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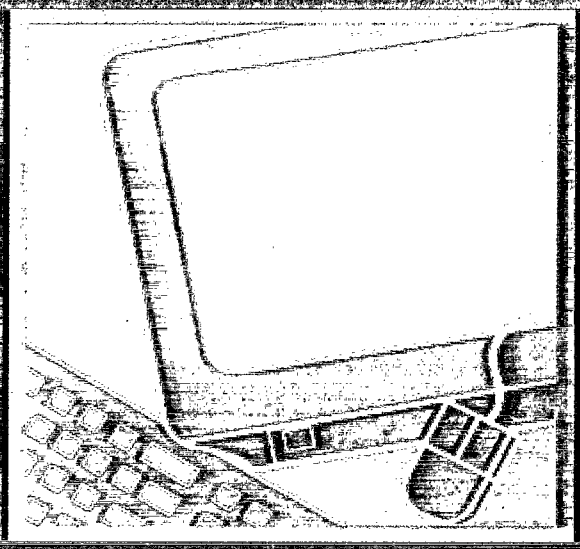
Desktop Computer Displays:



A Life-Cycle Assessment

VOLUME 1

Design for the Environment U.S. EPA

Electronic Industries Alliance

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Acronyms & Abbreviations

ABS	acrylonitrile-butadiene-styrene
AMLCD	active matrix liquid crystal display
AP	acidification potential
ATIP	Asian Technology Information Program
a:Si	amorphous silicon
BOD	biological oxygen demand
BOM	bill of materials
Bq	Bequerel
CAAA	Clean Air Act Amendments
CAS	Chemical Abstract Service
CCFL	cold cathode fluorescent lamp
CDP	Computer Display Project
CFC	chlorofluorocarbon
CFR	Code of Federal Regulations
CHEMS	Chemical Hazard Evaluation for Management Strategies
COD	chemical oxygen demand
CO_2	carbon dioxide
CPU	central processing unit
CRT	cathode ray tube
CTSA	Cleaner Technologies Substitutes Assessment
CWA	Clean Water Act
D	density
DEAM	Database for Environmental Analysis and Management
DfE	Design for the Environment
DOE	Department of Energy
DQI	data quality indicator
EF	equivalency factor
EIA	Energy Information Administration
ELF	extremely low frequency
EIME	Environmental Information and Management Explorer
EMF	electric and magnetic field
EOL	end-of-life
EP	eutrophication potential / electroplating
EPA	Environmental Protection Agency
EU	European Union
Fe	iron
FGD	flue gas desulfurization
FPD	flat panel display
GWP	global warming potential
H	heat value
HAP	hazardous air pollutant
HC	hydrocarbon
HCFC	hydrochlorofluorocarbon
HDPE	high density polyethylene

HEAST	Health Effects Assessment Summary Tables
HF	hydrofluoric acid
HIPS	high-impact polystyrene
HSDB	Hazardous Substances Data Bank
HV	hazard value
HWL	hazardous waste landfill
IARC	International Agency for Research on Cancer
IC	integrated circuit
IPCC	Intergovernmental Panel on Climate Change
IQR	interquartile range
IPS	in-plane switching
IRIS	Integrated Risk Information System
IS	impact score
ISO	International Standards Organization
ITO	indium-tin oxide
kg	kilogram
kWh	kilowatthour
L	liter
LC	lethal concentration
LCA	life-cycle assessment
LCD	liquid crystal display
LCI	life-cycle inventory
LCIA	life-cycle impact assessment
LD	lethal dose
LDPE	low density polyethylene
LNG	liquified natural gas
LOAEL	lowest observed adverse effect levels
LPG	liquified petroleum gas
m^3	cubic meter
MACT	maximum achievable control technology
MCC	Microelectronics and Computer Technology Corporation
Mfg	manufacturing
MJ	megajoule
MTBF	mean-time-before-failure
N	nitrogen
NESHAP	National Emission Standards for Hazardous Air Pollutants
Ni	nickel
NIEHS	National Institute of Environmental Health Sciences
NIOSH	National Institute of Occupational Safety and Health
NOAEL	no observed adverse effect levels
NO_2	nitrogen dioxide
NO_x	nitrogen oxides
NPDES	National Pollutant Discharge Elimination System
NRR	nonrenewable resource
NSC	National Safety Council
ODP	ozone depletion potential

OEM	original equipment manufacturer
ORNL	Oak Ridge National Laboratory
OSHA	Occupational Safety and Health Administration
OTV	odor threshold value
P	phosphorus
Pb	lead
PbO	lead oxide
PC	polycarbonate / personal computer
PECVD	plasma-enhanced chemical vapor deposition
PEE	polyethylene ether
PEL	permissible exposure limit
PET	polyethylene terephthalate
PM	particulate matter
PM_{10}	particulate matter with an aerodynamic diameter less than 10 micrometers
PMLCD	passive matrix liquid crystal display
PMMA	poly(methyl methacrylate)
PO_4^{3-}	phosphate
POCP	photochemical oxidant creation potential
POTW	publicly owned treatment works
PS	polystyrene
PVA	polyvinyl alcohol
PWB	printed wiring board
QSAR	quantitative structure-activity relationship
RAIS	Risk Assessment Information System
RC	recycled content
RCRA	Resource Conservation and Recovery Act
REL	recommended exposure limit
RfC	reference concentration
RfD	reference dose
RIE	reactive ion etching
RR	renewable resource
RTECS	Registry of Toxic Effects of Chemical Substances
RWL	radioactive waste landfill
SAR	structure-activity relationship
SD	standard deviation
SDWA	Safe Drinking Water Act
SETAC	Society of Environmental Toxicology and Chemistry
SF	slope factor
SF_6	sulfur hexafluoride
Sn	tin
SO_2	sulfur dioxide
SO_x	sulfur oxides
SWL	solid waste landfill
TCLP	Toxicity Characteristic Leachate Procedure
TFT	thin-film transistor
TORNRC	The Oak Ridge National Recycle Center

TN	twisted nematic
tox-kg	toxic-kilograms
TRI	toxic release inventory
TSP	total suspended particulate
TSS	total suspended solids
U	uranium
UT	University of Tennessee
UWR	Universal Waste Rule
VDU	video display unit
VOC	volatile organic compounds
WOE	weight of evidence
WWT	waste water treatment

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EXECUTIVE SUMMARY

This report presents the results of a voluntary, cooperative project among the Design for the Environment (DfE) Program in the Economics, Exposure, and Technology Division of the U.S. Environmental Protection Agency's (EPA) Office of Pollution Prevention and Toxics, the University of Tennessee (UT) Center for Clean Products and Clean Technologies, the electronics industry, and other interested parties to develop a model and assess the life-cycle environmental impacts of flat panel display (FPD) and cathode ray tube (CRT) technologies that can be used for desktop computer displays. The DfE Computer Display Project (CDP) report provides a baseline analysis and the opportunity to use the model as a stepping stone for further analyses and improvement assessments for these technologies.

The DfE CDP uses life-cycle assessment (LCA) as an environmental evaluation tool that looks at the full life cycle of the product from materials acquisition to manufacturing, use, and final disposition. As defined by the Society of Environmental Toxicology and Chemistry, there are four major components of an LCA study: goal definition and scoping, life-cycle inventory, impact assessment, and improvement assessment. The more recent International Standards Organizations definition of LCA includes the same first three components, but replaces the improvement assessment component of LCA with a life-cycle interpretation component. LCAs are generally global and non-site specific in scope.

The DfE CDP analysis also incorporates some elements of the Cleaner Technologies Substitutes Assessment (CTSA) methodology (Kincaid *et al.,* 1996), which was developed under the DfE Program to help businesses make environmentally informed choices and design for the environment. The CTSA process involves comparative evaluations of the relative human and ecological risk, energy and natural resource use, performance, and cost of substitute technologies, processes, products, or materials.

This project focuses on the LCA, while including some CTSA-related analyses. It performs the broad analysis of the LCA, which also incorporates many of the CTSA components (e.g., risk, energy impacts, natural resource use) into the impact assessment. The analysis also assesses more specific impacts for selected materials and acknowledges product cost and performance, typical of a CTSA. As only selected materials are qualitatively evaluated for the CTSA, this project is an LCA with a streamlined CTSA component.

LCAs evaluate the environmental impacts from each of the following major life-cycle stages: raw materials extraction/acquisition; materials processing; product manufacture; product use, maintenance, and repair; and final disposition/end-of-life. The inputs (e.g., resources and energy) and outputs (e.g., products, emissions, and waste) within each life-cycle stage, as well as the interaction between each stage (e.g., transportation) are evaluated to determine the environmental impacts.

In this study and project report, the goal and scope of the CDP are the subject of Chapter 1. The life-cycle inventory (LCI), which involves the quantification of raw material and fuel inputs, and solid, liquid, and gaseous emissions and effluents, is the subject of Chapter 2. The life-cycle impact assessment (LCIA) involves the translation of the environmental burdens identified in the LCI into environmental impacts and is the subject of Chapter 3. The improvement assessment or life-cycle interpretation is left to the electronics industry given the

results of this study. The report also includes a qualitative risk screening of selected materials to represent the CTSA component of the report in Chapter 4. The summary and conclusions are presented in Chapter 5.

I. GOAL DEFINITION AND SCOPE

Purpose and Need

The purpose of this study is two-fold: (1) to establish a scientific baseline that evaluates the life-cycle environmental impacts of active matrix liquid crystal display (LCD) and cathode ray tube (CRT) technologies for desktop computers, by combining LCA and CTSA methodologies; and (2) to develop a model that can be used with updated data for future life-cycle analyses. This study is designed to provide the electronics industry with information needed to improve the environmental attributes of desktop computer displays. The evaluation considers impacts related to material consumption, energy, air resources, water resources, landfills, human toxicity, and ecological toxicity. It is intended to provide valuable data not previously published, and an opportunity to use the model developed for this project in future improvement evaluations that consider life-cycle impacts. It will also provide the industry and consumers with valuable information to make environmentally informed decisions regarding display technologies, and enable them to consider the relative environmental merits of a technology along with its performance and cost. While there has been some work done on the life-cycle environmental impacts of either CRTs or LCDs, there has not been a quantitative LCA of both CRTs and LCDs.

At present, computer displays using CRTs dominate worldwide markets. The LCD, first used predominately in notebook computers, is now moving into the desktop computer market. CRTs use larger amounts of energy to operate than LCDs, and are associated with disposal concerns due to leaded glass in the displays. LCDs may consume more energy during manufacturing and contain small amounts of mercury. Given the expected market growth of LCDs for computer displays, the various environmental concerns throughout the life cycle of the computer displays, and the fact that the relative life-cycle environmental impacts of LCDs and CRTs have not been scientifically established to date, there is a need for an environmental life-cycle assessment of both of these types of desktop computer display technologies.

Targeted Audience and Use of the Study

The electronics industry is expected to be one of the primary users of the study results. The study is intended to provide industry with an analysis that evaluates the life-cycle environmental impacts of selected computer display technologies. Another result of the study is an accounting of the relative environmental impacts of various components of the computer displays, thus identifying opportunities for product improvements to reduce potential adverse environmental impacts and costs. Since this study incorporates a more detailed health effects component than in traditional LCAs, the electronics industry can use the tools and data to evaluate the health, environmental, and energy implications of the technologies. With this evaluation, the U.S. electronics industry may be more prepared to meet the demands of extended product responsibility that are growing in popularity in the global marketplace, and better able to

meet competitive challenges in the world market. In addition, the results and model in this study will provide a baseline LCA upon which alternative technologies can be evaluated. This will allow for more expedited display-related LCA studies, which are growing in popularity by industry and may be demanded by original equipment manufacturers (OEMs) or international organizations.

EPA and interested members of the public can also benefit from the results of the project. The project has provided a forum for industry and public stakeholders to work cooperatively, and the results can be used by stakeholders as a scientific reference for the evaluated display technologies. The results of the project could also be of value to other industries involved in designing environmental improvements into the life cycle of consumer products.

Product System

The product system being analyzed in this study is a standard desktop computer display that functions as a graphical interface between computer processing units and users. Besides the CRT display, several FPD technologies were considered for inclusion in this study. Among the FPD technologies that exist, the amorphous silicon (a:Si) thin-film transistor- (TFT) active matrix LCD technology meets the requirements of the functional unit within the parameters of this analysis and is assessed in this study.

The product system is the computer display itself and does not include the central processing unit (CPU) of the computer that sends signals to operate the display. It is assumed that the LCDs operate with an analog interface, and therefore are compatible with current CRT CPUs as plug-and-play alternatives.

In an LCA, product systems are evaluated on a functionally equivalent basis. The functional unit is used as the basis for the inventory and impact assessment to provide a reference to which the inputs and outputs are related. For this project, the functional unit is one desktop computer display over its lifespan, which meets the functional unit specifications presented in Table ES-1. The CRT technology is the current industry standard for this product system.

Table ES-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. This is because 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.

Assessment Boundaries

In a comprehensive cradle-to-grave analysis, the display system includes five life-cycle stages: (1) raw materials extraction/acquisition; (2) materials processing; (3) product manufacture; (4) product use, maintenance and repair; and (5) final disposition/end-of-life. Also included are the activities that are required to affect movement between the stages (e.g., transportation).

The geographic boundaries of this assessment depend on the life-cycle stage. This LCA focuses on the U.S. display market; therefore, the geographic boundary for the use and disposition stages of displays is limited to the United States. The geographic boundaries for raw material extraction, material processing, and product manufacture are worldwide (although actual product manufacturing data were only collected from the United States, Japan, and Korea, described in Chapter 2 of the report). While the geographic boundaries show where impacts might occur for various life-cycle stages, traditional LCAs do not provide an actual spatial relationship of impacts. That is, particular impacts cannot be attributed to a specific location. Rather, impacts are generally presented on a global or regional scale.

Considering the temporal boundaries, this study addresses impacts from the life cycle of a desktop computer display manufactured using 1997-2000 technology. The use and disposition stages cover a period that represents the life of a display. The lifespan, labeled as the "effective" life, is defined as the period of time the display is in use by primary, secondary, or even tertiary users before reaching its final disposition. The effective life, used as the baseline scenario, is estimated based on past and current use patterns of displays and represents a realistic estimate of the lifespan. As the effective life is subject to many variables, including fluctuating market trends, an alternative lifespan is presented in a sensitivity analysis. The alternative lifespan, or "manufactured" life, defined as the designed durability of a display (e.g., the time a display or key display component will operate before failing), is approximated based on the manufacturer's estimated durability of the display.

Impacts from the infrastructure needed to support the manufacturing facilities (e.g., maintenance of manufacturing plants) are beyond the scope of this study. However, maintenance of clean rooms used in the manufacturing of LCDs (and other components), which require substantial amounts of energy, are considered part of the manufacturing process.

Impacts from the transportation and distribution of materials, products, and wastes throughout the life-cycle of a display were originally included in the scope of the CDP LCA. However, only a small part of the overall transport in the life of a monitor was either reported in primary data collected for this project or available in secondary data. Inconsistencies between primary and secondary transportation data sources and the overall poor quality of transport data prevented an accurate assessment of the transportation inventory and impacts. Therefore, transportation impacts were excluded from the analysis. Section 2.6 describes transport data limitations and uncertainties in detail.

II. LIFE-CYCLE INVENTORY (LCI)

General Methodology

An LCI is the identification and quantification of the material and resource inputs and emission and product outputs from the unit processes in the life cycle of a product system. For the DfE CDP, LCI inputs include materials used in the computer display product itself, ancillary materials used in processing and manufacturing the displays, and energy and other resources consumed in the manufacturing, use, or final disposition of the displays. Outputs include products, air emissions, water effluents, and releases to land. Figures ES-1 and ES-2 show the unit processes that are included in the scope of this project for the CRT and LCD life cycles, respectively.

