintain a precise gap of five to ten micrometers between the two surfaces. The substrates are aligned and laminated using heat and pressure. Liquid crystal material is then injected into the small space in between the substrates. The last step in the display cell assembly is attaching polarizers (from rolls or precut sheets) to the outside of each glass panel.

Module assembly. The module assembly step includes attaching the backlight unit, which is the light source for the LCD. A typical desktop unit has four backlights, which are placed around the edges of the display. The light projects across a diffuser screen to provide uniform illumination. The printed wiring boards, the power supply assembly, and the plastic cover and stand are added to make an assembled monitor.

Question 3:
How were environmental and health impacts evaluated?

The environmental and health impacts of computer displays throughout their life cycles were evaluated through two sequential processes: a life-cycle inventory (LCI) and a life-cycle impact analysis (LCIA).

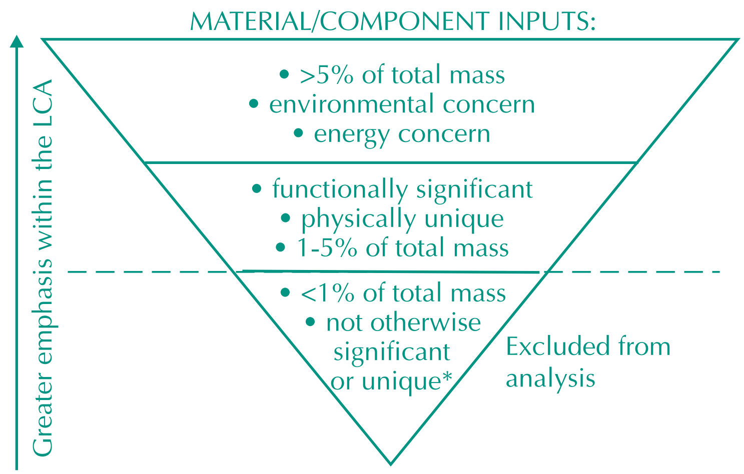
Life-cycle Inventory

The LCI is the process of collecting information about the quantity of materials used (inputs) and outputs of processes in each life-cycle stage. Quantitative inventory data for the processes in the life cycles of the displays were provided by 22 display manufacturers. Input information included the materials found in the actual display, as well as energy requirements and ancillary materials used during manufacturing. Because there are not established guidelines in standard LCA methodologies for determining where boundaries should be drawn for the analysis, it was decided the study would evaluate the impacts of inputs that met one or more of the following criteria:

- constitutes more than one percent to the mass of a display;
- is known or suspected to have environmental significance (e.g., it is toxic);
- is known or suspected to have large energy requirements;
- is functionally significant to the display; and
- is physically unique to one of the displays (i.e., the material is found in a CRT but not in an LCD or vice versa).

The following diagram demonstrates this selection process graphically.

Figure 3.1. Criteria for selecting inputs



*For example, materials are excluded if they are not of known environmental significance (e.g., toxic) or are not physically unique.

EPA also determined the outputs from each of the five life stages (i.e., materials extraction, materials processing, product manufacturing, product use, and end-of-life; see Figure 1.1) for each process included in the analysis. These outputs included air emissions, solid waste releases, and water effluents whenever appropriate and possible. Some information was collected specifically for this study; for example, much of the material and energy use data for the product manufacturing stage was provided by display and component manufacturers. Other data, such as outputs from material extraction, were obtained from existing information sources.

Life-cycle Impact Assessment

Life-cycle impact assessment (LCIA) is the process in which the input and output data from an LCI are aggregated across all life stages and translated into impacts on human health and the environment. There were two steps in the CDP LCIA: classification and characterization.

Classification

In order to evaluate similar impacts together, each input and output in the LCI was placed into one or more of 20 impact categories. These categories cover a range of effects that address natural resource impacts, abiotic ecosystem impacts, and human health and ecotoxicity. Some inputs and outputs can have multiple effects or impacts and are included in multiple categories. For example, methane is both a global warming gas and a photochemical smog contributor; this material is therefore represented in both of these impact categories.

Characterization

The impacts of inputs and outputs are not necessarily commensurate with their weight or volume. For example, methane and carbon dioxide are both global warming gases, but methane is much more potent on a mass basis. Conversion factors or scoring systems were therefore used for some impact categories to place different inputs and outputs in common units.

The 20 impact categories and a description of each are presented in Table 3.1.

Table 3.1. Impact categories

Impact Category	Inventory Type		Description
	Input	Output	
Natural Resource Impacts			
renewable resource use	material, water	----	Materials found in nature that are replenished through natural processes.
nonrenewable resource use/depletion	material, fuel	----	Materials, such as metals or fossil fuels, that are not regenerated naturally.
energy use	electricity, fuel	----	The amount of energy consumed. The impacts associated with energy are included under other impact categories.
solid waste landfill use	----	solid waste to landfill	The volume of landfill space required for solid waste.
hazardous waste landfill use	----	hazardous waste to landfill	The volume of space required in a hazardous waste landfill.
radioactive waste landfill use	----	radioactive waste to landfill	The volume of waste disposed of at a radioactive waste disposal facility.
Abiotic Ecosystem Impacts			
global warming	----	air	The mass of greenhouse gases emitted (chemical amounts are weighted according to their potency relative to carbon dioxide).
stratospheric ozone depletion	----	air	The mass of ozone depleting chemicals emitted (chemical amounts are weighted according to their potency relative to CFC-11).
photochemical smog	----	air	The mass of smog-producing chemicals emitted (chemical amounts are weighted according to their potency relative to ethene).
acidification	----	air	The mass of acidifying chemicals emitted (chemical amounts are weighted according to their potency relative to sulfur dioxide).
air quality (air particulates)	----	air	The mass of particulates emitted that have a diameter less than 10 micrometers.
water eutrophication (nutrient enrichment)	----	water	The mass of eutrophication chemicals released (chemical amounts are weighted according to their potency relative to phosphate).
water quality: BOD	----	water	Amount of oxygen-consuming material released to water [converted to Biological Oxygen Demand (BOD)].
water quality: TSS	----	water	Amount of suspended solids released to water.
radioactivity	---	radioactivity to air, water, or land	The amount of radioactive chemicals released (measured in Bequerels).
Human Health and Ecotoxicity			
chronic human health effects - occupational	material	----	Weighted score based on the amount and toxicity of releases affecting workers.
chronic human health effects - public	----	air, water	Weighted score based on the amount and toxicity of releases affecting the general public.
aesthetic impacts (odor)	----	air	Volume of air released that is above odor detection threshold.
aquatic ecotoxicity	----	water	Weighted score based on the amount and toxicity of releases affecting fish.
terrestrial ecotoxicity	----	air, water	Weighted score based on the amount and toxicity of releases affecting terrestrial organisms.

In addition to the general considerations of the LCA method discussed in Question 1, it should also be noted that because display technology is constantly improving, displays often are discarded while they are still functional. To reflect this situation, the analysis was based on the "effective" or typical life span of a display rather than the designed life span. Also, due to a lack of transportation data for the manufacturing, use, and end-of-life stages, transportation impacts were excluded for these stages, but in some instances were included in the existing data used for the materials extraction and materials processing stages.

Question 4:
What are the environmental and health impacts of CRTs?

This section presents a summary of the results for each impact category described in Question 3, for which CRTs had associated impacts. Although some LCAs assign importance ranks or weights to impact categories, this step was intentionally excluded from this study because it requires subjective choices that might not be appropriate for all stakeholders with an interest in this project. Table 4.1 identifies the process that contributes most significantly to each impact category.

Table 4.1. Summary of most significant CRT processes

Impact category	Most significant process	Associated life stage	Percent contribution to category score
Natural Resource Impacts			
renewable resource use	LPG production for glass manufacturing	manufacturing	79%
nonrenewable resource use/depletion	LPG production for glass manufacturing	manufacturing	56%
energy use	LPG production for glass manufacturing	manufacturing	72%
solid waste landfill use	coal waste from electricity generation	use	38%
hazardous waste landfill use	landfilled CRT monitor	end of life	91%
radioactive waste landfill use	low-level radioactive waste from electricity generation	use	61%
Abiotic Ecosystem Impacts			
global warming	carbon dioxide from electricity generation	use	64%
stratospheric ozone depletion	bromomethane from coal burned for electricity generation	use	49%
photochemical smog	hydrocarbons from energy generation used for LPG production for glass manufacturing	manufacturing	36%
acidification	sulfur dioxide from electricity generation	use	47%
air quality (air particulates)	particulate matter from energy generation used for LPG production for glass manufacturing	manufacturing	43%
water eutrophication (nutrient enrichment)	chemical oxygen demand from energy generation used for LPG production for glass manufacturing	manufacturing	72%
water quality: BOD	BOD from energy generation used for LPG production for glass manufacturing	manufacturing	96%
water quality: TSS	TSS from energy generation used for LPG production for glass manufacturing	manufacturing	97%
radioactivity	Plutonium released from energy generation used for steel production	upstream	62%

continued on next page

Table 4.1. Summary of most significant CRT processes (continued)

Impact category	Most significant process	Associated life stage	Percent contribution to category score
Human Health and Ecotoxicity			
chronic human health effects - occupational	LPG used for glass manufacturing	manufacturing	78%
chronic human health effects - public	Sulfur dioxide from fossil fuels burned for electricity generation	use	83%
aesthetic impacts (odor)	Hydrogen sulfide from energy generation used for LPG production for glass manufacturing	manufacturing	94%
aquatic ecotoxicity	phosphorous used in CRT tube manufacturing	manufacturing	26%
terrestrial ecotoxicity	Sulfur dioxide from fossil fuels burned for electricity generation	use	83%

[a]Acronyms: liquified petroleum gas (LPG), particulate matter with diameter less than 10 micrometers (PM_{10}), biological oxygen demand (BOD), total suspended solids (TSS).

Natural Resource Impacts

Renewable resource use. Renewable resources are materials found in nature that generally are replenished through natural processes. The most significant examples are water and forest products. The CRT manufacturing life stage creates the largest impact with respect to renewable resource consumption, representing 87 percent of the total in this impact category. More specifically, the production of liquified petroleum gas (LPG), which is subsequently used as an energy source in the glass manufacturing process, contributed nearly 80 percent alone to the impact score due to the water requirements of LPG manufacturing.

Nonrenewable resource use/depletion. Nonrenewable resources are materials, such as metals or fossil fuels, that are not readily regenerated naturally. The depletion of LPG reserves for glass manufacturing creates the largest impact in the CRT life cycle. The petroleum used to make LPG contributed 56 percent of the mass of nonrenewable resources used. Much of the remaining resource use is associated with other fuels. Less than two percent by weight of the nonrenewable resources used were actually incorporated into the CRT (i.e., were processed into metals, plastics, or other materials).

Energy use. This impact category considers only energy consumed during a display's life cycle; it does not include the releases associated with energy production. (Those effects are reported under other appropriate impact categories.) Most of the energy use associated with the CRT life cycle is consumed during the glass/frit manufacturing process (72 percent on a megajoule basis). Electricity consumed during the use of CRTs represented an additional 11 percent.

Solid waste landfill use. By consuming space in a landfill, solid waste necessitates the use of open land. The largest demand for solid waste space is caused by the use life stage. Solid wastes (primarily coal wastes) are created during the generation of electricity. Interestingly, based on an end-of-life scenario assuming that 15 percent of CRTs are incinerated, 71 percent are landfilled (46 percent as hazardous waste, 25 percent as solid waste), and 14 percent are recycled or remanufactured, the end-of-life stage of the CRT has a beneficial effect on solid waste landfill use. The solid waste avoided by recovering energy to generate electricity during CRT incineration (i.e., the solid waste that would have been generated from fossil fuel-burning electricity plants) more than offsets the volume of a CRT that is landfilled.

Hazardous waste landfill use. Hazardous waste consists of materials that are regulated under the Resource Conservation and Recovery Act. Like solid waste, this material contributes to the consumption of open land but also demands additional safety and environmental protection precautions. In contrast to the results for solid waste landfill use, the largest life stage for this impact category is the end-of-life stage. Over 90 percent of the weight disposed of in a hazardous waste landfill is attributed to the CRT itself.

Radioactive waste landfill use. Like hazardous waste, radioactive waste contributes to the consumption of open land and creates safety and environmental challenges. Nearly 80 percent of the CRT material disposed of in a radioactive waste landfill results from the electricity consumed during CRT use. This material principally is low-level radioactive waste and depleted uranium produced by nuclear power plants.

Abiotic Ecosystem Impacts

Global warming. Gases such as carbon dioxide and methane trap heat in the atmosphere. It is believed that by increasing the concentrations of these gases, humans are causing the atmosphere to become warmer and induce global climate change. Electricity consumption during the use of CRTs is the largest contributor of global warming impacts; carbon dioxide produced by power plants contributed 64 percent of the global warming potential associated with CRTs. This result should be compared with the energy use findings. Although CRT use is not the most significant life stage for energy use, electricity production generates considerably more carbon dioxide per unit of energy than LPG or other fossil fuels used directly.

Stratospheric ozone depletion. The stratospheric ozone layer blocks harmful ultraviolet (UV) sunlight from reaching the earth's surface. Chemicals such as chlorofluorocarbons (CFCs) may destroy ozone in the stratosphere, causing an increase in UV radiation on the earth's surface. The largest contributor to ozone depletion (weighted according to potency) is electricity production for CRT use. Bromomethane, an ozone depleting compound, is produced during the combustion of coal. CFCs used in the manufacture of some CRT materials are also an issue. It should be noted that the calculations for this impact category are uncertain because some secondary data for materials processing were collected prior to the phase-out of CFCs.

Photochemical smog. Photochemical smog is produced in the atmosphere by the reaction of hydrocarbons and nitrogen oxides in the presence of sunlight. Smog may cause or aggravate health problems, toxicity in plants, and deterioration of materials. The largest contributor to this impact category was the production of LPG used to manufacture glass. This process emitted chemicals that accounted for 67 percent of the photochemical smog.

Acidification. The release of acids into the air causes acid rain. Acid rain in turn harms surface water, soil, and plants. The production of electricity for the use of CRTs was the largest source of acidifying emissions. This process produced sulfur dioxide, nitrogen oxides, and hydrochloric acid to contribute 63 percent to the overall score for this category.

Air quality (particulate matter). Particulates in the air, especially those that have a diameter smaller than 10 micrometers (PM10), can cause respiratory illnesses in humans and animals. Two processes that significantly affect this impact category are LPG production for glass manufacturing, and steel production (in the materials processing life stage). It should be noted that because some of the output data did not specify the size of the particulates, some of the results for PM10 might be overestimated.