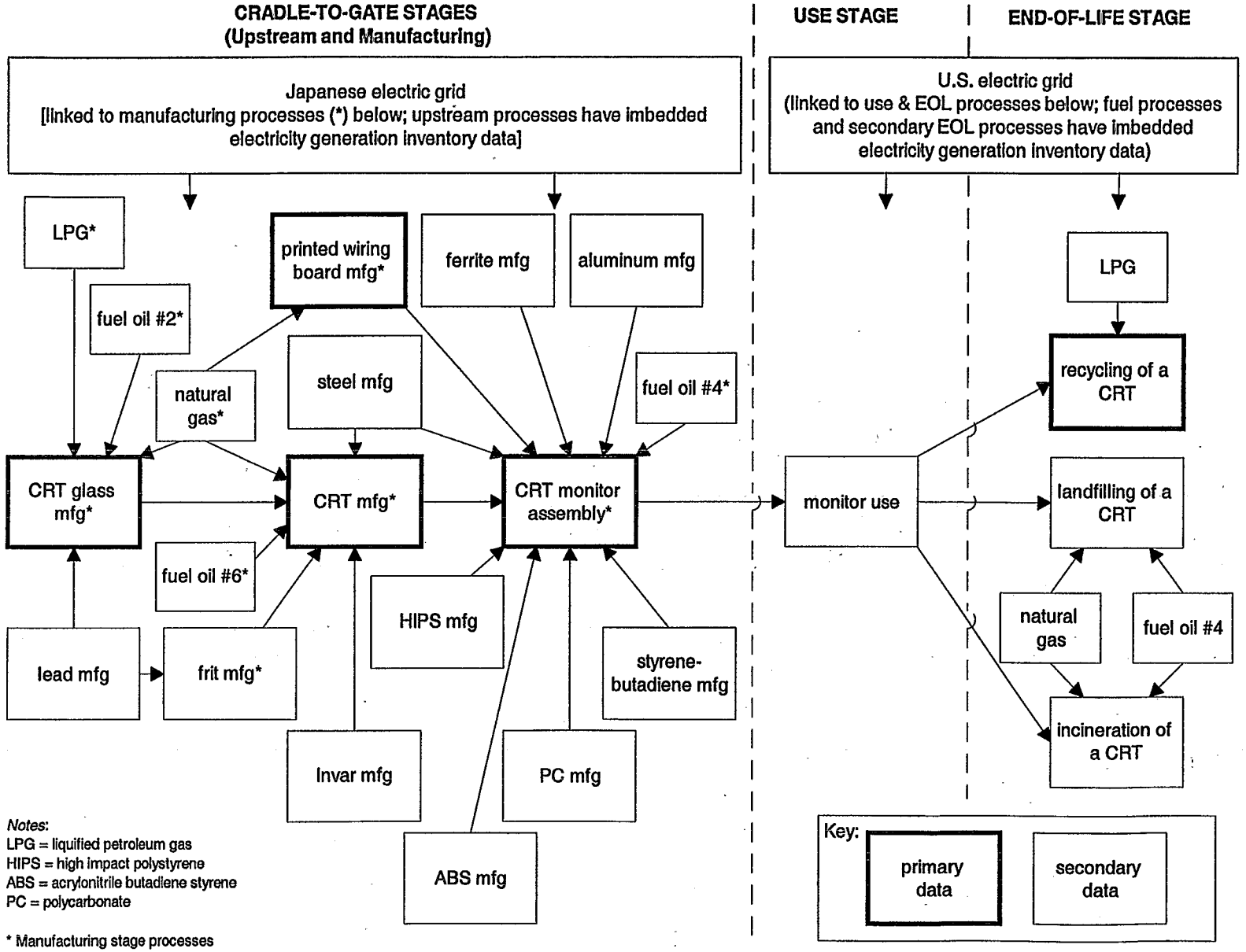

Figure ES-1. CRT linked processes

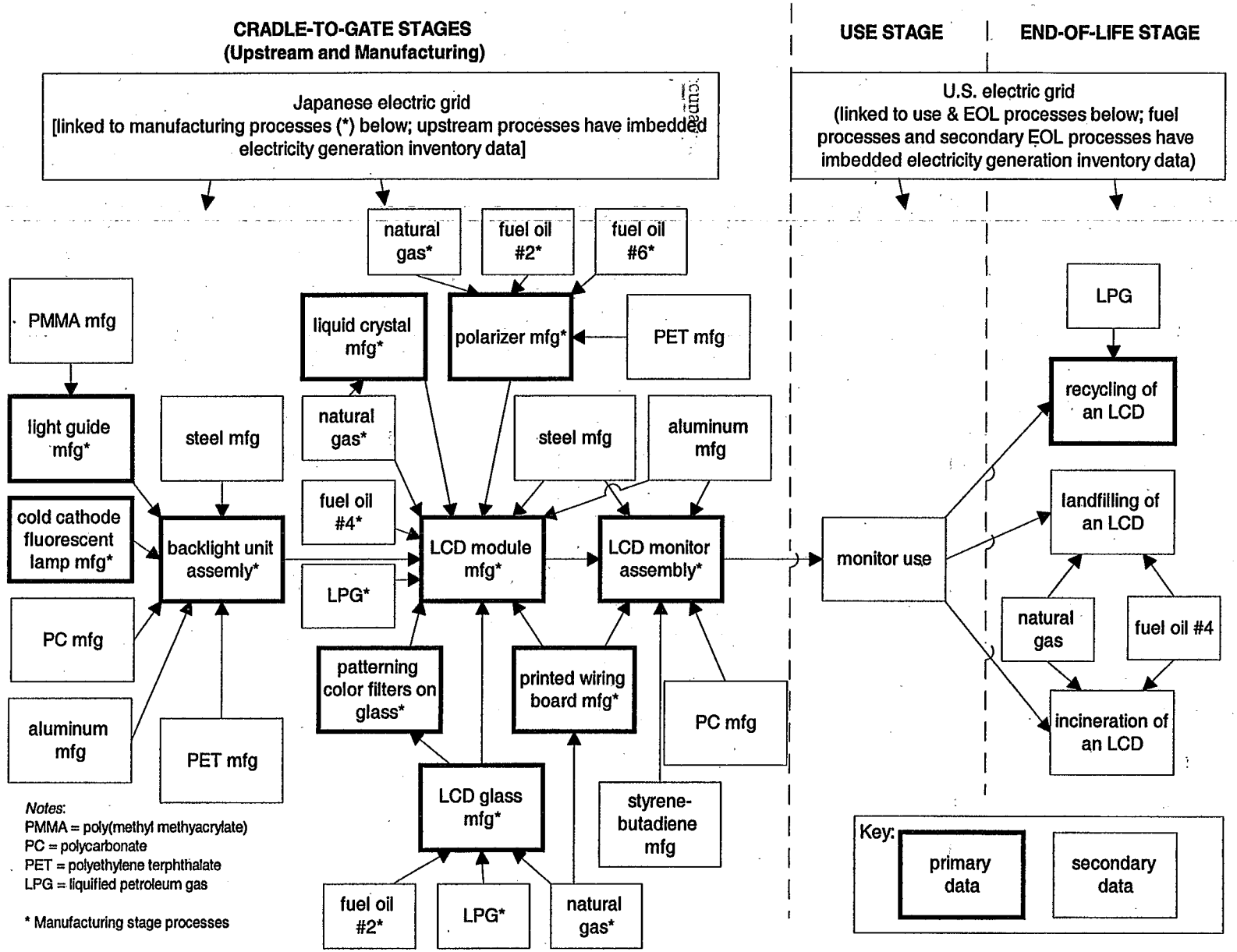

Figure ES-2. LCD linked processes

Data were also collected on the final disposition of emissions outputs, such as whether outputs are released directly to the environment, recycled, treated, and/or disposed. This information helps determine which impacts will be calculated for a particular inventory item. Methods for calculating impacts are discussed in Chapter 3, Life-cycle Impact Assessment.

Given the enormous amount of data involved in inventorying all of the inputs and outputs for a product system, decision rules, based on the mass, environmental, energy, and functional significance, were used to determine which materials or unit processes to include in the LCI. Decision rules are designed to make data collection manageable while still representative of the product system and its impacts. Data were collected from both primary and secondary sources. Table ES-2 lists the types of data (primary or secondary) used for each life-cycle stage in the CDP LCI. In general, greater emphasis was placed on collecting data and/or developing models for the product manufacturing, use, and end-of-life life-cycle stages.

Table ES-2. Data types by life-cycle stage

Life-cycle stage	Data types
Upstream (materials extraction and processing)	Secondary data.
Product and component manufacturing	Primary data, except secondary data used for frit.
Use	Modeled using secondary data; maintenance and repair are not included in the analysis.
Final disposition (recycling and/or disposal)	Modeled using secondary data plus primary data from CRT recycling facilities.
Packaging, transportation, distribution	Not included.

In the CDP LCI, data were allocated to the functional unit (i.e., a desktop computer display over its lifetime) as appropriate. The data that were collected for this study were either obtained from questionnaires developed for this project (i.e., primary data) or from existing databases (i.e., secondary data). LCI data were imported into a Life-Cycle Design Software Tool developed by the UT Center for Clean Products and Clean Technologies with funding from the EPA Office of Research and Development and Saturn Corporation. The UT Life-Cycle Design Software Tool organizes data in such a way that each process inventory is independent. Customized "profiles" (e.g., the manufacture of a CRT or the whole life-cycle of an LCD) can be developed by linking processes.

LCI data quality was evaluated based on the following data quality indicators (DQIs): (1) the source type (i.e., primary or secondary data sources); (2) the method in which the data were obtained (i.e., measured, calculated, estimated); and (3) the time period for which the data are representative. Any proprietary information required for the assessment was aggregated to protect confidentiality.

A critical review process was maintained in the CDP LCA to help ensure that appropriate methods were employed and study goals were met. A project Core Group and Technical Work Group, both consisting of representatives from industry, academia, and government, including EPA's DfE Work Group, provided critical reviews of the assessment. The Core Group served as the project steering committee and was responsible for approving all major scoping assumptions and decisions. The Technical Work Group and EPA's DfE Work Group provided technical

guidance and were given the opportunity to review all major project deliverables, including the final LCA report.

Upstream Life-cycle Stage Methodology

The materials extraction and processing inventories for key materials were obtained from a secondary LCI database developed by *Ecobilan* (1999). The U.S. electric grid inventory was developed from secondary sources by UT. The U.S. electric grid inventory was then modified, based on the distribution of fuels used in Japan, to develop the Japanese electric grid, which was used where manufacturing occurs in Asia. Electricity consumed in the life-cycles of the monitors was linked to the inventory of inputs and outputs from the U.S. or Japanese electric grid inventories, as appropriate.

Manufacturing Stage Methodology

The inventories for the product manufacturing life-cycle stage were developed from primary data collected from manufacturers in Asia and the United States. The manufacturing processes included in the study, as well as the number of data sets for each process and the country of origin of the data, are presented in Table ES-3. A total of 27 product manufacturing questionnaires were collected for 11 different processes. Allocation of data to the functional unit was conducted as necessary. Processes for which we collected more than one company's data were averaged together.

The quality of the manufacturing stage data can be evaluated against two factors: (1) the date of the data; and (2) the type of data (i.e., measured, calculated or estimated). The data collection phase of this project began in 1997 and extended through 2000. Some processes are more sensitive to production dates than others. Most processes included in this analysis are mature technologies and are not expected to differ significantly between the years 1997 and 2000. However, an exception is LCD panel/module manufacturing, which is an evolving and rapidly advancing process and has seen changes between these years. For the LCD panel and module manufacturing process, most data were from 1998 and 1999.

Data quality indicators were developed based on whether data were measured, calculated, or estimated, as reported in company data questionnaires. The weighted average of data collected and their associated DQIs are as follows: for the CRT, 43% of the data were measured, 34% calculated, 13% estimated, and 10% were not classified. For the LCD, a similar distribution shows 33% measured, 30% calculated, 23% estimated, and 14% not classified.

Product Use Life-cycle Stage Methodology

The baseline analysis in this project employs an effective life use stage scenario (the actual amount of time a monitor is used, by one or multiple users, before it is disposed of, recycled, or re-manufactured). A manufactured life scenario (the amount of time either an entire monitor or a single component will last before reaching a point where the equipment no longer functions, independent of user choice) is evaluated in a sensitivity analysis.

Table ES-3. Location of companies and number of process data sets

Process	Country of origin of data (# of data sets)
CRT monitor assembly	Japan (2), U.S. (1)
CRT (tube) manufacturing	Japan (2), U.S. (1)
CRT leaded glass manufacturing	Japan (1), U.S. (2)
CRT frit manufacturing	generic secondary data from the U.S.
LCD monitor assembly	Japan (2)
LCD panel and module manufacturing [a]	Japan (5), Korea (2)
LCD - glass manufacturing	Japan and U.S. (1) [b]
LCD - color filter patterning on front glass	Japan (1)
LCD - liquid crystal manufacturing	Japan (2)
LCD - polarizer manufacturing	Japan (1)
LCD - backlight unit assembly	Japan (3)
LCD - backlight light guide manufacturing	Japan (1)
LCD - cold cathode fluorescent lamp (CCFL) manufacturing	Japan (1)
PWB manufacturing (for CRT and LCD monitors)	generic secondary data from the U.S.

[a] The LCD *panel* consists of two glass panels patterned with transistors and color filters, liquid crystals inserted between the panels, and associated row and column drivers. The LCD *module* consists of the panel, backlight unit, and associated electronic boards for the entire panel, and the backlight.
[b] The average of three data sets for CRT leaded glass manufacturing was modified to remove lead from the inventory.

To develop the use stage inventory, energy use rates [e.g., kilowatts (kW)] were combined with the time a desktop monitor is on during its lifespan (hours/life) to calculate the total quantity of electrical energy consumed during the use life-cycle stage [e.g., kilowatthours (kWh)/life]. This was then combined with the electric grid inventory of inputs and outputs per kWh to make up the use stage inventory per monitor. The effective life scenario models the actual quantity of hours that an average monitor spends in each of the two primary power consumption modes (full-on and a lower power state) during its lifetime. Assumptions used to calculate the kilowatthours per effective life are detailed in Section 2.4. The total electricity consumption for each monitor was calculated to be 634 kWh/effective life (2,282 MJ/effective life) for the CRT and 237 kWh/effective life (853 MJ/effective life) for the LCD.

End-of-life (EOL) Methodology

For the EOL analysis, a monitor is assumed to have reached EOL status when:

- it has served its useful life;
- is no longer functional; and/or
- is rendered unusable due to technological obsolescence.

The major EOL dispositions considered in this analysis are as follows:

- recycling - including disassembly and materials recovery;
- landfilling - including hazardous [Resource Conservation and Recovery Act (RCRA), Subtitle C] and non-hazardous (RCRA, Subtitle D) landfills;
- remanufacturing - including refurbishing or reconditioning (to make usable again); and
- incineration - waste to energy incineration.

The functional unit in this analysis is one monitor; therefore, the different EOL dispositions were allocated as a probability of one monitor going to a certain EOL disposition. Data were somewhat scarce on the percent of monitors going to each disposition, especially for LCD monitors, which have not as yet reached EOL. After literature research and consultation with the project's Technical Work Group, as well as various other industry experts, project partners chose best estimates of disposition distributions (Table ES-4).

Table ES-4. Distribution of EOL disposition assumptions for the CRT and LCD

Disposition	CRT	LCD
Incineration	15%	15%
Recycling	11%	15%
Remanufacturing	3%	15%
Hazardous waste landfill	46%	5%
Solid waste landfill	25%	50%

Sources: NSC, 1999; EPA, 1998; CIA, 1997; EIA, 1999; Vorhees, 2000; TORNRC, 2001

Primary data were collected for CRT recycling from three companies. The data from these companies represent facility operations ranging from October 1999 to February 2000. In the absence of actual data for LCD recycling, data on a CRT shredding-and-materials-recovery process was used to model LCD recycling.

Hazardous/solid waste landfilling and incineration were developed from secondary data obtained from *Ecobilan*. Although data specific to landfilling and incineration operations for monitors alone were not available, existing inventories were available for landfilling and incinerating the following major monitor materials (by weight): steel, glass, plastic, and aluminum. These inventories were combined, based on the approximate proportion of each material in a CRT and an LCD, to create individual processes for landfilling and for incineration (for each monitor type). The majority of the assembled monitors by weight is accounted for in the overall incineration and landfilling processes.

Remanufacturing data were excluded from the assessment because no single set of operations could be identified to adequately represent remanufacturing activities that could be incorporated in our model.

LCI Limitations and Uncertainties

Several factors contribute to the overall quality of data for each life-cycle stage. For example, the manufacturing stage includes several different processes that were collected from several different companies. The quality of one data set from one company may be very different from that of another company. Relative data quality estimates have been made for each life-cycle stage, including electricity generation, which is included in the results of more than one life-cycle stage (Table ES-7). The table also lists the major limitations associated with each life-cycle stage.

Table ES-7. Relative data quality and major limitations

Life-cycle stage	Relative data quality	Major limitations
Upstream	Moderate	Used only secondary data, which has undetermined quality and not originally collected for the purpose of the CDP.
Manufacturing	Moderate to high	A few data points remain in question.
Use	Moderate to high	Assumptions regarding use patterns were made.
EOL	Low to moderate	Used only secondary data for incineration and landfilling processes; no data available for remanufacturing process.
Electricity generation	High	Used secondary data, however it was collected and modeled for the CDP, resulting in a higher quality rating despite use of secondary data.

Although the manufacturing stage was rated in Table ES-7 as having moderate to high data quality, some of the few data points that remained in question had large effects on the results and are therefore described below. Of the data collected from manufacturers, several attempts were made to verify or eliminate outliers in the data; however, uncertainty in some data remained due to large data ranges and outliers. Specific data with the greatest uncertainty include: (1) LCD glass manufacturing data; (2) CRT and LCD glass manufacturing energy inputs; (3) the distribution and amount of fuel/electricity inputs for LCD module manufacturing; and (4) the use of a large amount of liquified natural gas (LNG) as an "ancillary material" in LCD module manufacturing and not as a fuel.

Uncertainties in the LCD glass manufacturing data stem from the fact that no LCD glass manufacturers were willing to supply inventory data. Therefore, the LCD glass manufacturing inventory was derived from the CRT glass manufacturing data modified to exclude leaded compounds from the inventory. Thus, the baseline analysis in this study assumes the energy use per kilogram of CRT glass and LCD glass are equivalent, which is uncertain. In addition to the uncertainty in the difference between energy used to manufacture CRT glass and LCD glass, the energy reported to produce a kilogram of CRT glass varied greatly between the three data sets received for this project, with the highest total energy value being about 150 times that of the smallest value. Due to this large discrepancy and because there were not enough data sets to evaluate the data for outliers, the glass energy data were evaluated in a sensitivity analysis. The high glass energy use values were mostly a function of liquefied petroleum gas (LPG) used as a fuel.

Other data for which large ranges were reported, and which could be important to the results, are energy data from LCD panel/module manufacturing. Energy data provided by six LCD panel/module manufacturers were highly variable in both the distribution of energy sources and the total energy required to produce one LCD panel. The percent of energy from electricity ranged from approximately 3% to 87%, and the total energy per panel ranged from 440 MJ to 7,000 MJ. The average energy use per panel was approximately 2,270 MJ, and the standard deviation was about 2,910 MJ.

Given the wide variability in the data and large standard deviation, CDP researchers evaluated these data for outliers. One data set was found to be a minor outlier and another was found to be a major outlier. These outliers were excluded from the averages used in the baseline analysis, but included in the averages used in a sensitivity analysis (see Section 2.7.3.3).

Finally, a large amount of LNG (194 kg, on average) was reported to be used as an ancillary material (not a fuel) in LCD panel/module manufacturing. CDP researchers confirmed this application of LNG and the amount with the company providing the data, but it is still uncertain due to problems in communication (e.g., the language barrier). This data point remained in the inventory data set for LCD manufacturing, and was assumed to indeed be an ancillary material, and not a fuel. Keeping the LNG ancillary material in the inventory will not affect the energy impact results, since LNG used as an ancillary material is only linked to the production of that material, and not to the use of it as a fuel.

Baseline LCI Results

Tables ES-5 and ES-6 present the total quantity of inputs and outputs for each life-cycle stage of the CRT and LCD based on input and output types.

Table ES-5. CRT inventory by life-cycle stage

Inventory type	Upstream	Mfg	Use	EOL	Total	Units [a]
Inputs						
Primary materials	1.58e+01	4.21e+02	2.19e+02	-3.32e+00	6.53e+02	kg
Ancillary materials	2.11e+00	3.54e+00	3.47e+00	1.07e+01	1.98e+01	kg
Water	5.54e+02	1.14e+04	1.14e+03	-2.73e+01	1.31e+04	kg (or L)
Fuels	8.00e+00	4.28e+02	0	-2.95e+00	4.33e+02	kg
Electricity	7.32e+01	1.29e+02	2.29e+03	2.29e-01	2.49e+03	MJ [b]
Total energy	3.66e+02	1.83e+04	2.29e+03	-1.28e+02	2.08e+04	MJ [b]
Outputs						
Air pollutants	3.00e+01	1.83e+02	4.49e+02	2.47e+00	6.64e+02	kg
Wastewater	1.70e+01	1.51e+03	0	-3.65e+00	1.52e+03	kg (or L)
Water pollutants	8.12e-01	2.01e+01	7.02e-02	-6.18e-02	2.09e+01	kg
Hazardous waste	4.89e+02	1.13e+02	0	8.28e+00	9.46e+00	kg
Solid waste	9.55e+00	8.12e+01	8.33e+01	-1.66e+00	1.72e+02	kg
Radioactive waste	4.39e-04	1.80e-04	2.28e-03	2.29e-07	2.90e-03	kg
Radioactivity	3.80e+07	3.78e+06	4.80e+07	4.80e+03	8.98e+07	Bq

[a] Per functional unit (i.e., one CRT monitor over its effective life).

[b] 3.6 MJ = 1 kWh

Table ES-6. LCD inventory by life-cycle stage

Inventory type	Upstream	Mfg	Use	EOL	Total	Units [a]
Inputs						
Primary materials	2.35e+02	4.92e+01	8.01e+01	-2.19e+00	3.62e+02	kg
Ancillary materials	1.06e+00	2.04e+02	1.29e+00	2.11e+00	2.08e+02	kg
Water	2.63e+02	2.15e+03	4.25e+02	-1.80e+01	2.82e+03	kg
Fuels	1.47e+01	2.58e+01	0	-1.95e+00	3.86e+01	kg (or L)
Electricity	3.46e+01	3.16e+02	8.53e+02	1.62e-01	1.20e+03	MJ [b]
Total energy	6.33e+02	1.44e+03	8.53e+02	-8.44e+01	2.84e+03	MJ [b]
Outputs						
Air pollutants	1.12e+02	6.48e+01	1.68e+02	1.30e+00	3.46e+02	kg
Wastewater	8.57e+00	3.12e+03	0	-2.41e+00	3.13e+03	kg
Water pollutants	4.60e-01	1.23e+00	2.62e-02	-4.09e-02	1.68e+00	kg (or L)
Hazardous waste	6.72e-03	4.64e+00	0	1.64e+00	6.29e+00	kg
Solid waste	1.31e+01	1.26e+01	3.11e+01	-4.42e+00	5.23e+01	kg
Radioactive waste	2.21e+01	3.14e+03	3.11e+01	-5.23e+00	3.19e+03	kg
Radioactivity	1.20e+07	1.02e+07	1.79e+07	3.40e+03	4.01e+07	Bq

[a] Per functional unit (i.e., one LCD monitor over its effective life).

[b] 3.6 MJ = 1 kWh

The total inventory results for life-cycle inputs reveal that more primary materials,[1] water, fuels, electricity, and total energy (i.e., fuel energy plus electricity) are used throughout the CRT life-cycle, while more ancillary materials are used throughout the LCD life-cycle. For the life-cycle outputs, the CRT releases more air emissions; water pollutants; hazardous, solid, and radioactive waste; and radioactivity than the LCD. The LCD releases more total wastewater than the CRT. Complete inventory tables for each input and output type by life-cycle stage for the CRT and LCD are provided in Appendix J.

For the CRT (Table ES-5), of the inputs measured in mass, the water inputs in the manufacturing life-cycle stage constitute the majority of the inputs for the entire life cycle. Water inputs from the LPG production process constitute almost 80% of the water inputs for all life-cycle stages. In this inventory, the LPG is used in large quantities as a fuel in CRT glass manufacturing. When considering which life-cycle stage contributes most to an inventory category, the manufacturing stage has the largest inventory by mass for primary materials, ancillary materials, water inputs, and fuel inputs. This is also due to the production of LPG as needed for CRT glass production. Fuel inputs are dominated by the manufacturing stage and electricity inputs are dominated by the use stage. The total energy (which is calculated by converting the mass of the fuel into units of energy and combining the fuel energy with the electrical energy) is dominated by the manufacturing life-cycle stage, again mostly due to the large LPG fuel energy used in CRT glass production.

CRT outputs measured in mass include air emissions, wastewater, water pollutants, and hazardous, solid, and radioactive waste. Wastewater, by mass (or volume), constitutes the greatest output; however, total wastewater volume is not used to calculate water-related impacts. Instead, individual water pollutants are used to calculate water-related impacts. Of the remaining outputs measured in mass, which are used to calculate impacts (i.e., air emissions, and hazardous, solid and radioactive waste), air emissions are the greatest contributor to outputs in mass. Note that radioactivity is measured in Bequerels (Bq) and cannot be compared on the same scale.

Considering each CRT inventory type and their contributions by life-cycle stage, the mass of wastewater and water pollutants are greatest in the manufacturing life-cycle stage (again due to LPG consumption). The outputs of air emissions, hazardous waste, solid waste, radioactive waste, and radioactivity all have the greatest contribution from the use stage.

For the CRT outputs, all the totals represented in Table ES-5 include outputs to all dispositions. For example, water outputs sent offsite to treatment as well as those directly discharged to surface waters are all included. Similarly, hazardous, solid and radioactive waste outputs may be landfilled, treated, or recycled. The inventory shows these as totals; however, when impacts are calculated, the dispositions dictate which inventory items will be used to calculate impacts (Chapter 3).

For the LCD (Table ES-6), of the inputs measured in mass, the water inputs constitute the majority of the inputs for the entire life cycle, and most of the water inputs are in the manufacturing life-cycle stage. When considering which life-cycle stage contributes most to an inventory category, the manufacturing stage has the largest inventory by mass for ancillary materials, fuels, and water inputs. Primary material inputs are dominated by the upstream stages,

[1] Note that the total mass of primary materials includes the inputs to each process, which may duplicate materials used in processes subsequent to other processes. For example, the primary materials used in steel production are added to the steel used as a primary material for monitor assembly.

while electricity inputs are dominated by the use stage. The total energy is dominated by the manufacturing life-cycle stage. Note that LPG production from glass manufacturing does not dominate much of the LCD inventory as it did for the CRT, because of the smaller amount of glass used in the LCD compared to the CRT.

Of the LCD outputs measured in mass (air emissions, wastewater, water pollutants and hazardous, solid, and radioactive waste), wastewater constitutes the greatest output; however, total wastewater volume alone is not used to calculate impacts. Of the remaining outputs measured in mass, which are used to calculate impacts (i.e., air emissions, water pollutants, and hazardous, solid and radioactive waste), air emissions are the greatest contributor to the outputs. Note again, as mentioned for the CRT, that radioactivity is measured in Bequerels (Bq) and cannot be compared on the same scale.

Considering each LCD output type and their contributions by life-cycle stage, the mass of water pollutants is greatest in the manufacturing life-cycle stage, due to the fuel production processes that support fuel consumption in the manufacturing processes being included in the manufacturing life-cycle stage. Wastewater and hazardous waste outputs are greatest in the manufacturing stage; air emissions, solid waste, radioactive waste, and radioactivity have the greatest contribution from the use stage. As with the CRT, all the output totals represented in Table ES-6 include outputs to all dispositions.

III. LIFE-CYCLE IMPACT ASSESSMENT (LCIA)

LCIA Methodology

LCIA involves the translation of the environmental burdens identified in the LCI into environmental impacts. LCIA does not seek to determine actual impacts, but rather to link the data gathered from the LCI to impact categories and to quantify the relative magnitude of contribution to the impact category (Fava *et al.*, 1993; Barnthouse *et al.*, 1997). Further, impacts in different impact categories are generally calculated based on differing scales and therefore cannot be directly compared.

Within LCA, the LCI is a well established methodology; however, LCIA methods are less well defined and continue to evolve (Barnthouse *et al.*,1997; Fava *et al.*, 1993). For toxicity impacts in particular, there are some methods being applied in practice (e.g., toxicity potentials, critical volume, and direct valuation) (Guinee *et al.*, 1996; ILSI, 1996; Curran, 1996), while others are in development. However, there is currently no general consensus among the LCA community as to one method over another.

The UT LCIA methodology employed in this study calculates life-cycle impact category indicators for a number of traditional impact categories, such as global warming, stratospheric ozone depletion, photochemical smog, and energy consumption. Furthermore, the method calculates relative category indicators for potential chronic human health, aquatic ecotoxicity, and terrestrial ecotoxicity impacts in order to address project partner's interest in human and ecological toxicity and to fill a common gap in LCIAs.

LCIAs generally classify the consumption and loading data from the inventory stage into various impact categories (know as "classification"). "Characterization" methods are then used to quantify the magnitude of the contribution that loading or consumption could have in producing the associated impact. The impact categories included in the CDP LCIA are as

follows: renewable resource use, nonrenewable materials use/depletion, energy use, solid waste landfill use, hazardous waste landfill use, radioactive waste landfill use, global warming, stratospheric ozone depletion, photochemical smog, acidification, air quality (particulate matter loading), water eutrophication (nutrient enrichment), water quality (biological oxygen demand [BOD] and total suspended solids [TSS]), radioactivity, chronic human health effects (occupational and public), aesthetic impacts (odor), aquatic ecotoxicity, and terrestrial ecotoxicity.

Classification of an inventory item into impact categories depends on whether the inventory item is an input or output, what the disposition of the output is, and in some cases the material properties of the inventory item. Outputs with direct release dispositions are classified into impact categories for which impacts will be calculated in the characterization phase of the LCIA. Outputs sent to treatment or recycle/reuse are considered inputs to treatment or recycle/reuse processes and impacts are not calculated until direct releases from these processes occur. Once impact categories for each inventory item are classified, life-cycle impact category indicators are quantitatively estimated through the characterization step.

The characterization step of LCIA includes the conversion and aggregation of LCI results to common units within an impact category. Different assessment tools are used to quantify the magnitude of potential impacts, depending on the impact category. Three types of approaches are used in the characterization method for the CDP:

- **Loading** - An impact score is based on the inventory amount (e.g., resource use).
- **Equivalency** - An impact score is based on the inventory amount weighed by a certain effect, equivalent to a reference chemical [e.g., global warming impacts relative to carbon dioxide (CO_2)].
  - *Full equivalency* - all substances are addressed in a unified, technical model.
  - *Partial equivalency* - a subset of substances can be converted into equivalency factors.
- **Scoring of inherent properties** - An impact score is based on the inventory amount weighed by a score representing a certain effect for a specific material (e.g., toxicity impacts are weighed using a toxicity scoring method).

The scoring of inherent properties method is employed for the human and ecological toxicity impact categories, based on the CHEMS-1 method described by Swanson *et al.* (1997). The scoring method provides a hazard value (HV) for each potentially toxic material, which is then multiplied by the inventory amount to calculate the toxicity impact score.

Using the various approaches, the UT LCIA method calculates impact scores for each inventory item for each applicable impact category. Impact scores are therefore based on either a direct measure of the inventory amount or some modification (e.g., equivalency or scoring) of that amount based on the potential effect the inventory item may have on a particular impact category. The specific calculation methods for each impact category are detailed in Chapter 3. Impact scores are then aggregated within each impact category to calculate the various life-cycle impact category indicators.

General LCIA Methodology Limitations and Uncertainties

The purpose of an LCIA is to evaluate the *relative potential* impacts of a product system for various impact categories. There is no intent to measure the *actual* impacts or provide spatial or temporal relationships linking the inventory to specific impacts. The LCIA is intended to provide a screening-level evaluation of impacts. In addition to lacking temporal or spatial relationships and providing only relative impacts, LCA is also limited by the availability and quality of the inventory data. Data collection can be very time consuming and expensive. Confidentiality issues may also inhibit the availability of primary data.

Uncertainties are inherent in each parameter used to calculate impacts. For example, toxicity data require extrapolations from animals to humans and from high to low doses (for chronic effects) and can have a high degree of uncertainty.

Uncertainties also are inherent in chemical ranking and scoring systems, such as the scoring of inherent properties approach used for human health and ecotoxicity effects. In particular, systems that do not consider the fate and transport of chemicals in the environment can contribute to misclassifications of chemicals with respect to risk. Also, uncertainty is introduced where it was assumed that all chronic endpoints are equivalent, which is likely not the case. The human health and ecotoxicity impact characterization methods presented here are screening tools that cannot substitute for more detailed risk characterization methods. However, it should be noted that in LCA, chemical toxicity is often not considered at all. This methodology is an attempt to consider chemical toxicity where it is often ignored.

Uncertainty in the inventory data depends on the responses to the data collection questionnaires and other limitations identified during inventory data collection. These uncertainties are carried into impact assessment. In this LCA, there was uncertainty in the inventory data, which included but was not limited to the following:

- missing individual inventory items,
- missing processes or sets of data,
- measurement uncertainty,
- estimation uncertainty,
- allocation uncertainty/working with aggregated data, and
- unspeciated chemical data.

The goal definition and scoping process helped reduce the uncertainty from missing data, although it is certain that some missing data still exist. As far as possible, the remaining uncertainties were reduced primarily through quality assurance/quality control measures (e.g., performing systematic double-checks of all calculations on manipulated data).

Baseline LCIA Results

Table ES-8 presents the baseline CRT and LCD LCIA indicator results for each impact category. Appendix M presents complete LCIA results by material, process, and life-cycle stage. The indicator results presented in Table ES-8 are the result of the characterization step of LCIA methodology where LCI results are converted to common units and aggregated within an impact

category. Note that the impact category indicator results are in a number of different units and therefore can not be summed or compared across impact categories.