Water eutrophication (nutrient enrichment). In most surface water, the level of biological activity is limited by the concentration of nitrogen and phosphorous. When these two nutrients are released to water, fast-growing organisms such as algae outcompete established organisms such as fish. LPG production for glass manufacturing was the source of roughly 90 percent of the impacts in this category. This process released chemical oxygen demand-related chemicals and ammonia ions.

Water quality (BOD). Organic chemicals that are released to water ultimately lead to a depletion of dissolved oxygen, which in turn reduces the survival rate of organisms such as fish. One measure of this impact is biological oxygen demand (BOD). As for water eutrophication, LPG production was the source of most (96 percent) of the impacts in this category.

Water quality (TSS). In turbid (cloudy) water, only a fraction of the usual amount of sunlight penetrates the water. As a result, less sunlight reaches plants and other dependent organisms and less biological activity occurs. Total suspended solids (TSS) indicates the magnitude of this effect for a stream of wastewater. LPG production is the primary influence (97 percent) for this impact category.

Radioactivity. Radioactive materials released to the environment can cause cancer in humans and animals. Nearly all of the radioactivity releases are associated with materials processing, particularly steel, invar, and ferrite. Specifically, the impacts result from reprocessing nuclear fuel used to generate electricity at steel, invar, and ferrite facilities outside the United States. Because reprocessing is not conducted in the U.S., only a minute amount of radioactivity release is associated with electricity consumption during CRT use.

Human Health and Ecotoxicity

Chronic human health effects – occupational. Workers might experience health effects, including cancer, from long term exposure to materials associated with computer displays. LPG used in glass manufacturing accounted for much of the impact score in this category.

Chronic human health effects – public. Members of the general public might be at risk of developing adverse health effects, including cancer, due to air or water releases from the life cycle of computer displays. The largest impact on the public is the sulfur dioxide (SO_2) released due to electricity generation for CRT use. SO_2 produced for the product use stage contributed 83 percent of the score because of this pollutant's relatively high non-cancer hazard value and high release rate.

Aesthetic impacts (odor). Some air emissions may be released in concentrations that are detectable by smell. Odor does not by itself represent a human health or environmental problem, but it is considered a nuisance. Hydrogen sulfide produced during the production of LPG for glass manufacturing generated the largest odor impact. This chemical accounted for 94 percent of the impacts in this category.

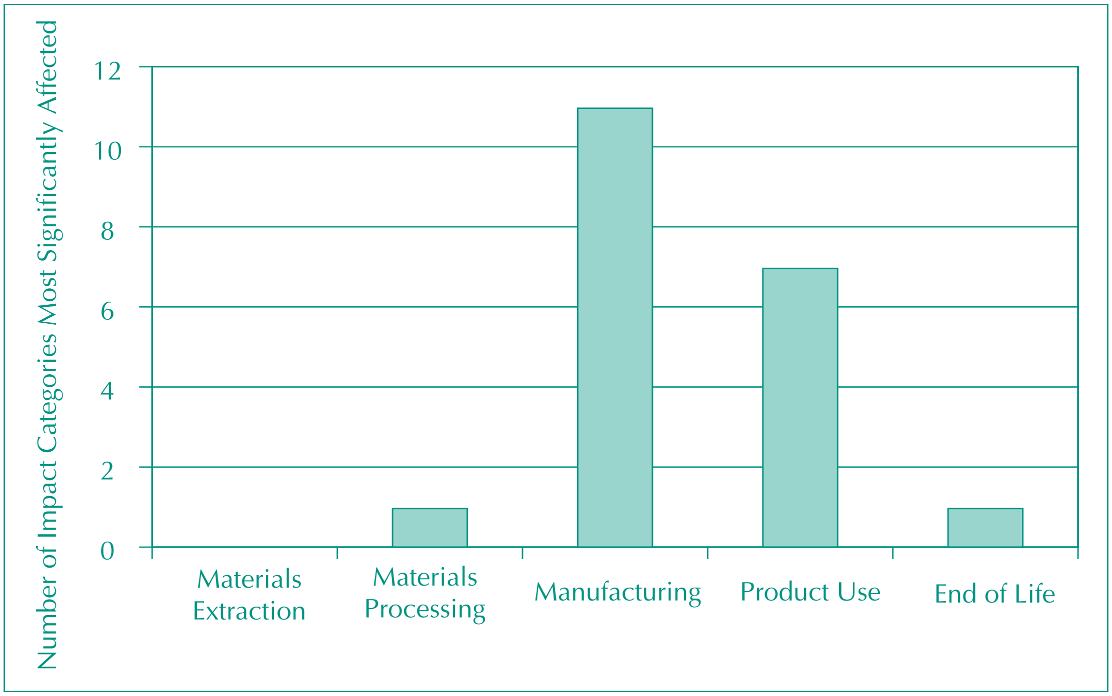
Aquatic ecotoxicity. Organisms that live in water, particularly fish, can be harmed by toxic chemicals released to water. The results were broadly distributed. Phosphorous, used in the manufacturing life-cycle stage to produce the CRT tube, was the most significant contributor but accounted for only 26 percent of the impact score. Other materials contributing significantly to the aquatic ecotoxicity score included aluminum, copper, and zinc from the materials processing stage.

Terrestrial ecotoxicity. Organisms living on land can be adversely affected by toxic chemicals in the air or in surface water. Results for this impact category are based on the effects on rodents. As for chronic public health effects, SO_2 produced during electricity generation for CRT use was the most significant material. In large part, this similarity resulted because the same non-cancer toxicity rating for SO_2 applies for both impact categories.

Comparison across CRT life stages

As shown in Figure 4.1, the manufacturing life-cycle stage was the largest contributor in 11 of the 20 impact categories. In most cases, this was due to the very high requirements of LPG in the glass manufacturing process and the associated environmental impacts of processing that LPG. CRT use was important in seven of the impact categories, due mainly to the diverse impacts of electricity generation. It is important to note that the figure does not indicate the overall magnitude of impacts in each life-cycle stage; it was beyond the scope of the project to weigh the relative importance of each impact category. Instead, the figure indicates the areas in the CRT life cycle where the effects of certain processes may be more multifaceted or worthy of further investigation.

Figure 4.1. Distribution of Largst CRT Impacts



Question 5:
What are the environmental and health impacts of LCDs?

Like CRTs, LCDs had impacts associated with each impact category; this section presents a summary of the results. Table 5.1 identifies the processes that contribute most significantly to each impact category.