As shown in the table, under the baseline conditions the CRT indicators are greater than the LCD indicators in the following categories: renewable resource use, nonrenewable resource use, energy use, solid waste landfill use, hazardous waste landfill use, radioactive waste landfill use, global warming, ozone depletion, photochemical smog, acidification, air particulates, biological oxygen demand (BOD), total suspended solids (TSS), radioactivity, chronic public health effects, chronic occupational health effects, aesthetics, and terrestrial toxicity. The LCD indicators are greater than the CRT indicators in the following categories: water eutrophication and aquatic toxicity. In addition, as noted in Table ES-8, if phased-out substances are removed from the CRT and LCD inventories, the LCD ozone depletion indicator would exceed that of the CRT. Details of each impact category and major contributors to the impacts in those categories are presented in Chapter 3.

Summary of Top Contributors by Impact Category

Tables ES-9 and ES-10 summarize the top contributors to CRT and LCD life-cycle impacts by impact category. As shown in Table ES-9, CRT impacts are largely driven by two factors: (1) the large amount of LPG fuel used in CRT glass/frit manufacturing, and (2) the relatively large amount of electricity consumed during the use stage. The LPG production process yields the CRT's top contributor in eight of 20 impact categories. Most of this LPG is used as a fuel source in CRT glass manufacturing in the glass/frit process group, which, in turn, produces the top contributor to two of 20 impact categories. Thus, LPG used in the glass/frit process group (primarily CRT glass manufacturing) is ultimately the key driver for CRT impacts in ten categories. Similarly, outputs from electricity generation during the use stage result in the

Table ES-8. Baseline life-cycle impact category indicators[a]

Impact category	Units per monitor	CRT	LCD
Renewable resource use	kg	**1.31E+04**	2.80E+03
Nonrenewable resource use	kg	**6.68E+02**	3.64E+02
Energy use	MJ	**2.08E+04**	2.84E+03
Solid waste landfill use	m^3	**1.67E-01**	5.43E-02
Hazardous waste landfill use	m^3	**1.68E-02**	3.61E-03
Radioactive waste landfill use	m^3	**1.81E-04**	9.22E-05
Global warming	kg-CO_2 equivalents	**6.95E+02**	5.93E+02
Ozone depletion	kg-CFC-11 equivalents	2.05E-05[b,c]	1.37E-05[b]
Photochemical smog	kg-ethene equivalents	**1.71E-01**	1.41E-01
Acidification	kg-SO_2 equivalents	**5.25E+00**	2.96E+00
Air particulates	kg	**3.01E-01**	1.15E-01
Water eutrophication	kg-phosphate equivalents	4.82E-02	**4.96E-02**
Water quality, BOD	kg	**1.95E-01**	2.83E-02
Water quality, TSS	kg	**8.74E-01**	6.15E-02
Radioactivity	Bq	**3.85E+07**[d]	1.22E+07[d]

Table ES-8. Baseline life-cycle impact category indicators[a]

Impact category	Units per monitor	CRT	LCD
Chronic health effects, occupational	tox-kg	**9.34E+02**	6.96E+02
Chronic health effects, public	tox-kg	**1.98E+03**	9.02E+02
Aesthetics (odor)	m^3	**7.58E+06**	5.04E+06
Aquatic toxicity	tox-kg	2.25E-01	**5.19E+00**
Terrestrial toxicity	tox-kg	**1.97E+03**	8.94E+02

[a] Bold indicates the larger value within an impact category when comparing the CRT and LCD.

[b] Several of the substances included in this category were phased out of production by January 1, 1996. Excluding phased out substances decreases the CRT ozone depletion indicator to 1.09E-05 kg CFC-11 equivalents per monitor and the LCD ozone depletion indicator to 1.18E-05 kg CFC-11 equivalents per monitor. These ozone depletion indicators are probably more representative of the CDP temporal boundaries and current operating practices. See section 3.3.6 for details.

[c] Although the CRT indicator appears larger than the LCD indicator, uncertainties in the inventory make it difficult to determine which monitor has the greater value. Therefore, this value is not shown in bold.

[d] Radioactivity impacts are being driven by radioactive releases from nuclear fuel reprocessing in France, which are included in the electricity data in some of the upstream, materials processing data sets. See section 3.3.12 for details.

top contributor to seven CRT impact categories. Note that in 14 of the 20 impact categories, the top contributor to CRT impacts is responsible for more than 50% of impacts.

LCD impacts are not as dominated by a few data points, but a few processes (LCD monitor/module manufacturing and electricity generation in the use stage) are responsible for a large percent of the impacts. As shown in Table ES-10, both of these processes result in the top contributors to six LCD impact categories each. In addition, the process to produce LNG used as an ancillary material in LCD monitor/module manufacturing is the top contributor to an additional impact category (photochemical smog). Note that in 11 of the 20 impact categories, the top contributor to LCD impacts is responsible for more than 50% of impacts.

As a number of the impact results for both monitor types, and for the CRT in particular, are being driven by a few data points with relatively high uncertainty, sensitivity analyses of the baseline results were also conducted.

Table ES-9. Summary of top contributors to CRT impacts by impact category

Impact category	Top contributors			
	Life-cycle stage	Process group	Material	Contribution to impact score
Renewable resource use	Manufacturing	LPG production	water	79%
Nonrenewable resource use	Manufacturing	LPG production	Petroleum (in ground)	56%
Energy use	Manufacturing	CRT glass/frit mfg.	Liquefied petroleum gas	72%
Solid waste landfill use	Use	U.S. electric grid	Coal waste	38%

Table ES-9. Summary of top contributors to CRT impacts by impact category

Impact category	Top contributors			
	Life-cycle stage	Process group	Material	Contribution to impact score
Hazardous waste landfill use	End-of-life	CRT landfilling	EOL CRT monitor, landfilled	91%
Radioactive waste landfill use	Use	U.S. electric grid	Low-level radioactive waste	61%
Global warming	Use	U.S. electric grid	Carbon dioxide	64%
Ozone depletion	Use	U.S. electric grid	Bromomethane	49%
Photochemical smog	Manufacturing	LPG production	Hydrocarbons, unspeciated	36%
Acidification	Use	U.S. electric grid	Sulfur dioxide	47%
Air particulates	Manufacturing	LPG production	PM	43%
Water eutrophication	Manufacturing	LPG production	COD	72%
Water quality, BOD	Manufacturing	LPG production	BOD	96%
Water quality, TSS	Manufacturing	LPG production	Suspended solids	97%
Radioactivity	Materials Processing	Steel production, cold-rolled, semi-finished	Plutonium-241 (isotope)	62%
Chronic health effects, occupational	Manufacturing	CRT glass/frit manufacturing	Liquefied petroleum gas	78%
Chronic health effects, public	Use	U.S. electric grid	Sulfur dioxide	83%
Aesthetics (odor)	Manufacturing	LPG production	Hydrogen sulfide	94%
Aquatic toxicity	Manufacturing	CRT tube manufacturing	Phosphorus (yellow or white)	26%
Terrestrial toxicity	Use	U.S. electric grid	Sulfur dioxide	83%

Table ES-10. Summary of top contributors to LCD impacts by impact category

Impact category	Top contributors			
	Life-cycle stage	Process group	Material	Contribution to impact score
Renewable resource use	Manufacturing	LCD monitor/module mfg.	Water	38%
Nonrenewable resource use	Materials processing	Natural gas production	Natural gas (in ground)	65%
Energy use	Use	LCD monitor use	Electricity	30%
Solid waste landfill use	Use	U.S. electric grid	Coal waste	44%
Hazardous waste landfill use	End-of-life	LCD landfilling	EOL LCD monitor, landfilled	97%
Radioactive waste landfill use	Use	U.S. electric grid	Low-level radioactive waste	44%

Table ES-10. Summary of top contributors to LCD impacts by impact category

Impact category	Top contributors			
	Life-cycle stage	Process group	Material	Contribution to impact score
Global warming	Manufacturing	LCD monitor/module mfg.	Sulfur hexafluoride	29%
Ozone depletion	Manufacturing	LCD panel components manufacturing	HCFC-225cb	34%
Photochemical smog	Materials processing	Natural gas production	Nonmethane hydrocarbons, unspeciated	45%
Acidification	Use	U.S. electric grid	Sulfur dioxide	31%
Air particulates	Materials processing	Steel production, cold-rolled, semi-finished	PM	45%
Water eutrophication	Manufacturing	LCD monitor/module mfg.	Nitrogen	67%
Water quality, BOD	Manufacturing	LCD monitor/module mfg.	BOD	61%
Water quality, TSS	Manufacturing	LPG production	Suspended solids	66%
Radioactivity	Materials processing	Steel production, cold-rolled, semi-finished	Plutonium-241 (isotope)	96%
Chronic health effects, occupational	Manufacturing	LCD monitor/module mfg.	Liquefied natural gas	58%
Chronic health effects, public	Use	U.S. electric grid	Sulfur dioxide	68%
Aesthetics (odor)	Manufacturing	LPG production	Hydrogen sulfide	94%
Aquatic toxicity	Manufacturing	LCD monitor/module mfg.	Phosphorus (yellow or white)	98%
Terrestrial toxicity	Use	U.S. electric grid	Sulfur dioxide	68%

Sensitivity Analyses

Due to assumptions and uncertainties in this LCA, as in any LCA, the following sensitivity analyses of the baseline results were conducted: use stage manufactured life scenario, modified glass energy assumptions, modified LCD module manufacturing energy assumptions, and modified LCD EOL distribution assumptions. The sensitivity analyses were chosen because they evaluated data with either the greatest uncertainties or with large uncertainty and major contributors to the inventory results. Table ES-11 shows the different sensitivity analyses or scenarios that are considered in the impact assessment results.

Table ES-11. List of sensitivity analysis scenarios

Monitor type	Sensitivity analysis scenario
Baseline analyses (for reference)	
CRT	Effective life scenario with average glass energy inputs (all glass manufacturing energy data used)
LCD	Effective life scenario with average glass energy inputs (all glass manufacturing energy data used) and outliers in the LCD module manufacturing energy data removed
Sensitivity analyses	
CRT	Manufactured life scenario same as baseline except lifespan is based on manufactured life instead of effective life, which results in some revised functional equivalency calculations
LCD	Manufactured life scenario same as baseline except lifespan is based on manufactured life, which results in some revised functional equivalency calculations
CRT	Modified glass energy scenario same as baseline except comparatively high glass manufacturing energy inputs are removed
LCD	Modified glass energy scenario same as baseline except comparatively high glass manufacturing energy inputs are removed
LCD	Modified LCD module energy scenario same as baseline except LCD monitor/ module manufacturing energy outliers are included in the average
LCD	Modified LCD EOL scenario same as baseline except LCD EOL dispositions are modified

Based on the sensitivity analyses, it appears that CRT life-cycle impacts are highly sensitive to the glass energy data, and less sensitive to the lifespan assumptions (lifespan assumptions greatly affect the magnitude of CRT life-cycle impacts, but they do not greatly affect the distribution of impacts among life-cycle stages). LCD impacts are less sensitive to the glass energy data and in fact are not greatly affected by any of the sensitivity analysis scenarios, except the longer lifespan under the manufactured life scenario.

Sensitivity results are also useful to interested members of the public who may be evaluating the relative impacts of different monitor types and are interested in whether the CRT or LCD has greater life-cycle impacts in any given impact category. Table ES-12 presents the monitor type with greatest impacts by impact category and by scenario. This information helps us determine whether major assumptions (e.g., the monitor lifespan and LCD EOL distribution assumptions) or uncertain data (e.g., glass energy data and LCD monitor manufacturing energy) are driving results. As shown in the table, the modified glass energy scenario is the only scenario that significantly changes from the baseline. Under this scenario, life-cycle impact results in seven categories reverse direction from the baseline assessment, such that the LCD has greater impacts than the CRT. Therefore, under this scenario, a total of nine out of 20 categories are greater for the LCD than the CRT, compared to two out of 20 categories under the baseline scenario. The only other scenario that affects these results is the manufactured life scenario, when impacts in the water eutrophication category are greater for the CRT than the LCD.

Table ES-12. Summary of CRT and LCD LCIA results

Impact category	Monitor type with greatest impacts by scenario				
	Baseline	Manu-factured life	Modified glass energy	Modified LCD module energy	Modified LCD EOL distribution[a]
Renewable resource use	CRT	CRT	CRT	CRT	CRT
Nonrenewable resource use	CRT	CRT	LCD	CRT	CRT
Energy use	CRT	CRT	CRT	CRT	CRT
Solid waste landfill use	CRT	CRT	CRT	CRT	CRT
Hazardous waste landfill use	CRT	CRT	CRT	CRT	CRT
Radioactive waste landfill use	CRT	CRT	CRT	CRT	CRT
Global warming	CRT	CRT	LCD	CRT	CRT
Ozone depletion	b	b	b	b	b
Photochemical smog	CRT	CRT	LCD	CRT	CRT
Acidification	CRT	CRT	CRT	CRT	CRT
Air particulates	CRT	CRT	CRT	CRT	CRT
Water eutrophication	LCD	CRT	LCD	LCD	LCD
Water quality, BOD	CRT	CRT	LCD	CRT	CRT
Water quality, TSS	CRT	CRT	LCD	CRT	CRT
Radioactivity	CRT	CRT	CRT	CRT	CRT
Chronic health effects, occupational	CRT	CRT	LCD	CRT	CRT
Chronic health effects, public	CRT	CRT	CRT	CRT	CRT
Aesthetics (odor)	CRT	CRT	LCD	CRT	CRT
Aquatic toxicity	LCD	LCD	LCD	LCD	LCD
Terrestrial toxicity	CRT	CRT	CRT	CRT	CRT

[a] Based on a qualitative evaluation, not quantitative results.

[b] CRT impacts are greater than LCD impacts in this category when all data are included in the inventories, including data for substances that have been phased out. However, LCD impacts are greater than CRT impacts when phased out substances are removed from the inventories (see Section 3.3.6).

IV. QUALITATIVE RISK SCREENING OF SELECTED CHEMICALS

The scope of the DfE CDP included a streamlined Cleaner Technologies Substitutes Assessment (CTSA) component to perform a qualitative risk screening of specific materials or processes. 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.

Within the human and environmental health effects impact categories of the LCIA, the input and output amounts are used as surrogates for exposure. The additional CTSA-related analyses are intended to better understand the potential exposures to those materials, during any processes that use those materials, in order to try to better understand potential chemical risks.

Lead, mercury, and liquid crystals were selected by the CDP Core Group for further analysis. These materials were selected for their known or suspected toxicity to humans and the

environment, or because they are of particular interest to industry 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.

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 attributable to lead 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.

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 methyl mercury 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.

Liquid Crystals

Liquid crystals (LCs) 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 LC's 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.

V. SUMMARY AND CONCLUSIONS

The purpose of the CDP, as stated in Chapter 1, is to provide a scientific baseline of life-cycle environmental impacts of CRTs and LCDs, and to develop a life-cycle model for future analyses. The primary targeted audience is the electronics industry, for whom results may provide insight into improvement opportunities in the life cycle of CRTs and/or LCDs. In addition, the general public may also find results useful when considering environmental impacts of each display type. This report, however, does not include direct comparative assertions or improvement assessments based on the results. Alternatively, results and conclusions are described in terms of the overall LCI versus the LCIA, and details of the impact assessment, including the additional assessments of lead, mercury and liquid crystals, and the sensitivity analyses. Major uncertainties, cost and performance considerations, suggestions for improvement opportunities, and suggestions for further research are also provided.

LCI vs. LCIA

Inventory data provide information on how much material is being consumed in the life cycle (i.e., inputs) and how much material is generated/released (i.e., outputs). The LCI alone, however, does not always translate directly into impact categories that may be of interest. Impacts are sometimes driven by materials other than the top inventory contributors. For example, the top air emission for LCDs is carbon dioxide, however the greatest global warming impact score is from SF_6 in the LCD monitor/module manufacturing process.

Some impact categories associated with ancillary materials and water pollutant inventory types had different outcomes in the LCI versus the LCIA. For example, the three impact categories affected by the ancillary materials inventory had greater *impacts* for the CRT (Table ES-8), although the ancillary material *inventory* had greater amounts of inputs for the LCD (see Tables ES-5 and ES-6). In this case, both primary and ancillary materials contribute to the impact categories, contributing to the differing results.

In addition, the LCD had greater inventory amounts of wastewater outputs than the CRT; however, the impacts related to water releases are in some cases greater for the CRT than the LCD. In the LCIA, the LCD has greater impacts for water eutrophication and aquatic toxicity, but not for the two water quality categories (BOD and TSS), chronic health effects to the public, nor terrestrial toxicity, all of which include water emissions in calculating the impact score. These results show that the inventory results may not directly translate into impact results.

CRT and LCD Baseline LCIA Results

The LCIA results showed that the CRT has greater total life-cycle impact indicators than the LCD in most of the impact categories (see Table ES-8). In the baseline scenario, the CRT has greater impacts than the LCD in all but two impact categories (eutrophication and aquatic toxicity). However, note that for the ozone depletion category, the LCIs for both the CRT and LCD contain data for substances that were phased out of production by 1996 due to their ozone depletion potential. Whether these emissions still occur in countries that were signatories to the Montreal Protocol and its Amendments and Adjustments (such as the United States and Japan) is not known, but considered to be unlikely. When phased-out substances are included in the

inventory, the CRT has greater ozone depletion impacts than the LCD. However, if phased-out substances are removed from the inventories, the results are switched, with the LCD having greater 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 ES-13 lists the number of impact categories with the greatest impacts by life-cycle stage.

A more detailed evaluation of lead, mercury and liquid crystals was completed in Chapter 4. As expected, the CRT, which has lead in the glass, frit, and printed wiring boards (PWBs), had greater impacts from lead than did the LCD, which only has lead in the PWBs. Regarding mercury, there were greater inventories of mercury in the CRT life cycle than in the LCD life cycle, despite the fact that only the LCD has mercury directly in the product. The greater amount of mercury in the CRT life cycle is from the release of mercury and mercury compounds from the generation of electricity. The CRT consumes significantly more electricity in the use stage than the LCD. Liquid crystals are only found in LCDs, and therefore, there are no associated impacts for the CRT. Little conclusive information was available on the liquid crystal materials. A detailed literature search was conducted, however very little data were available on the toxicity of these materials. Based on the limited toxicity data obtained, liquid crystals currently do not appear to be a significant human health or environmental hazard in the LCD life cycle. However, there were insufficient toxicity data available to make a definitive conclusion about LC toxicity.

Table ES-13. Number of impact categories in each life-cycle stage with greatest impacts among life-cycle stages (baseline scenario)

Monitor type	# of impact categories with greatest impacts among life-cycle stages			
	Upstream	Manufacturing	Use	EOL
CRT	3	9	6	2
LCD	3	11	4	2

CRT Results

For the CRT, many of the impacts were driven by a single material in the inventory. As shown in Table ES-9, in 14 of the 20 impact categories, the top individual contributor to the impacts was responsible for greater than 50 percent of the impacts. This shows that the CRT data are highly sensitive to a few data points. Major conclusions from the CRT LCIA are as follows:

- Energy used in glass manufacturing and associated production of LPG are driving the baseline CRT results (they dominate ten impact categories, including overall life-cycle energy use).
- The large amounts of fuel used as energy sources are driving occupational health effects. Occupational impacts are calculated from inventory input amounts, and therefore there may or may not actually be exposure to these fuels (e.g., they may be contained);

however, the results illustrate the potential for health effects, especially under spill or upset conditions.

- The generation of electricity for the use stage dominates seven impact categories.
- Air emissions of sulfur dioxide from electricity generation (for the use life-cycle stage) drive chronic public health effects, acidification, and terrestrial toxicity impacts. This may be a concern, for example, in areas in nonattainment of regulated levels of sulfur dioxide in the United States.

The use of LPG fuel in glass manufacturing dominated ten impact categories: two directly from the LPG used in glass/frit manufacturing (energy use impacts and chronic occupational health effects) and eight from LPG production (renewable resource use, nonrenewable resource use, photochemical smog, air particulates, water eutrophication, BOD water quality, TSS water quality, and aesthetics). In addition, impacts from the generation of electricity during the use stage dominated seven impact categories: solid waste landfill use, radioactive waste landfill use, global warming, ozone depletion, acidification, chronic public health, and terrestrial toxicity. The CRT tube manufacturing process, which represents the most functionally and physically (by mass) significant component of the CRT monitor, only dominated one impact category (aquatic toxicity). Twenty-six percent of the aquatic toxicity score was from phosphorus outputs from tube manufacturing, while most of the rest were from the materials processing life-cycle stage. The remaining two impact categories (hazardous waste landfill use and radioactivity) had greatest impacts from the landfilling of the assumed hazardous proportion of CRT monitors, and the release of Plutonium-241 in steel production, respectively (Table ES-9). The radioactivity impacts are driven by the radionuclide Pu-241, due to the electric grid inventory included in the steel production secondary data set, which includes nuclear fuel reprocessing.

The large amount of LPG reported for glass manufacturing was originally questioned during the data collection and verification stage of this project. While no compelling reason could justify removing the LPG data in the baseline case, a sensitivity analysis was conducted in which the glass energy data were modified. Other sensitivity analyses were also conducted (i.e., manufactured life, modified LCD monitor manufacturing energy, and modified LCD EOL distributions). However, the only scenario that substantially altered results was the modified glass energy scenario (see Table ES-12). It is likely that the actual energy inputs to the glass manufacturing process is somewhere between the baseline and modified glass scenarios. More information is needed on energy used in glass manufacturing, which is driving CRT baseline results.

The additional analyses for the CRT of lead and mercury also revealed that the use of lead could present health risks, but the CDP method for calculating occupational impacts uses only process *inputs* (not outputs) and may not adequately represent occupational exposures and risks. Further refinement of the occupational impact analysis may be warranted.

Although there is no mercury in the CRT monitor, mercury emissions from electricity generation in the CRT life cycle were greater (in mass) than the mercury used in the LCD. Therefore, to reduce mercury emissions from the CRT life cycle, efforts to reduce electricity consumption could be taken. Additionally, changes to the electric grid could also reduce mercury emissions from the CRT life-cycle.

LCD Results

The LCD impact results were less sensitive to an individual input or output than the CRT results, although in 11 of the 20 impact categories an individual input was still responsible for greater than 50% of the total impacts. In general, the LCD results are less uncertain than the CRT results. This is because most of the CRT results are being driven by either glass input data or data from secondary sources, while LCD impacts are being driven more by data from primary sources. Some results to note are as follows:

- The LCD monitor/module manufacturing process group had greatest impacts in six impact categories (Table 3-58).
- Although the top contributor to the energy impact category was electricity consumed in the use stage (30%), the overall energy impacts were greater from the manufacturing stage than the use stage.
- In the glass energy sensitivity scenario, the use stage had greatest energy impacts, although only by a small margin over the manufacturing stage (see Figure 3-26).
- Sulfur dioxide [emitted from electricity generation in the use stage, and constituting only 0.37% of the air emission inventory (see Table 2-49)] dominates the acidification, chronic public health, and terrestrial toxicity impact categories (Table 3-58). The high public health and terrestrial toxicity scores are due to its low non-cancer toxicity value and resulting high hazard value (HV).
- Sulfur hexafluoride (SF_6) from LCD monitor/module manufacturing was the single greatest contributor to the global warming impact score; however, carbon dioxide from the use stage and the materials processing stage also contributed significantly to the global warming impacts (Table 3-25).
- The glass energy inputs did not directly dominate any impact categories, as they did for the CRT (due to the smaller mass of glass in the LCD); however, LPG production (required for the glass energy fuel) dominated two categories: TSS water quality and aesthetics (Table 3-58).
- LNG as an ancillary inventory material was questionably very large and had greatest impacts in two categories: nonrenewable resource use and photochemical smog (Table 3-58; shown there as "Natural Gas Production" due to that process being used as a surrogate for LNG production).

The additional analyses of lead, mercury, and liquid crystals showed that the LCIA alone is not adequate enough to determine all the potential impacts within the life-cycle of the LCD monitors. Further, the LCIA method in this LCA used only process inputs as surrogates for occupational exposure. If the occupational impacts methodology were refined, outputs into the occupational environment should also be considered.

For mercury, which is found in the backlights of the LCD monitors, there is nearly the same amount of mercury by mass emitted to the air during electricity generation as there is mercury used to make the backlight unit. The mass of mercury input for backlights is only about 20% greater than the mercury air emissions from electricity generation (across all life-cycle stages).

Liquid crystals were also identified by the CDP Core Group as a material for which additional information would be reviewed. The LCIA did not find the liquid crystals to be significant contributors to any impact categories; however, this could partially be due to the lack of information on them. The additional analysis revealed limited information; however, qualitatively, it did not show significant potential risk.

CRT vs. LCD Sensitivity Analysis Results

The only sensitivity analysis to show significant difference in the results was the modified glass energy scenario. In comparing the CRT and LCD, the CRT *baseline* scenario had greater impacts than the LCD in all but two impact categories (eutrophication and aquatic toxicity) and possibly three (ozone depletion). In the *modified glass energy scenario*, nine of the 20 categories had greater impacts from the LCD life-cycle than the CRT. Energy use remained greater for the CRT; however, nonrenewable resource use, global warming, photochemical smog, eutrophication, BOD and TSS water quality, chronic occupational health effects, and aesthetics all reversed such that the LCD had greater impacts than the CRT (Table ES-12). As stated above, it is believed that a more true representation of the monitor life cycles lies somewhere between the baseline and modified glass energy scenario. Further work is recommended in clarifying and refining glass energy input information.

Uncertainties

As with any LCA, it is not uncommon for there to be uncertainty associated with such a large data collection effort. The limitations and uncertainties associated with this LCA and LCAs in general have been discussed elsewhere in the executive summary. Two of the largest sources of uncertainty in this LCA that have a significant effect on the results are as follows:

- *CRT and LCD glass manufacturing energy inputs (from primary data)*: The larger amount of glass used in CRTs than LCDs results in the CRT having greater associated uncertainty than the LCD results.
- *Secondary data for upstream and fuel production processes*: When any one material is used in the life-cycle of either monitor in large quantities, the impacts associated with the inputs and outputs from the production of that material may become significant. For example, LPG and LNG production were both used in significant enough amounts to influence some impact categories. Therefore, the uncertainty in the secondary data becomes important. This highlights the need for a consistent, national (or international) LCI database that is updated regularly.

Other uncertainties associated with individual data points had less effect on the overall results than the uncertainties mentioned above. For manufacturers interested in conducting improvement assessments, closer review of such uncertainties may be warranted.

Another point that should be recognized in the overall LCA of CRTs and LCDs is that CRTs are a more mature technology than LCDs. Changes in LCD manufacturing processes have likely occurred during the development and publication of this report. Therefore, conclusions must be carefully drawn when evaluating the mature CRT compared to the newer LCD technology.

Cost and Performance Considerations

The focus of this study has been on the environmental effects associated with CRTs and LCDs. The environmental attributes or burdens of a product are not expected to be considered alone when evaluating the marketability and commercial success of a product. The cost and performance of each monitor type are obviously critical components to a company's or consumer's decisions of whether to produce or purchase a product. The report briefly addresses direct retail costs of the monitors and electricity costs associated with the monitors; however, a complete cost analysis, including all direct costs (e.g., material costs) and indirect costs (e.g., environmental costs to society) is beyond the scope of this report.

The average retail price of 1997-2000 model year monitors, collected from the manufacturers who supplied data for this project, is $541 for the CRT and $1,450 for the LCD. From these data, the LCD is approximately 2.7 times more costly. More recent data show that prices have come down, and the difference in prices between the CRT and LCD has also been reduced.

The costs from the use stage can be represented by the use stage electricity costs. Based on the average cost of residential and commercial electricity in the United States, and the amount of energy consumed per functional unit in the use stage (baseline scenario), the electricity costs to consumers over the life of the monitors during the use stage are $48 for the CRT and $18 for the LCD. In addition, the upstream and manufacturing costs of electricity in the baseline scenario for the CRT are approximately $1.3/functional unit and $1.5/functional unit, respectively; for the LCD they are $0.10/functional unit and $3.4/functional unit, respectively.

The LCA is defined such that the monitor assessments are performed on a functionally equivalent basis. To the extent possible, data were collected on functionally equivalent monitors. When companies were approached to participate in the study, they were informed of the performance specification parameters within which the study boundaries were defined. Therefore, it is assumed that they meet the specifications as presented in Table ES-1, and that they perform relatively equivalently. From the primary data, the reported brightness of the CRT was less than the LCD, otherwise, they are functionally similar.

Improvement Assessment Opportunities and Targeted Audience Uses of Report

To meet the primary objective of providing the display industry with data to perform improvement assessments, the industry should look at the manufacturing life-cycle stage, while recognizing the influences of the other stages. CRT improvement opportunities could include improved energy efficiency during glass manufacturing and display use, as well as reductions in lead content. LCD improvement opportunities could also include improved energy efficiency, especially during manufacturing. Certain materials, such as SF_6 and its contribution to global warming, may also be of concern and an area to focus on in future improvement assessments.

In addition, any improvement assessment should consider how changes in one life-cycle stage will affect impacts in other stages. For example, in Chapter 4 we saw that 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 usage by the CRT and the emissions of mercury from electricity generation. In this example, we can see that on a pure mass basis, a product's energy efficiency is a key consideration and any changes in manufacturing should consider if it will affect changes in use.

Another objective of this study was to provide an LCA model for future analyses. Companies or individuals who have more current data for the CRT or LCD can apply them to the model presented here. For example, changes in an individual process can be identified and incorporated into the model. The other processes that are not expected to change significantly can be left unchanged, and only limited data would need to be altered. This would reduce the time and resources that would normally be required for a complete analysis.

Finally, those interested in comparing the results of the two monitors can apply their own set of importance weights to each impact category to determine their individual decision. For example, if energy impacts are much more important than aesthetics to a particular person, they can weigh energy more heavily in concluding which monitor may have fewer environmental impacts, while keeping in mind the data limitations and uncertainties, as well as cost and performance considerations.

Suggestions for Future Research

Areas where future research could be conducted to refine and/or continue the use of the results in this study are as follows:

- gather more information on energy use in glass manufacturing;
- develop consistent materials and fuel processing data in a national (or international) LCI database that is updated regularly;
- refine and/or update some of the LCD manufacturing data (e.g., LNG data);
- collect more complete EOL data (e.g., remanufacturing data, and primary data for incineration and landfilling) to determine better representation of the EOL impacts;
- conduct more research on the EOL options for LCDs;
- collect more detailed data on landfilling and other treatment processes, such as water treatment where no impacts were calculated;
- update manufacturing data to meet more recent monitor model years;
- conduct a more focused analysis on selected areas for detailed improvement assessments; and
- evaluate process changes or other alternatives against an "average 1997-2000 model year" to evaluate impacts of changes or improvements over time.

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Chapter 1

GOAL DEFINITION AND SCOPE

1.1 BACKGROUND

This report presents the results of a voluntary, cooperative project among the Design for the Environment (DfE) Program in the U.S. Environmental Protection Agency's (EPA) Office of Pollution Prevention and Toxics, the University of Tennessee (UT) Center for Clean Products and Clean Technologies, the electronics industry, and other interested parties to develop a model and assess the life-cycle environmental impacts of flat panel display (FPD) and cathode ray tube (CRT) technologies that can be used for desktop computers. The DfE Computer Display Project (CDP) analysis provides a baseline report and the opportunity to use the model as a stepping stone for further analyses and improvement assessments for these technologies.

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 efforts 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 CDP partnership consists of members of electronic industry trade associations, computer monitor and component manufacturers, suppliers to the electronics industry, academic institutions, EPA, and a public interest group. The direction and focus of this project was chosen by the project partners.

The DfE CDP uses life-cycle assessment (LCA) as an environmental evaluation tool, which is increasingly being used by industry. LCA can be used to evaluate the environmental effects of a product, process, or activity. An LCA looks at the full life cycle of the product from materials acquisition to manufacturing, use, and final disposition. It is a comprehensive method for evaluating the full environmental consequences of a product system. There are four major components of an LCA study: goal definition and scoping, life-cycle inventory, impact assessment, and improvement assessment. LCAs are generally global and non-site specific.

Under the DfE Program, the Cleaner Technologies Substitutes Assessment (CTSA) methodology (Kincaid *et al.*,1996) was developed to generate information needed by businesses to make environmentally informed choices and to design for the environment. The CTSA process involves comparative evaluations of substitute technologies, processes, products, or materials. Impact areas that are evaluated include human and ecological risk, energy and natural resource use, performance, and cost.

Both evaluation tools have similar objectives; however, their applications generally differ. A CTSA is more site specific and evaluates actual (predicted) impacts. For example, techniques such as health risk assessment are incorporated into a CTSA. An LCA is more global and generic in nature and generally would not incorporate site-specific parameters when evaluating impacts. The LCA may also use surrogate measures to represent impacts instead of predicting or measuring actual impacts.

This project focuses on the LCA, while including some CTSA-related analyses. It performs the broad analysis of the LCA, which also incorporates many of the CTSA components (e.g., risk, energy impacts, natural resource use) into the impact assessment. The analysis also

assesses more specific impacts for selected materials and acknowledges product cost and performance, typical of a CTSA. Because both methodologies require intensive data gathering efforts and can be extensive undertakings, the scope must be carefully and clearly defined. As only selected materials are evaluated for the CTSA, this project could be considered an LCA with a streamlined CTSA component.