Table 5.1. Summary of most significant LCD processes

Impact category	Most significant process	Associated life stage	Percent contribution to category score
Natural Resource Impacts			
renewable resource use	water use in LCD module manufacturing	upstream	38%
nonrenewable resource use/depletion	natural gas extraction	upstream	65%
energy use	electricity consumed for LCD use	use	30%
solid waste landfill use	coal waste from electricity generation	use	44%
hazardous waste landfill use	landfilled LCD monitor	end of life	97%
radioactive waste landfill use	low-level radioactive waste from electricity generation	use	44%
Abiotic Ecosystem Impacts			
global warming	sodium hexafluoride in LCD module manufacturing	manufacturing	29%
stratospheric ozone depletion	HCFC-225 in LCD component manufacturing	manufacturing	34%
photochemical smog	non-methane hydrocarbons from natural gas production	upstream	45%
acidification	sulfur dioxide from electricity generation	use	31%
air quality (air particulates)	particulate matter from energy generation used for steel production	use	45%
water eutrophication (nutrient enrichment)	nitrogen from LCD module manufacturing	manufacturing	67%
water quality: BOD	BOD from LCD module manufacturing	manufacturing	61%
water quality: TSS	TSS from LPG production for LCD glass manufacturing	manufacturing	66%
radioactivity	plutonium released from energy generation used for steel production	upstream	96%
Human Health and Ecotoxicity			
chronic human health effects - occupational	LPG used for LCD glass manufacturing	manufacturing	58%
chronic human health effects - public	sulfur dioxide from fossil fuels burned for electricity generation	use	68%
aesthetic impacts (odor)	phosphine from LCD module manufacturing	manufacturing	89%
aquatic ecotoxicity	phosphorous from LCD module manufacturing	manufacturing	98%
terrestrial ecotoxicity	sulfur dioxide from fossil fuels burned for electricity generation	manufacturing	68%

[a]Acronyms: liquified petroleum gas (LPG), hydrochlorofluorocarbon (HCFC), particulate matter with diameter less than 10 micrometers (PM10), biological oxygen demand (BOD), total suspended solids (TSS).

Natural Resource Impacts

Renewable resource use. Renewable resources are materials found in nature that generally are replenished through natural processes. The most significant examples are water and forest products. The manufacturing life stage accounted for over 75 percent of the renewable resource use. The most water-intensive manufacturing steps were LCD monitor manufacturing and the production of liquified petroleum gas (LPG) used in glass manufacturing.

Nonrenewable resource use/depletion. Nonrenewable resources are materials, such as metals or fossil fuels, that are not readily regenerated naturally. The vast majority of nonrenewable resource use (97 percent on a mass basis) is associated with the depletion of fossil fuels. The largest single process step is the depletion of natural gas in the materials processing life stage.

Energy use. This impact category considers only the energy consumed during a display's life cycle; it does not include the releases associated with energy production. (Those effects are reported under other appropriate impact categories.) The electricity consumed during LCD use is the largest single contributor to the energy use results. Other energy-intensive processes include LCD glass manufacturing, which uses LPG and electricity, and natural gas production, which uses unprocessed natural gas.

Solid waste landfill use. By consuming space in a landfill, solid waste necessitates the use of open land. Most of the solid waste (65 percent by weight) is associated with electricity production for LCD use. This solid waste material includes coal waste, dirt/sludge, and fly/bottom ash. Like CRTs, LCDs are calculated to reduce solid waste landfill use in the end-of-life stage, because the incineration of some LCDs and the resulting energy offsets the solid waste impacts of landfilled displays and fossil fuel-derived energy.

Hazardous waste landfill use. Hazardous waste consists of materials regulated under the Resource Conservation and Recovery Act. This material has the same space requirements as solid waste and also demands additional safety and environmental protection precautions. The landfilling of LCDs produced most of the impacts in this category, even though only five percent of LCDs were expected to be landfilled. Hazardous waste from LPG production and acetic acid from LCD monitor manufacturing represent the remaining amount.

Radioactive waste landfill use. Like hazardous waste, radioactive waste contributes to the consumption of open land and creates safety and environmental challenges. The wastes in this impact category are low-level radioactive waste and depleted uranium generated during electricity production at nuclear power plants.

Abiotic Ecosystem Impacts

Global warming. Gases such as carbon dioxide and methane trap heat in the atmosphere. It is believed that by increasing the concentrations of these gases, humans are causing the atmosphere to grow warmer and induce global climate change. Several processes contributed to the global warming impact of LCDs. Sulfur hexafluoride used in the LCD module manufacturing process contributed 29 percent of the global warming potential of LCDs. Most of the remaining impacts were caused by carbon dioxide released during electricity generation for LCD use and during natural gas production.

Stratospheric ozone depletion. The stratospheric ozone layer blocks harmful ultraviolet (UV) sunlight from reaching the earth's surface. Chemicals such as chlorofluorocarbons may destroy ozone in the stratosphere, causing an increase in UV radiation on the earth's surface. Roughly 60 percent of the impacts in this category were caused by hydrochlorofluorocarbons (HCFCs) used in manufacturing LCD panel components. Unlike the CFCs that contributed significantly to CRT ozone depletion impacts, the HCFCs used to manufacture LCD panel components are not scheduled for phaseout until 2015. Another 27 percent of ozone depletion impacts was contributed by electricity generation for LCD use, which released bromomethane during the combustion of coal.

Photochemical smog. Photochemical smog is produced in the atmosphere by the reaction of hydrocarbons and nitrogen oxides in the presence of sunlight. Smog may cause or aggravate health problems, toxicity in plants, and deterioration of materials. Approximately 75 percent of the photochemical smog results were caused by natural gas production in the materials processing life-cycle stage. Important releases included methane, benzene, and other non-methane hydrocarbons.

Acidification. The release of acids into the air causes acid precipitation, which in turn harms surface water, soil, and plants. Roughly 40 percent of the impacts in this category were caused by sulfur dioxide and nitrogen oxides released during electricity generation for product use. Other important processes include natural gas production, which released nitrogen oxides, ammonia, and sulfur oxides; and LCD module manufacturing, which produced nitrogen oxides, ammonia, hydrofluoric acid, and hydrochloric acid.

Air quality (particulate matter). Particulates in the air, especially those that have a diameter smaller than 10 micrometers, can cause respiratory illnesses in humans and animals. The largest contributor to this impact category was steel production in the materials processing life stage. This process accounted for 45 percent of the particulate matter released by weight. Natural gas production contributed an additional 25 percent to the overall amount of particulate matter.

Water eutrophication (nutrient enrichment). In most surface water, the level of biological activity is limited by the concentration of nitrogen and phosphorous. When these two nutrients are released to water, fast-growing organisms such as algae outcompete established organisms such as fish. Most of the nutrient enrichment (94 percent) was caused during the LCD module manufacturing process; nitrogen and phosphorous were both released.

Water quality (BOD). Organic chemicals that are released to water ultimately lead to a depletion of dissolved oxygen, which in turn reduces the survival rate of organisms such as fish. One measure of this impact is biological oxygen demand (BOD). The LCD module manufacturing process generated most of the BOD output from the LCD life cycle; it accounted for 61 percent of the score in this impact category. LPG production was another significant source of BOD.

Water quality (TSS). In turbid (cloudy) water, only a fraction of the usual amount of sunlight penetrates the water. As a result, less sunlight reaches plants and other dependent organisms and less biological activity occurs. Total suspended solids (TSS) indicates the magnitude of this effect for a stream of wastewater. LPG production generated the largest amount of TSS; 66 percent of the TSS resulted from this process.

Radioactivity. Radioactive materials released to the environment can cause cancer in humans and animals. As with CRTs, nearly all of the estimated radioactivity impacts of LCDs were associated with steel produced in countries that reprocess nuclear fuel. Only a small amount of radioactivity is released by nuclear power plants in the United States.

Human Health and Ecotoxicity

Chronic human health effects – occupational. Workers might experience health effects, including cancer, from long-term exposure to materials associated with computer displays. Liquified natural gas, which is used in LCD module manufacturing, was the single most significant material for this impact category. The sulfuric acid used in the same process also was significant. Together, these two chemicals accounted for 81 percent of the score.