Life-cycle assessment (LCA) is a comprehensive method for evaluating the full environmental consequences of a product system. Another related assessment strategy *is life-cycle design*, which is a systems-oriented approach for designing more ecologically and economically sustainable product systems. It integrates environmental requirements into the earliest stages of design so total impacts caused by product systems can be reduced. Environmental, performance, cost, cultural, and legal requirements are balanced (Curran, 1996). Environmental impacts and health risks caused by product development are intended to be reduced. This is very similar to *design for environment* (DfE) programs where environmental issues are incorporated into a product system design process. DfE and life-cycle design have similar objectives, although their origins differ. DfE was developed as an off-shoot of *design for X*, where *X* could be any number of criteria (e.g., manufacturability, testability, reliability, recyclability). In DfE, *X* is environmental protection and sustainability.

The EPA DfE Program, where *X* is also environmental protection and sustainability, promotes risk reduction, pollution prevention, energy efficiency, and other resource conservation measures through process choices at a facility level. EPA's DfE CTSA process also includes an analysis of performance and cost. Typically, EPA's DfE Program focuses less on the entire life cycle and more on evaluating technology or material substitutes to reduce environmental impacts. This project combines the DfE Program's CTSA process (Kincaid *et al.*, 1996) and the LCA process, and thus resembles a life-cycle design approach.

LCAs evaluate the environmental impacts from each of the following major life-cycle stages:

- Raw materials extraction/acquisition;
- Materials processing;
- Product manufacture;
- Product use, maintenance, and repair; and
- Final disposition/end-of-life.

Figure 1-1 briefly describes each of these stages for a computer display product system. The inputs (e.g., resources and energy) and outputs (e.g., product and waste) within each life-cycle stage, as well as the interaction between each stage (e.g., transportation) are evaluated to determine the environmental impacts.

As defined by the Society of Environmental Toxicology and Chemistry (SETAC), the four major components of an LCA are: (1) goal definition and scoping; (2) inventory analysis; (3) impact assessment; and (4) improvement assessment. More recently, the international standard, ISO 14040: Environmental Management—Lifecycle Assessment—Principles and Framework, has defined the four major components of an LCA as: (1) goal and scope; (2) inventory analysis; (3) impact assessment; and (4) interpretation of results. The SETAC and International Standards Organization (ISO) framework are essentially synonymous with respect to the first three components, but differ somewhat with respect to the fourth component,

improvement assessment or life cycle interpretation. Improvement assessment is the systematic evaluation of opportunities for reducing the environmental impacts of a product, process, or activity. Interpretation is the phase of LCA in which the findings from the inventory analyses and the impact assessment are combined together, consistent with the defined goal and scope in order to reach conclusions and recommendations. In this study and project report, the goal and scope are the subject of Chapter 1. The inventory analysis and impact assessment are the subjects of Chapters 2 and 3 respectively; and the improvement assessment or life-cycle interpretation are left to the electronics industry given the results of this study. The life-cycle inventory and impact assessment strategies are briefly described below.

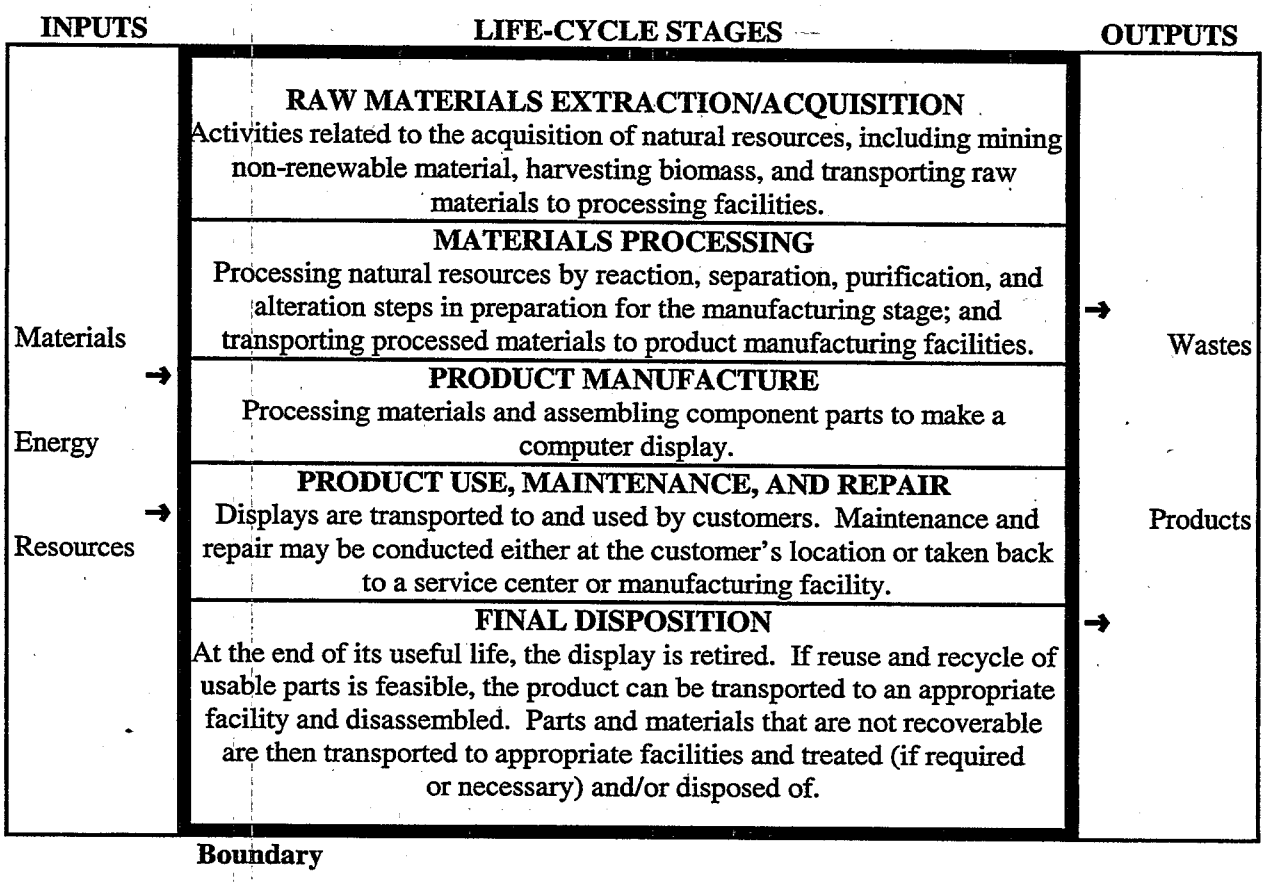


Figure 1-1. Life-cycle stages of a computer display

The life-cycle inventory (LCI) involves the quantification of raw material and fuel inputs, and solid, liquid, and gaseous emissions and effluents. Traditional LCIs quantify pollutant categories (e.g., volatile organic compounds [VOCs]) rather than particular chemicals. This project also includes a more detailed evaluation of a few specific chemicals found in computer displays (lead, mercury, and liquid crystals) to enable a more thorough evaluation of risk from chemical exposure. The approach to the LCI in this study involves defining product components, developing a bill of materials (BOM), and collecting inventory data on each life-cycle stage for computer displays. Details of the LCI data gathering activities are provided in Chapter 2.

The life-cycle impact assessment (LCIA) involves the translation of the environmental burdens identified in the LCI into environmental impacts. LCIA is typically a semi-quantitative process involving characterization of burdens and assessment of their effects on human and ecological health, as well as other effects such as smog formation and global warming. Details of the LCIA methodology and results are presented in Chapter 3. This project has furthered the development of LCIA methodology by including health effect concerns into the LCIA. This study also qualitatively assesses exposure and chemical risk of selected chemicals in the life cycles of the computer displays (Chapter 4).

1.2 INTRODUCTION

Goal and scope definition is the first phase of LCA and is important to the CTSA as well. This phase is important because it determines why the LCA or CTSA is being conducted and its intended use, as well as the system and data categories to be studied.

This chapter presents the goal and scope of the DfE CDP, including its purpose and goals, previous research and market trends, descriptions of the product systems being evaluated, and the boundaries used in this study. It incorporates scoping as it is recommended in both the LCA (e.g., Curran, 1996; Fava *et al.*, 1991; ISO, 1996) and CTSA processes (Kincaid *et al.*, 1996).

1.2.1 Purpose

The purpose of this study is two-fold: (1) to establish a scientific baseline that evaluates the life-cycle environmental impacts of flat panel displays (FPDs) and cathode ray tubes (CRTs) for desktop computers, by combining LCA and CTSA methodologies; and (2) to develop a model that can be used with updated data for future analyses. This study evaluates the newer active matrix liquid crystal display (LCD) and the more traditional CRT technologies. The evaluation considers impacts related to material consumption, energy, air resources, water resources, landfills, human toxicity, and ecological toxicity. This study is designed to provide the electronics industry with information needed to improve the environmental attributes of desktop computer displays. It is intended to provide valuable data not previously published, and an opportunity to use the model developed for this project in future improvement evaluations that consider life-cycle impacts. It will also provide the industry and consumers with valuable information to make environmentally informed decisions regarding display technologies, and enable them to consider the relative environmental merits of a technology along with its performance and cost.

1.2.2 Previous Research

While there has been some work done on the life-cycle environmental impacts of either CRTs or LCDs, there has not been a quantitative LCA addressing both CRTs and LCDs. For example, Microelectronics and Computer Technology Corporation (MCC) published an *Electronics Industry Environmental Roadmap* (1994) that qualitatively discussed environmental issues and priority needs for reducing impacts from computer CRTs and FPDs, but this project did not, nor was it intended to, focus on all aspects of the displays' life cycles.

Some of the environmental impacts of CRTs (e.g., energy use, disposal of lead, and other end-of-life issues such as recycling) have been identified but not quantified in previous work, such as that done by EPA's Common Sense Initiative Computer and Electronics Subcommittee. Atlantic Consulting completed a draft LCA of the personal computer (including a 15" monitor) for the European Union's (EU) Eco-Label program (Atlantic Consulting and IPU, 1998). Further, the New Jersey Institute of Technology conducted an LCA of television CRTs, which have the same technology as the computer monitor CRT.

Studies on the environmental impacts of FPDs are much less prevalent. A University of Michigan master's thesis (Koch, 1996) evaluated the environmental performance of an LCD manufacturer. The thesis did not quantitatively assess environmental impacts from all life-cycle stages, as would be done in an LCA. The EU Eco-Label Program also evaluated a portable computer with a 13.3" LCD screen (Orango AB and Atlantic Consulting, 1999). The scope was limited to energy consumption for the impact assessment, and it provided some inventories for raw materials production. Human and ecological toxicity were excluded from the scope of the portable computer analysis.

1.2.3 Market Trends

At present, computer displays using CRTs dominate worldwide markets. They provide a rich, high-resolution display well suited to a wide range of user requirements. However, CRT displays are bulky, use larger amounts of energy to operate than LCDs, and are associated with disposal concerns due to the presence of lead in the glass. Color CRT monitors contain lead to help shield the users from x-rays (x-ray attenuation) and can, under some circumstances, be classified as a hazardous waste when disposed of. Newer technologies, collectively referred to as FPDs, have captured significant market segments. FPDs exhibit desirable qualities such as reduced size and weight and greater portability. Environmentally, they are expected to consume less energy during use and do not use leaded glass. However, they may consume more energy during manufacturing, contain small amounts of mercury, are more costly, and in the past have had lower resolution and image quality than the CRT. The LCD, first used predominately in notebook computers, is now moving into the desktop computer market. The 1998 worldwide market for desktop computer monitors was 90 million units. The 1998 actual and 2001 projected markets for desktop computer CRTs and LCDs are presented in Table 1-1. Market projections anticipate that LCDs will capture sizable market share for desktop computer displays.

Table 1-1. 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

Sources: DisplaySearch, 2001.

1.2.4 Need for the Project

Given the expected market growth of LCDs for computer displays, the various environmental concerns throughout the life cycle of the computer displays, and the fact that the relative life-cycle environmental impacts of LCDs and CRTs have not been scientifically established to date, there is a need for a quantitative environmental life-cycle analysis of desktop computer display technologies. Manufacturers can use these results or the model developed here to identify areas for improvement concerning the environmental burdens. Further, as companies or consumers are considering investing in certain displays, they can refer to the results of this study to assist them in making environmentally informed decisions.

1.2.5 Targeted Audience and Use of the Study

The electronics industry is expected to be one of the primary users of the study results. The study is intended to provide industry with an analysis that evaluates the life-cycle environmental impacts of selected computer display technologies. Scientific verification of the relative environmental impacts will allow industry to consider environmental concerns, along with traditionally evaluated parameters of cost and performance, and to potentially redirect efforts towards products and processes that reduce releases of toxic chemicals and reduce risks to health and the environment. Given the results, the industry can then perform an improvement assessment of the display technologies. This also allows the electronics industry to make environmentally informed choices about display technologies when assessing and implementing improvements such as changes in product, process, and activity design; raw material use; industrial processing; consumer use; and waste management.

Another result of the study is an accounting of the relative environmental impacts of various components of the computer displays, thus identifying opportunities for product improvements to reduce potential adverse environmental impacts and costs. Identification of impacts from the computer display technologies can also encourage industry to implement pollution prevention options, such as development and demonstration projects, and technical assistance and training. Since this study incorporates a more detailed health effects component than in traditional LCAs, the electronics industry can use the tools and data to evaluate the health, environmental, and energy implications of the technologies. With this evaluation, the U.S. electronics industry may be more prepared to meet the demands of extended product responsibility that are growing in popularity in the global marketplace, and better able to meet competitive challenges in the world market. In addition, the results and model in this study will provide a baseline LCA upon which alternative technologies can be evaluated. This will allow for more expedited display-related LCA studies, which are growing in popularity by industry and may be demanded by original equipment manufacturers (OEMs) or international organizations.

EPA and interested members of the public can also benefit from the results of the project. The project has provided a forum for industry and public stakeholders to work cooperatively, and the results can be used by stakeholders as a scientific reference for the evaluated display technologies. The results of the project could also be of value to other industries involved in designing environmental improvements into the life cycle of consumer products.

1.3 PRODUCT SYSTEM

1.3.1 Functional Unit

The product system being analyzed in this study is a standard desktop computer display that functions as a graphical interface between computer processing units and users. The desktop market was chosen to evaluate CRTs and FPDs because it represents a large market for CRTs and an anticipated large market for some FPDs. Also, there are a limited number of technologies that meet desktop specifications. Therefore, focusing on the desktop market will affect a significant number of products, while keeping the scope of this project manageable.

The product system is the computer display itself and does not include the central processing unit (CPU) of the computer that sends signals to operate the display. It is assumed that the LCDs operate with an analog interface, and therefore are compatible with current CRT CPUs as plug-and-play alternatives.

In an LCA, product systems are evaluated on a functionally equivalent basis. The functional unit is used as the basis for the inventory and impact assessment to provide a reference to which the inputs and outputs are related. For this project, the functional unit is one desktop computer display over its lifespan. Data collected in this project have been normalized to a display that meets the functional unit specifications, which are presented in Table 1-2. These product performance specifications are assumed to meet the requirements of the system functional unit in the predictable future (i.e., computer technology as predicted through the year 2001). The CRT technology is the current industry standard for this product system.

Table 1-2. 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. This is because 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.

Besides the CRT display, several FPD technologies were considered for inclusion in this study. Among the FPD technologies that exist, the amorphous silicon (a:Si) thin-film transistor-(TFT) active matrix LCD technology meets the requirements of the functional unit within the parameters of this analysis and is assessed in this study. Section 1.3.3.1 describes the LCD technology further, and Appendix A briefly describes several FPD technologies and explains why the non-LCD technologies are not considered for standard desktop computer uses as defined for this study. The following subsections briefly describe both CRT and LCD technologies.

1.3.2 Cathode Ray Tube

1.3.2.1 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. In color CRTs, the phosphors are patterned in dots or stripes of red, green, and blue phosphors. The electrons are emitted from three cathodes in an electron gun assembly and pass through an apertured metal "shadow mask" during their passage to the phosphor. Electrons from each cathode that are directed at the wrong color phosphor are absorbed by the shadow mask. Pictures are created by first focusing the electron beams into tiny spots, which are moved by deflecting the electron beams electromagnetically with the "yoke." This system is extremely efficient in that it only requires three video drivers and connections instead of the 2000 or so in the most common FPD (MCC, 1994).

The high voltages used to accelerate the electrons must be insulated from the external surfaces of the tube and the CRT must have excellent electrical insulating properties. The decelerating electrons produce x-rays and the CRT must also be a good x-ray absorber. Leaded glass surrounds the cathode ray tube to absorb the x-rays.

The major parts of the CRT display are the faceplate (glass panel), shadow mask (also referred to as the aperture mask), a leaded glass funnel, and the electron gun with the deflection yoke. Various connectors, wiring, an implosion band, printed wiring boards (PWBs), and the casing comprise most of the rest of the display. Table 1-3 presents a more comprehensive list of the CRT components and a list of the component materials identified from disassembling a monitor, and additional research to identify the material makeup of some components (MCC, 1998).