Chronic human health effects – public. Members of the general public might be at risk of developing adverse health effects, including cancer, due to air or water releases from a life-cycle stage of computer displays. The SO_2 released during electricity production was the largest contributor to the public health effects category. The largest share was attributed to electricity consumed for LCD use (68 percent of the score), and another 21 percent was attributed to electricity use in LCD manufacturing.

Aesthetic impacts (odor). Some air emissions may be released in concentrations that are detectable by smell. Odor does not by itself represent a human health or environmental problem, but it is considered a nuisance. Most of the odor generated in the LCD life cycle was attributed to phosphine, which was emitted in the LCD module manufacturing process. Hydrogen sulfide released during LPG production also contributed a small amount to the total impacts.

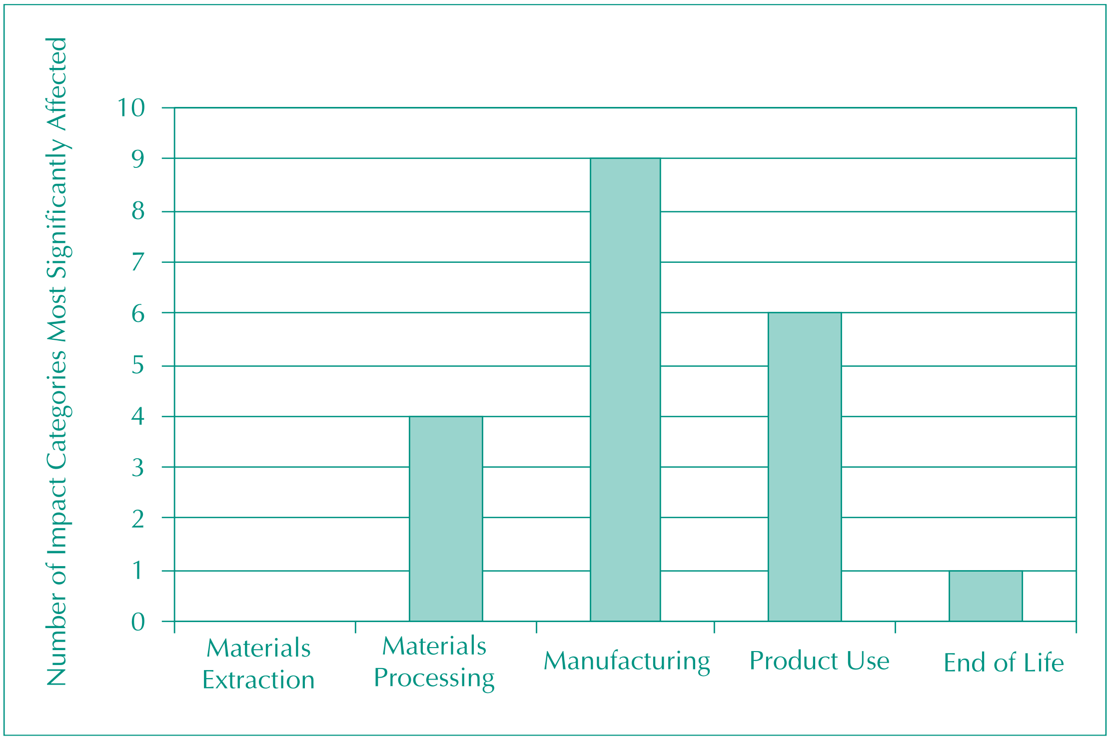
Aquatic ecotoxicity. Organisms that live in water, particularly fish, can be harmed by toxic chemicals released to water. Nearly all of the aquatic ecotoxicity impacts were from phosphorous, which was released to wastewater during the LCD module manufacturing process.

Terrestrial ecotoxicity. Organisms living on land can be adversely affected by toxic chemicals in the air or in surface water. Results for this impact category are based on the effects on rodents. As with the public health impact category, SO_2 from electricity generation is the primary source of toxicity to land-based organisms. The electricity used in the LCD use life stage accounted for 68 percent of the indicator score, and the electricity used in manufacturing accounted for an additional 21 percent.

Comparison across LCD life stages

Figure 5.1 indicates the number of impact categories for which each life stage was the largest contributor. As with CRTs, manufacturing and product use most frequently were the largest contributors for an impact category. Glass manufacturing and the associated fuel requirements were a significant cause of impacts in the manufacturing life stage. Other materials used in LCD manufacturing, such as phosphorous- and nitrogen-containing compounds, were also important contributors to some of the impacts related to water quality. In the product use life stage, energy consumption significantly affected several of the impact categories.

Figure 5.1. Distribution of Largest LCD Impacts



Question 6:
Overall, where were the greatest environmental and health impacts?

CRTs have greater life-cycle impacts than LCDs in most impact categories. The results of the LCIA show that the CRT has greater total life-cycle impacts than the LCD in 18 of the 20 impact categories. The LCD has greater impacts in only two categories: eutrophication and aquatic toxicity. Note, however, that these results do not indicate the magnitude of the impact itself or the magnitude of the difference between impacts for the CRT and LCD. Additionally, in the ozone depletion category, the analysis included substances that were phased out of production by 1996 by the countries that were signatories to the Montreal Protocol. When phased-out substances are removed from the inventories, the results for the ozone depletion category are reversed, with the LCD having the greatest impacts.

Manufacturing is the life-cycle stage with the greatest impacts. When considering which life-cycle stage has greater impacts, the LCIA results showed that the manufacturing life-cycle stage dominates impacts for most impact categories for both the CRT and LCD. Table 6.1 summarizes which life-cycle stages have the greatest impacts for each impact category. As shown in the table, nine out of the 20 impact categories showed the greatest impacts during the manufacturing stage for the CRT, and 11 of the 20 categories showed the greatest impacts during the manufacturing stage for the LCD. Impacts were greatest from the use stage for six of the 20 categories for the CRT, and for four of the 20 categories for the LCD. Impacts were greatest from the upstream life-cycle stage (i.e., raw material extraction plus materials processing) in three categories for both the CRT and LCD. Impacts were greatest from the end-of-life stage for the same two impact categories (hazardous waste landfill use and radioactive waste landfill use) for both the CRT and LCD.

Energy generation and use in the CRT life-cycle is the largest contributor in almost all impact categories. The largest contributor in 18 of the 20 impact categories for CRTs is related to energy generation and use. Energy use in glass manufacturing and associated production of LPG drive the CRT results in ten impact categories, including overall life-cycle energy use. The generation of electricity for the use stage dominates seven impact categories. The only categories in which energy is not a major contributor are hazardous waste landfill use (where landfilled CRTs have the greatest impact) and aquatic ecotoxicity (where phosphorous used in CRT manufacturing is the largest contributor).

More information is needed on energy used in CRT glass manufacturing. The large amount of LPG reported for glass manufacturing was originally questioned during the data collection and verification stage of this project. A sensitivity analysis was conducted where the glass energy data were modified. The overall energy required to produce a kilogram of CRT glass in the original analysis was nearly 100 times greater than that in the modified scenario. As a result, the

CRT modified glass energy scenario had greater energy use impacts in the use stage than in the manufacturing stage. It is likely that the actual energy inputs are somewhere between the baseline and modified glass scenarios, but additional information is needed to verify this assumption.

Energy use and generation also impacted many categories in the LCD life-cycle. Impact results for LCDs were less sensitive than those for CRTs to an individual input or output, although energy still played a prominent role. The most significant contributor in 12 of the 20 impact categories was energy related.

Table 6.1. Life-cycle stage with greatest impact for each display, by impact category

Impact category	Life-cycle stage with greatest impacts			
	Upstream	Manufacturing	Use	EOL
Renewable resource use	LCD	CRT		
Nonrenewable resource use		CRT, LCD		
Energy use		CRT, LCD		
Solid waste landfill use			CRT, LCD	
Hazardous waste landfill use				CRT, LCD
Radioactive waste landfill use				CRT, LCD
Global warming		LCD	CRT	
Ozone depletion		LCD	CRT	
Photochemical smog	LCD	CRT		
Acidification			CRT, LCD	
Air particulates			CRT, LCD	
Water eutrophication	CRT	LCD		
Water quality, BOD		CRT, LCD		
Water quality, TSS		CRT, LCD		
Radioactivity	CRT, LCD			
Chronic health effects, occupational		CRT, LCD		
Chronic health effects, public			CRT, LCD	
Aesthetics (odor)		CRT, LCD		
Aquatic toxicity	CRT	LCD		
Terrestrial toxicity		CRT, LCD		
TOTALS	**CRT=3 LCD=3**	**CRT=9 LCD=11**	**CRT=6 LCD=4**	**CRT=2 LCD=2**

Question 7:
What are the performance and cost differences between the two technologies?

Although the study summarized in this booklet focused on the environmental effects associated with computer displays, comparative cost and performance information are the other obvious considerations in a company's or consumer's decision-making. A complete analysis of cost and performance was beyond the scope of this study; however, summary performance and cost information are presented here.

COMPUTER DISPLAY PERFORMANCE

Performance data and costs for monitors on the market at the time of the study were collected (summer, 2001) and are presented in Table 7.1.

Table 7.1. Performance data and cost collected for some currently selling displays[a]

Monitor[a]	Display size (inches)	Resolution (pixels)	Brightness (cd/m²)	Contrast ratio	Number of colors	2001 cost
CRTs						
Monitor 1	17/16	1280x1040	---	---	---	$158
Monitor 2	17/16.1	1280x1040	---	"High contrast, anti-static, anti-glare coating."	---	$171
Monitor 3	17/16	1600x1200	---	---	---	$316
LCDs						
Monitor 1	15.1	1024x768	---	200:1	16.7 million	$349
Monitor 2[b]	15.1	1024x768	200	250:1	16.7 million	$400
Monitor 3	15.1	1024x768	200[c]	200:1[c]	16+ million	$439
Monitor 4[b]	15.1	1024x768	200	250:1	16.7 million	$499
Monitor 5	15	1024x768	210[c]	350:1	---	$554

a All information from Vol. EC23 of the eCOST.com catalog, except where noted otherwise.
b Data from manufacturer's web site except for prices, which were obtained from http://www.cdw.com.
c Data from manufacturer's web site.

Performance of computer displays can be based on many factors, but is focused mainly on the quality of the image on the screen. This quality can be measured in terms such as display size, resolution, dot pitch, brightness, and contrast ratio. The performance characteristics presented in the table above include the following.

Display size. The CRT size advertised is generally not the size of the image on the screen, but the nominal size of the entire faceplate, including the part that is not visible. Instead, the viewable-image size (VIS), which is the diagonal measurement of the image on the screen, is the more meaningful metric. The VIS is typically about an inch smaller than the nominal size. An LCD's VIS is the same as its nominal size, making a 15-inch LCD nearly the equal of a 17-inch CRT. (The 17-inch CRT provides about 14 percent more viewable area than the 15-inch LCD.)

Resolution. This refers to the number of picture elements, or pixels, that constitute an image. Computer displays can usually can be set at various resolutions, with the higher resolutions showing more detail. A resolution of 1,024x768 can render flicker-free images. Displays may have noticeable image degradation when set at any resolution lower than 1,024x768 pixels, where images look smeared and text can become harder to read.

Brightness. Reported in cd/m2 (candela per square meter), this is a measurement of the display's maximum brightness. A range of brightness allows the user to adjust the brightness for well-lit uses (where maximum brightness is needed) to dark settings.

Contrast ratio. The contrast ratio of an LCD is defined as the ratio of brightness (or luminance) of the pixel to the background, or the ratio of peak white to black level. The larger the contrast ratio, the deeper the blacks and the brighter the whites, improving the display's ability to show subtle color details and tolerate extraneous room light.

Number of colors. Refers to the total number of colors possible.

2001 Cost. Prices were obtained from the website of CDW Computer Centers, Inc. (www.cdw.com) on August 29, 2001.

COMPUTER DISPLAY COSTS — USE STAGE

Costs from the use stage of the computer display life are primarily electricity costs. The average cost of residential and commercial electricity in the U.S. is approximately $0.021/MJ and the CRT and LCD monitors use about 2,290 and 853 MJ/functional unit, respectively, in the use stage. The electricity costs to consumers during the use stage are therefore $48 for the CRT and $18 for the LCD. The amount of electricity consumed and the associated cost of that electricity for each life-cycle stage are presented in Table 7.2.

This cost information represents only a small part of all the components of cost that would be considered in a thorough cost analysis. A complete cost analysis would require assessing the costs from each life-cycle stage, and would include both direct costs (e.g., material costs) and indirect costs (e.g., environmental costs to society). While such a detailed analysis was beyond the scope of this study, some of the costs that should be considered in a complete cost analysis include:

- material costs;
- production costs (e.g., labor, transportation of material);
- maintenance costs (e.g., equipment maintenance, line set-up);
- capital costs (e.g., equipment procurement, installation, and facility floor space);

- utility costs (e.g., water, electricity, natural gas);
- licensing/permit cost (e.g., wastewater discharge, air emissions); and
- environmental treatment costs (e.g., wastewater, air, hazardous waste treatment).

Table 7.2. Life-cycle electricity costs

	CRT			LCD		
Life-cycle stage	**Electricity use** (MJ/functional unit)	**Unit cost** ($/MJ)	**Cost** ($US)	**Electricity use** (MJ/functional unit)	**Unit cost** ($/MJ)	**Cost** ($US)
Upstream	73.2	0.012[a]	$1.3	8.55	0.012[a]	$0.10
Manufacturing	129	0.012[a]	$1.5	278	0.012[a]	$3.4
Use	2,290	0.021[b]	$48	853	0.021[b]	$18
End-of-life	0.229	0.012[a]	$0.003	0	0.012[a]	$0
Total	**2,492**	**---**	**$51**	**1,140**	**---**	**$22**

[a]1999 U.S. average cost of electricity for the industrial sector is $0.0443/kWh. Assuming 3.6 MJ/kWh, ($0.0443/kWh)/(3.6 MJ/kWh)= $0.012/MJ. Source: www.eia.doe.gov/cneaf/electricity/esr/t11.txt.

[b]1999 U.S. average cost of electricity for the residential and commercial sectors is $0.0771/kWh. Assuming 3.6 MJ/kWh, ($0.0771/kWh)/(3.6 MJ/kWh)= $0.021/MJ. Source: www.eia.doe.gov/cneaf/electricity/esr/t11.txt.

Question 8:
Can the lead, mercury, and liquid crystals in computer displays pose health risks?