Table 1-3. Preliminary list of CRT display components and materials

Component parts				Materials
Tube	Faceplate assembly	Phosphor-coated faceplate	Glass panel (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 (grille dag)	Aquadag**
			Lacquer coating	Mixture of alcohol and plastics
			Aluminum coating	Al
		Internal electron shield *		Al
		Shadow mask assembly	Mask	Steel, Ni
			Supports	CrNiFe and NiFe
	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 PWB		Misc. electronics and resin board
	Implosion band			Steel

Table 1-3. Preliminary list of CRT display components and materials

Component parts		Materials
Electron gun	Electrostatic field shaping electrodes	300/400 series steels (Fe, Ni, Cr)
	Cathodes	Ni (coated with mixtures of Ba, Sr, CaCO3)
	Glass pillars	Borosilicate glass
	Wire heater (filament heater)	Tungsten, aluminum oxide
	Glass stem	Leaded glass (29% PbO alkali aluminosilicate)
	Springs and washers	Steel
	Gunmount (glass)	Potassium aluminosilicate sintering
Powerboard	Main CRT PWB (includes power supply PWB, etc.)	Misc. electronics and resin board
	Flyback transformer	Misc.: e.g., potting material (epoxy), steel, Cu
Casing (chassis and base)		Polystyrene
Other misc. parts	Brackets	Brass
	Brackets	Polystyrene
	XY controls	Polycarbonate
	Connectors	Al
	Screws	Zn-plated steel
	Brackets, anode connection	Steel
	Shields (right, left, top, back)	
	Rubber feet	Silicone rubber
	Anode cap	Rubber
	Insulator pad	Polyester

1.3.2.2 CRT manufacturing

The manufacturing process of the CRT (Figure 1-2) involves first preparing the glass panel and shadow mask. The shadow mask is a steel panel with a mask pattern applied through photolithography. The color phosphors and a black matrix coating (aquadag) are applied to the faceplate, also using photolithography, which involves several steps and several chemicals that etch the material into specific patterns. 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 and as a conductor to allow the use of voltages over 12 kilovolts without charging of the phosphor screen. An electron shield (typically aluminum) is attached to the shadow mask assembly to prevent stray electrons from reaching outside the screen area (EPA, 1995; MCC, 1994). This then comprises the faceplate assembly. The two major remaining parts are the funnel and electron gun.

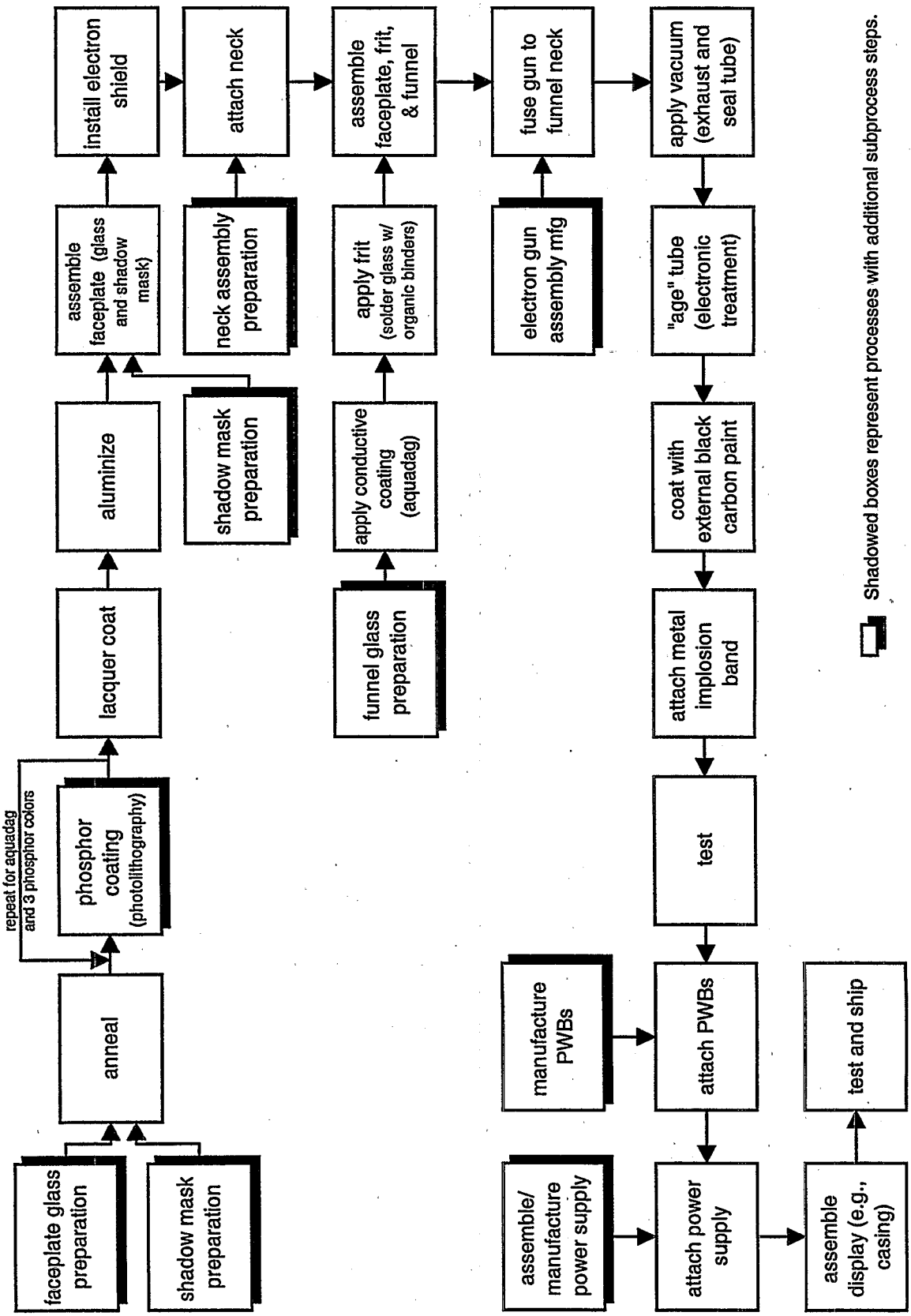


Figure 1-2. CRT manufacturing process

The leaded-glass funnel is washed and coated with a black coating (aquadag), which is a good electrical conductor and a non-reflective surface. The funnel and faceplate assembly are joined using frit (solder glass) that is approximately 70% lead oxide. The electron gun is an assembly of glass and several metal parts that are heated to embed the metal in the glass. The electron gun is then fused to the funnel neck. Finishing steps are conducted to complete the manufacturing of the CRT (or "tube") (e.g., attaching a metal implosion band for implosion protection and safety) and then the entire monitor is assembled with other necessary parts (e.g., the main and neck PWBs, power cord, casing).

1.3.3 Liquid Crystal Display

LCDs are used for various applications, with their largest market currently in notebook computers. LCDs have been gaining a presence in the desktop computer display market and are expected to continue to do so. Compared to the CRT, the LCD provides a more compact display, as well as being of higher contrast, sunlight readable, more reliable, and more durable (i.e., requiring much less maintenance) (Koch and Keoleian, 1995). In general, the major functional disadvantages have been that the resolution and quality of the image have not matched that of CRTs. However, emerging technologies are expected to meet user requirements.

The two most common types of LCDs are passive matrix (PMLCD) and active matrix (AMLCD). Brief descriptions of these and other LCD technologies are presented in Appendix A, Table A-1. In 1998, AMLCDs constituted approximately 81% and PMLCDs 19% of computer monitor LCD production (MCC, 1998). PMLCDs are used primarily for low-end products (e.g., cannot perform video applications); AMLCDs are used for high-end multimedia products and better meet the specifications for standard desktop computers. PMLCDs are forecasted to decline to less than one percent of the LCD desktop display market by 2002 (Young, 1998). Therefore, this project's focus is on AMLCDs.

1.3.3.1 LCD technology

In general, an LCD is comprised 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 most common type of AMLCD, and the one that meets the functional unit specifications of this project, is the a:Si TFT AMLCD (see Appendix A, Table A-1 for descriptions of various types of AMLCDs). AMLCDs consist of driver tabs along the columns and rows of the display glass and transparent parallel electrical lines across the glass arranged to form a matrix. Each intersection of the matrix forms a pixel. The TFT AMLCD has a transistor at each pixel which functions as an electronic switch to activate an individual pixel. This active addressing technique allows for high contrast between the on and off states of a pixel.

Operation of the AMLCD is determined by how the liquid crystals are aligned when activated by an electrical current. Traditional AMLCDs use a twisted nematic (TN) operating principle of the liquid crystal, which is evaluated in this study. 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 a polyimide orientation film (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 affect an on or off state of the LCD cell (see Appendix B for further explanation; also see Castellano [1992] and OTA [1995]). The backlight supplies the light source for the display and generally has four cold cathode 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, are emitting displays which emit electrons to illuminate appropriate phosphors.

There is a variation of the a:Si TFT AMLCD technology called in-plane switching (IPS). Compared to the traditional TN mode, IPS TFT allows for a wider viewing angle that is comparable to the CRT. The traditional TN mechanism vertically twists the liquid crystals by sending voltage through the display from electrodes that are on both the front and rear glass panels. IPS mode twists the liquid crystals horizontally in response to a voltage applied by electrodes on the rear glass only. The TN TFT uses indium-tin oxide (ITO) as the transparent electrode on the front and rear glass panels. For the IPS TFT, no ITO is needed on the front glass and the electrode on the rear glass is made of any of a number of other materials (e.g., Mo, Ta, Al/Cr, MoW). Therefore, no ITO is used for the IPS mode. However, the IPS TFT display demands an increase in the number of backlights to meet the brightness requirements for desktop applications (DisplaySearch, 1998). Although this technology may be produced for displays that meet this study's functional unit, the manufacturers of 15" AMLCDs that supplied data for this study provided data only for traditional a:Si TFT AMLCDs. IPS was forecasted to have a 35% market share of LCD desktop monitors in 2000 (Young, 1998) and therefore, studying IPS technology may be an area for future research.

Based on the disassembly of an LCD monitor conducted by MCC, a summary of the materials that are in an AMLCD are presented in Table 1-4 (MCC, 1998). The major components of the AMLCD are the glass panel (which includes the transistors, electrodes, liquid crystals, orientation film, polarizers, and row and column drivers), the backlight assembly (including the cold cathode fluorescent tube, light guide, and associated electronics), other electronics (main LCD controller), and the stand and cover. The remaining components and materials are listed in Table 1-4. In this report we will also refer to the LCD "module" as a component. This is comprised of the LCD panel, backlight unit, and main LCD controller. Module manufacturing as a process modeled in this study includes the major process in LCD manufacturing, which is panel manufacturing described below.

Table 1-4. LCD components and materials

LCD component parts				Materials
LCD assembly	LCD glass panel assembly	AMLCD cell	Glass	Soda lime or borosilicate
			Thin film transistor (TFT)	Misc. (e.g., Si, Mo, Al, etc) *
			Electrode	Indium-tin oxide (ITO)
			Polarizers	Iodine, cellulose triacetate-acrylic, etc.
			Orientation film (alignment layer)	Polyimide
			Liquid crystals	e.g., phenylcyclohexanes biphenyls
			Color filters	Resins
		Row/column driver tabs		IC chip on polyimide
		Row/column driver PWBs		Misc. (Si, Cu, etc.)
		Connection flex		Cu on film of polyimide
	Plastic frame			Polycarbonate, glass filled
	Gaskets			Silicone rubber
	Screws			Steel (Fe)
	Metal clip			BeCu
	Brightness enhancer			Polyester
	Cable assembly	Misc. wires & connectors		Misc. (Cu, plastic, etc.)
Controller (PWB)				Misc. (Si, Cu, etc.)
Power supply assembly	Housing			Steel (Fe)
	Screws			
	Insulator			Polyester
	Power switch			
	Power cord recepticle			ABS/Cu
	Heat sink			Aluminum
	Power supply PWB			Misc. (Si, Cu, etc.)

Table 1-4. LCD components and materials

LCD component parts				Materials
Backlight assembly	Metal plate			Steel (Fe)
	Screws			
	Brass threaded stand off			Brass
	Gasket			Foam rubber
	Nylon strain relief			Nylon
	Nylon clamp			
	Clear protector			Plexiglas
	Opaque diffuser			Polyester
	White reflector			
	Light pipe			Polycarbonate
	Corner tape			Aluminized mylar
	Light assembly	Cold cathode tube		Glass, phosphor, Hg
		Shock cushion		Silicone rubber
		Cable assembly		Insulated Cu
	Rear plate assembly	Rear plate		Steel (Fe)
		Screws		
		Hold-down plate		
		Cable clamp		Nylon
		Plastic tube		Polycarbonate
		Flat cable toroid		Hi-mu ferric
		Caution label		Paper
	Backlight PWB			Misc. (Si, Cu, etc.)

Table 1-4. LCD components and materials

LCD component parts		Materials
Rear cover assembly	Screws	Steel (Fe)
	Metal plate	
	BeCu fingers	BeCu
	Cloth mesh	Polyester
	Insulator	
	Rear cover	Plastic (ABS)
Base/stand assembly	Brackets & washers	Steel (Fe)
	Axle & spring	
	Base weight	
	C-clip	
	Swivel bearing 1	Stainless steel
	Swivel bearing 2	Polyoxymethylene (acetal)
	Covers	Plastic (ABS)
	Upright	unsaturated polyester, glass filled
	Bushing	Nylon
	Rubber feet	Silicone rubber
Other misc. parts	Screws	Steel (Fe)
	Power supply cover	
	Front bezel	ABS
	Knob	
	Power switch	
	LED light pipe	Polycarbonate
	Adjustment PWB	Misc. (Si, Cu, etc.)
	Cable clamp	Nylon
	Insulator	Polyester

Source: MCC, 1998.

*Example of TFT materials: gate metal (Al or Cr), S_iO_2, SiN, a-Si/SiNx, a-Si, drain metal

1.3.3.2 LCD manufacturing

LCD technology uses a glass substrate (e.g., soda lime or borosilicate glass). Once the glass is acquired, it must be cleaned, which is a critical step in reliable manufacturing. The manufacturing techniques of the LCD are similar to the production of semiconductor chips, which require energy intensive "clean rooms" for manufacturing. A conductor or semiconductor is deposited on the glass substrate. Most FPDs require a transparent conductor (electrode) such as ITO, which is usually deposited by a sputtering method. TFT devices in AMLCDs use semiconducting materials (e.g., silicon, cadmium selenide) for transistors at each pixel. These semiconducting materials can be prepared by vacuum evaporation, using either electron beam evaporation, sputtering, or chemical vapor deposition. Electrode patterns are then formed by a photolithographic process that begins with the coating of photoresist on the ITO or metal-coated substrate.

The photoresist (photosensitive organic polymer) is then "developed" using liquid organic chemicals. This is similar to the manufacture of silicon integrated circuits (ICs). The ITO or metal is then etched to form electrodes. FPD manufacturing employs etchants (e.g., H_3PO_4/HNO_3, HF/HCl, $HClO_4$, CF_4/SF_6) that differ from those used in silicon IC manufacturing. LCDs use alignment layers and iodine/dye based polarizers. AMLCDs use amorphous silicon, silicon nitride, various oxides and metals. The silicon IC manufacturing process of plasma-enhanced chemical vapor deposition (PECVD) is used for some of these layers, as are more conventional vacuum deposition techniques. Finally, various organic liquids (the liquid crystals) are injected between the top and bottom substrate of LCDs (MCC, 1993).

The general process flow of AMLCD manufacturing is presented in Figure 1-3. The photolithographic subprocess steps for the front and rear glass panels are presented in Figures 1-4 and 1-5. Various processes include sputtering, PECVD, photolithography, wet etching, reactive ion etching (RIE), in-process testing, liquid crystal processing, and lamination among others. The manufacturing process of IPS differs from traditional TN in that there are fewer photolithography steps required since no ITO is patterned onto the front or rear glass plates.

Once the photolithographic processes are completed, the polyamide orientation film is applied and rubbed on the glass. The front and rear glass substrates are merged and the liquid crystals are inserted. Polarizers are laminated to the front and rear panels, completing the "AMLCD cell" of the LCD glass panel assembly (see Table 1-4). The electronic components that operate the AMLCD cell (i.e., the column and row driver tabs and wiring boards) are then attached to the glass. This completes the LCD glass panel assembly. The other major components of the LCD are then assembled. Adding the controller PWB and the backlight assembly make up what may also be called the "LCD module." Finally, the power supply assembly and the plastic cover and stand are added to make an assembled monitor.

In total, there are six PWBs needed for the LCD: controller, row driver, column driver, backlight, power supply, and adjustment knob PWB. The major ones by size and function are the larger controller and backlight PWBs, and the smaller column and row PWBs. These are compared to the two major PWBs in the CRT: the main and neck PWBs (see Table 1-3).