In addition to the environmental life-cycle assessment of desktop computer displays, a more detailed analysis was conducted for a few select materials of interest to EPA, industry, and others who participated in the project. This additional analysis provides more detailed information on the potential exposures and chemical risks of these materials to both human and ecological populations. The materials selected for further analysis were lead, mercury, and liquid crystals. Having chosen these three materials a *priori* does not presume that these are the only materials worthy of additional analyses.

Lead

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

CRTs contain over 25 times more lead than LCDs. Lead is a significant material in current CRTs, accounting for up to eight percent of the overall composition of the CRT by weight. As shown in Table 8.1, lead is used in the CRT glass parts (funnel, panel, and neck glass), the sealing frit, and the solder on the printed wiring boards within the CRT. Lead is not as prevalent in LCDs, being found only on printed wiring boards.

Table 8.1. 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]
Printed wiring boards (total)	CRT	0.051	NA
Printed wiring boards (total)	LCD	0.043	NA

[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.
NA= Not applicable

Lead-based impacts were greater in CRTs than in LCDs. Impacts from lead were found in the following eight categories: non-renewable resources, hazardous waste landfill use, solid waste landfill use, radioactivity, chronic public health effects, chronic occupational health effects, aquatic toxicity, and terrestrial toxicity. 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, resulting primarily from the lead (a non-renewable resource) used in manufacturing the CRT glass. In this impact category, the CRT (989 grams) used over 40 thousand times more lead over the course of its life cycle than LCD (0.025 grams). Other categories where CRTs had notably greater differences in impacts were in hazardous waste landfill use, chronic public health effects, and terrestrial toxicity.

Even in CRTs, lead-based impacts are low relative to impacts from other materials. While the use of lead in a computer display life cycle does contribute to several impact categories, in relation to other materials used in computer displays, such as glass and copper wire, lead's impacts are relatively low. For example, the lead impacts for CRTs in the non-renewable resources category account for only 0.2 percent of the overall impact score in the category.

For workers, inhalation is the most likely route of exposure to lead. Many of the processes required to manufacture computer displays use lead in the workplace; correspondingly, there is the potential for worker exposure. Exposure occurs through inhalation, dermal contact (when lead or materials containing lead come into contact with workers' skin), or through ingestion (e.g., ingestion of lead-bearing dust). The greatest potential for high-level occupational exposure occurs in lead smelting and refining operations, where lead is vaporized during high-temperature heating. This heating releases lead fumes and small respirable lead particles. Existing studies of smelting and refining operations have found mean concentrations of lead in the air nearly 90 times higher than the OSHA recommended safety levels for worker exposure. 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.

Many occupational exposures can be minimized or avoided. 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 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. Additionally, 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.

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 power plants, which contribute to the life-cycle impacts of both CRTs and LCDs. Because of mercury's toxicity to both humans and the environment, a more detailed analysis of mercury in this study was warranted. 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.

Life-cycle mercury emissions are similar for CRTs and LCDs. The mercury emitted from the generation of power consumed by the CRT during manufacturing and use (7.75 mg), is slightly greater than 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 intentionally incorporated into LCDs, but not in CRTs, 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.

Mercury outputs from LCDs had a broader effect on the environment than those from CRTs. The life-cycle mercury-based outputs from LCDs affected six impact categories, while those from CRTs showed impacts in three categories, as shown in Table 8.2. LCD impacts to both solid and hazardous waste landfill use, as well as to the chronic health effects of workers, all result directly from the use of mercury in the LCD backlights. No mercury is required in CRT fabrication. Although the quantities of mercury are not large, they cannot be discounted given the toxicity of mercury to both human health and the environment.

Table 8.2. Mercury-based impact categories for CRTs and LCDs

Impact category	Impact calculated for CRT life-cycle	Impact calculated for LCD life-cycle
Hazardous Waste Landfill Use (m^3)	0	7.73E-15
Solid Waste Landfill Use (m^3)	0	1.98E-11
Chronic Health Effects-Public (tox-kg)	5.22E-04	3.11E-04
Chronic Health Effects-Occupational (tox-kg)	0	3.99E-06
Aquatic Toxicity (tox-kg)	9.02E-04	5.43E-04
Terrestrial Toxicity (tox-kg)	5.21E-04	3.11E-04

Overall, mercury-based impacts are low relative to impacts from other materials. Contributions from mercury-based impacts are not significant relative to the total life-cycle impacts from other materials (e.g., glass, copper wire), with the greatest contribution of mercury-based outputs occurring in the aquatic toxicity category (contributing 0.4 percent for CRTs, 0.01 percent for LCDs).

Worker exposure may occur during backlight fabrication for LCDs. About 4 mg of elemental mercury is used to manufacture the fluorescent backlight for the LCD. Possible pathways of worker exposure during backlight fabrication include inhalation of mercury vapors, dermal exposure, or ingestion. Occupational chronic health effect scores from mercury exposures (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 most likely pathway for general population exposure to mercury is inhalation. Per functional unit, LCDs are responsible for approximately 4 mg of mercury releases to the air and CRTs are responsible for approximately 12 mg. Mercury is naturally present in coal and becomes airborne when coal is burned to generate electricity for the manufacturing and use of the computer displays. Airborne mercury can stay in the atmosphere for up to a year and can travel thousands of miles, potentially resulting in general population exposures.

Alternative backlights could reduce the mercury impacts of LCDs. Alternative backlights have been developed that not only eliminate mercury from the light, but also improve many of the optical characteristics of the displays. Current development is focused on improving the energy efficiency of the alternative lights.

Liquid Crystals

Liquid crystals are organic compounds responsible for generating an image for the LCD. The toxicity of the liquid crystals in LCDs has been alluded to in the literature, yet there is very little known about the toxicity of these materials. The following conclusions were drawn from a focused look at the role of liquid crystals in the life cycle of the computer display, and its effects on human health and the environment.

Liquid crystals are not used in CRTs. Liquid crystals are not used to fabricate CRTs and so have no environmental impacts in the CRT life cycle.

Toxicological data on liquid crystals are limited. There are several hundred liquid crystal substances that may be used in an LCD; therefore, comprehensive toxicological data are not available. However, limited tests that have been conducted by manufacturers indicate that few liquid crystals have acute toxic potential to humans. The study also reviewed toxicological data from eight liquid crystal compounds identified as part of the life-cycle inventory. The review failed to identify toxicological thresholds, indicating that the testing of these chemicals is probably insufficient to determine their potential for chronic human effects.

Liquid crystals do not appear to contribute significantly to any of the impact categories for LCDs. When no toxicity data were available, the study used a default average toxicity value. This practice prevents the study from assuming there are no toxic impacts just because there are no data. Of the 20 impact categories designed for this study, liquid crystals contribute only to the category of "chronic occupational health effects." Relative to other materials used in LCDs, however, the impact of liquid crystals on this impact category is very small. Specifically, the impacts from liquid crystals on overall chronic occupational health effects represent less than 0.01 percent of the total impact for the functional unit of one LCD. Impacts were not calculated for liquid crystal *releases* because data regarding liquid crystal outputs were not available to the project.

Question 9:
What can computer display manufacturers do to reduce environmental impacts?

The final step of an LCA is an "improvement assessment" or "interpretation of results." An improvement assessment is the systematic evaluation of opportunities for reducing the environmental impacts of a product, process, or activity. In this LCA, the improvement assessment is left to individual computer display manufacturers.

The improvement assessment can be done at various levels of effort, beginning with looking at the overall results as presented in the CDP report by life-cycle stage, or looking at individual material contributions to impacts. Using the LCIA data reported in the CDP, one would first apply individual subjective importance weights to each impact category to help determine where to focus improvements. This can be done at the life-cycle stage level, the process or process group level, or individual material level. All the data presented in the CDP report should allow for this type of assessment, with the exception of the subjective importance weights. The importance weights simply mean looking at which impact categories have greater importance to the decision-maker and weighing those impacts accordingly. This will assist in making decisions about where the greatest impacts of particular interest to a company are and where one would choose to target improvements.

If more analyses are desired about a certain process, a company may perform the analysis internally with additional data they have collected or they may contact the University of Tennessee to determine if additional analyses can be done and still protect confidentiality of data. Additional analyses by the University of Tennessee beyond those presented in the final report would be done for a fee as negotiated with the University of Tennessee.

The LCA results do identify several areas manufacturers should consider as part of their improvement assessment. Regardless of whether a manufacturer is conducting a complete improvement assessment, the LCA methodology itself provides a systematic process for considering the environmental and health impacts of the computer display's life. Specifically, manufacturers should consider the following when conducting an improvement assessment or evaluating potential process improvements:

Of the various life-cycle stages, the actual manufacturing process presents the most opportunities for improvement. Opportunities for improvement in CRT manufacture could include improved energy efficiency during glass manufacturing and reductions in lead content. Opportunities for improvement in manufacturing LCDs could also include improved energy efficiency. Certain materials, such as sulfur hexaflouride, are of concern due to their contribution to global warming, and should be an area of focus in an improvement assessment.

Consider the impacts of manufacturing changes on other stages of the product's life cycle. Computer display manufacturers will likely have the most control over the manufacturing life-cycle stage, but they should also recognize the influences on the other stages on total environmental impacts. Any improvement assessment should consider how changes in one life-cycle stage will affect impacts in other stages. For example, the mercury inputs and outputs from the intentional use of mercury in an LCD backlight are less (by mass) than the mercury emissions from the CRT use stage, due to the relative energy inefficiency of the CRT and the emissions of mercury from electricity generation. This example illustrates that on a pure mass basis, a product's energy efficiency is a key consideration, and any changes in manufacturing should be examined to determine whether they will increase energy use. In general, life-cycle trade-offs must be considered in any improvement assessment.

Identify opportunities by evaluating the relative environmental impacts of different process steps and components. The LCA provides an accounting of the relative, potential environmental and health impacts of various components of the computer displays. This information can help computer display manufacturers identify opportunities for product improvements to reduce potential adverse environmental impacts and costs. Identification of impacts from the computer display technologies can also help manufacturers determine where their best opportunities lie for implementing pollution prevention options.

Manufacturers can use this study as a basis to evaluate company-specific processes. One of the objectives of this study was to provide a model for future analyses. Companies that have more current data for the CRT or LCD can apply them to the study's model. For example, changes in an individual process can be identified and incorporated into the results. The other processes that are not expected to change significantly can be left unchanged, and only limited data would need to be altered. This method would reduce the time and resources that would normally be required for a complete analysis. Companies may examine their processes internally or contact the University of Tennessee to discuss opportunities to conduct additional analyses.

Manufacturers can weigh criteria to reflect site-specific factors. Those interested in comparing the results of the two computer display technologies can apply their own set of importance weights to each impact category to make their site-specific decision. For example, if energy impacts are considered to be much more important than aesthetics, energy can be weighed more heavily in concluding which monitor may have fewer environmental impacts. When applying the study results, it is also important to keep in mind the data limitations and uncertainties, as well as cost and performance considerations.

Question 10:
Where can I find more information about the computer display industry?

DOCUMENTS

In addition to the LCA report and this summary booklet, the Design for the Environment (DfE) program has supported the development of several documents specifically for the computer display industry. These documents can be downloaded from the DfE website at www.epa.gov/dfe, or hardcopies may be ordered through the Pollution Prevention Information Clearinghouse (PPIC), at the address below. Additional copies of this booklet and a limited number of copies of the overall Life-Cycle Assessment report can also be obtained through the DfE website or through PPIC.

Pollution Prevention Information Clearinghouse (PPIC)
U.S. Environmental Protection Agency (Mailcode 7407)
1200 Pennsylvania Ave., NW
Washington, DC 20460
Phone: (202) 260-1023
Fax: (202) 260-4659
E-mail: ppic@epa.gov
web site: www.epa.gov/opptintr/library/libppic.htm

Document titles available and their EPA document numbers are as follows:

Computer Display Project Fact Sheet (EPA/744-F98-010)
August 1998; 2 pages
This fact sheet provides basic information about the Computer Display Project. It explains the EPA partnership with the industry, examines the nature and goals of the project, and provides an overview of work conducted by the project team, including the Life-Cycle Assessment/Cleaner Technologies Substitutes Assessment study.

Computer Display Industry and Technology Profile (EPA/744-R-98-005)
December 1998; 67 pages
This report contains an overview of the cathode ray tube (CRT) and liquid crystal display (LCD) computer monitor markets, and explains the basic operation and manufacturing of CRTs and thin-film transistor LCDs.

Desktop Computer Displays: A Life-Cycle Assessment (EPA/744-R01-004a and b)
*December 2001; LCA: 383 page*s (EPA/744-R01-004a) + *Appendices: 566 pages* (EPA/744-R01-004b)
This report presents the results of the Life-Cycle Assessment developed for DfE's Computer Display Project. The study assessed the life-cycle environmental impacts of two technologies that can be used for desktop computer displays: the traditional cathode ray tube (CRT) technology, and the newer liquid crystal display (LCD) technology. The LCA examined the full life cycle of the computer displays from materials acquisition to manufacturing, use, and end-of-life.

Relevant Trade Associations and Research Institutions

University of Tennessee Center for Clean Products and Clean Technologies
311 Conference Center Building
Knoxville, TN 37996-4134
Phone: (865) 974-8979
Fax: (865) 974-1838
eerc.ra.utk.edu/clean

The Center for Clean Products and Clean Technologies is located at the University of Tennessee, Knoxville. The Center's mission is to develop, evaluate, and promote cleaner products and cleaner technologies that minimize pollution at the source and contribute to long-term sustainable development.

Electronics Industries Alliance
2500 Wilson Boulevard
Arlington, VA 22201
(703) 907-7966
www.eia.org

The Electronic Industries Alliance (EIA) is an alliance of electronic and high tech associations committed to shared knowledge and shared influence. EIA's mission is to promote the competitiveness and market development of the U.S. high tech industry, through domestic and international policy efforts.

U.S. Display Consortium
60 S. Market Street, Suite 480
San Jose, CA 95113
Phone: (408) 277-2400
Fax: (408) 277-2490
www.usdc.org

The United States Display Consortium (USDC) is an industry-led public/private partnership providing a forum for flat panel manufacturers, developers, users, and equipment materials suppliers.

Asian Technology Information Program
P.O. Box 9678
Albuquerque, NM 87119-9678
Phone: (505) 842-9020
Fax: (505) 766-5166
www.atip.or.jp

Asian Technology Information Program's objective is to help bridge the technology information gap by promoting collaborations and other profitable interactions between Western and Japan/Asian organizations. This organization assisted the DfE CDP project by collecting life-cycle inventory data from computer display manufacturers in Japan and Korea.