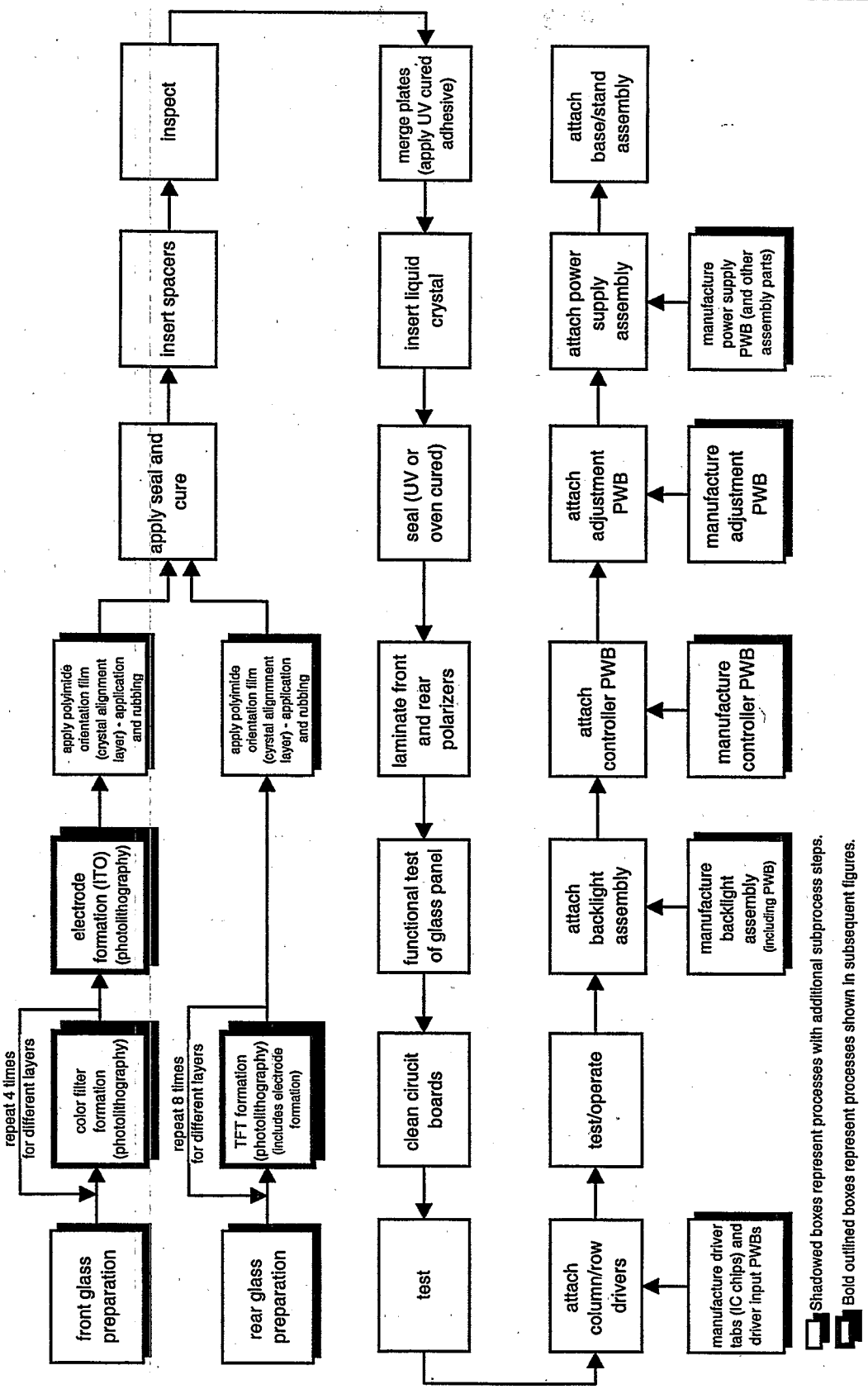


Figure 1-3. Traditional twisted nematicAMLCD manufacturing process

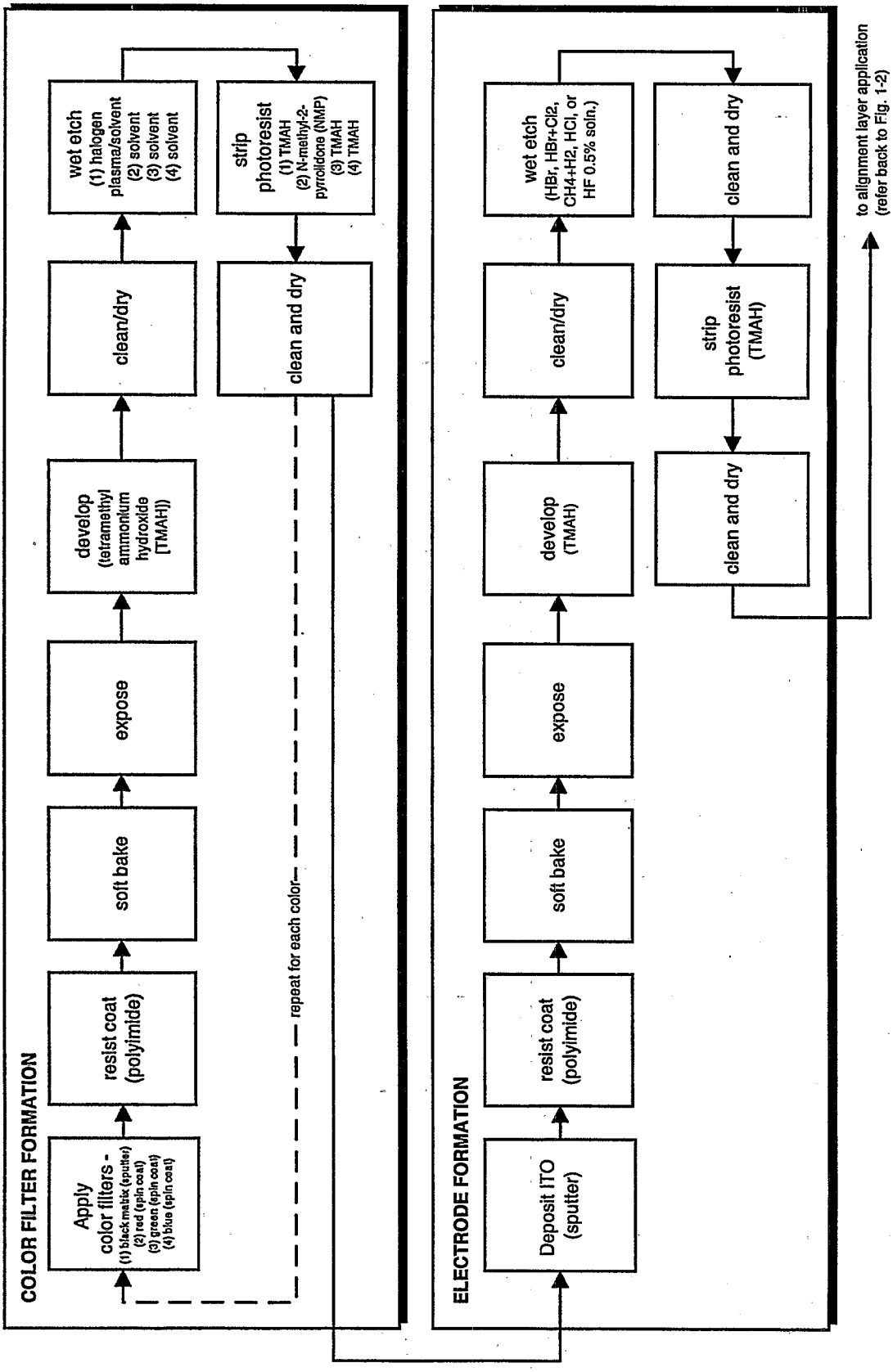


Figure 1-4. Front glass AMLCD manufacturing (photolithography)

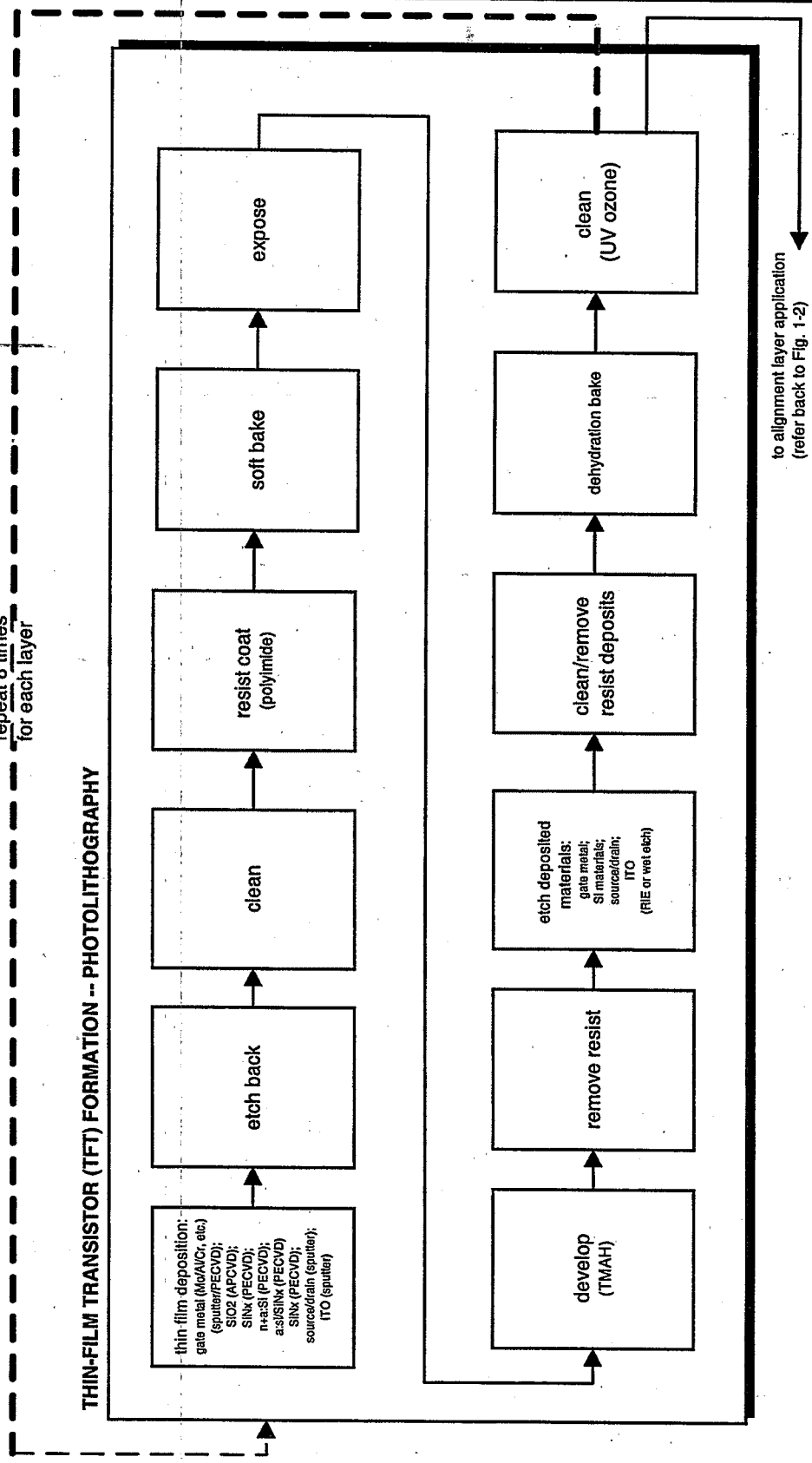


Figure 1-5. Rear glass AMLCD manufacturing (photolithography)

1.4 ASSESSMENT BOUNDARIES

1.4.1 Life-Cycle Stages and Unit Processes

In a comprehensive cradle-to-grave analysis, the display system includes five life-cycle stages: (1) raw materials acquisition; (2) materials processing; (3) product manufacture; (4) product use, maintenance and repair; and (5) final disposition/end-of-life. Also included are the activities that are required to affect movement between the stages (e.g., transportation). The major processes within the life cycles of CRTs and LCDs, which are modeled in this study, are depicted in Figures 1-6 and 1-7, respectively. Details on collecting data for these processes are presented in Chapter 2.

1.4.2 Spatial and Temporal Boundaries

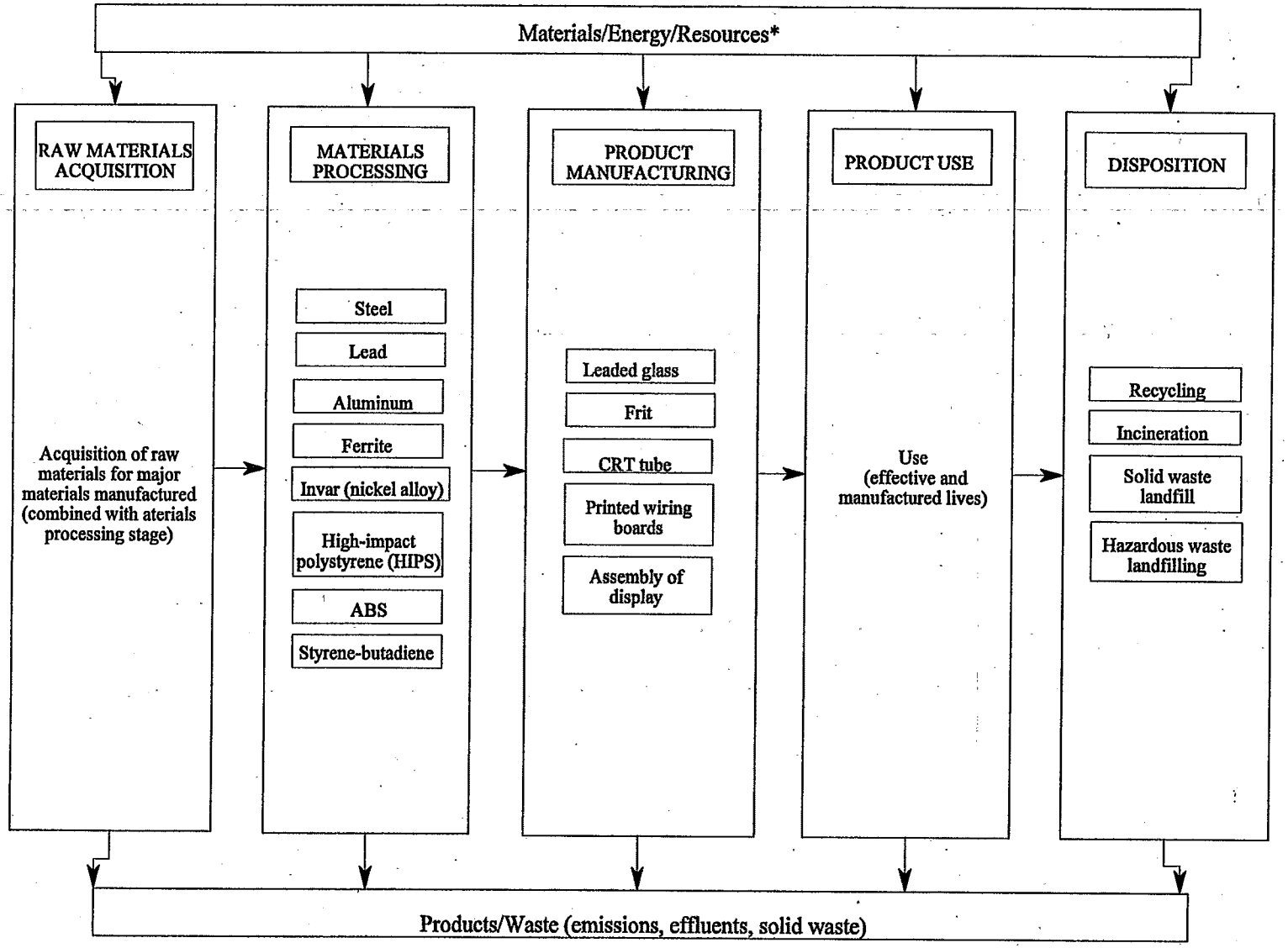
The geographic boundaries of this assessment are shown in Table 1-5. This LCA will focus on the U.S. display market; therefore, the geographic boundary for the use and disposition stages of displays is limited to the United States. Raw materials acquisition and material processing for materials used in the manufacture of computer displays are done throughout the world. Product manufacturing is done predominately in Asia, although there are foreign-owned desktop display manufacturers operating plants in the United States and other countries. Therefore, for purposes of this study, the geographic boundaries for raw material extraction, material processing, and product manufacture are worldwide.

Table 1-5. Geographic coverage for each life-cycle stage

Life-cycle stage	Geographic coverage
Raw materials acquisition	worldwide[a]
Material processing	worldwide[a]
Product manufacture	worldwide[a]
Use	United States
Disposition	United States

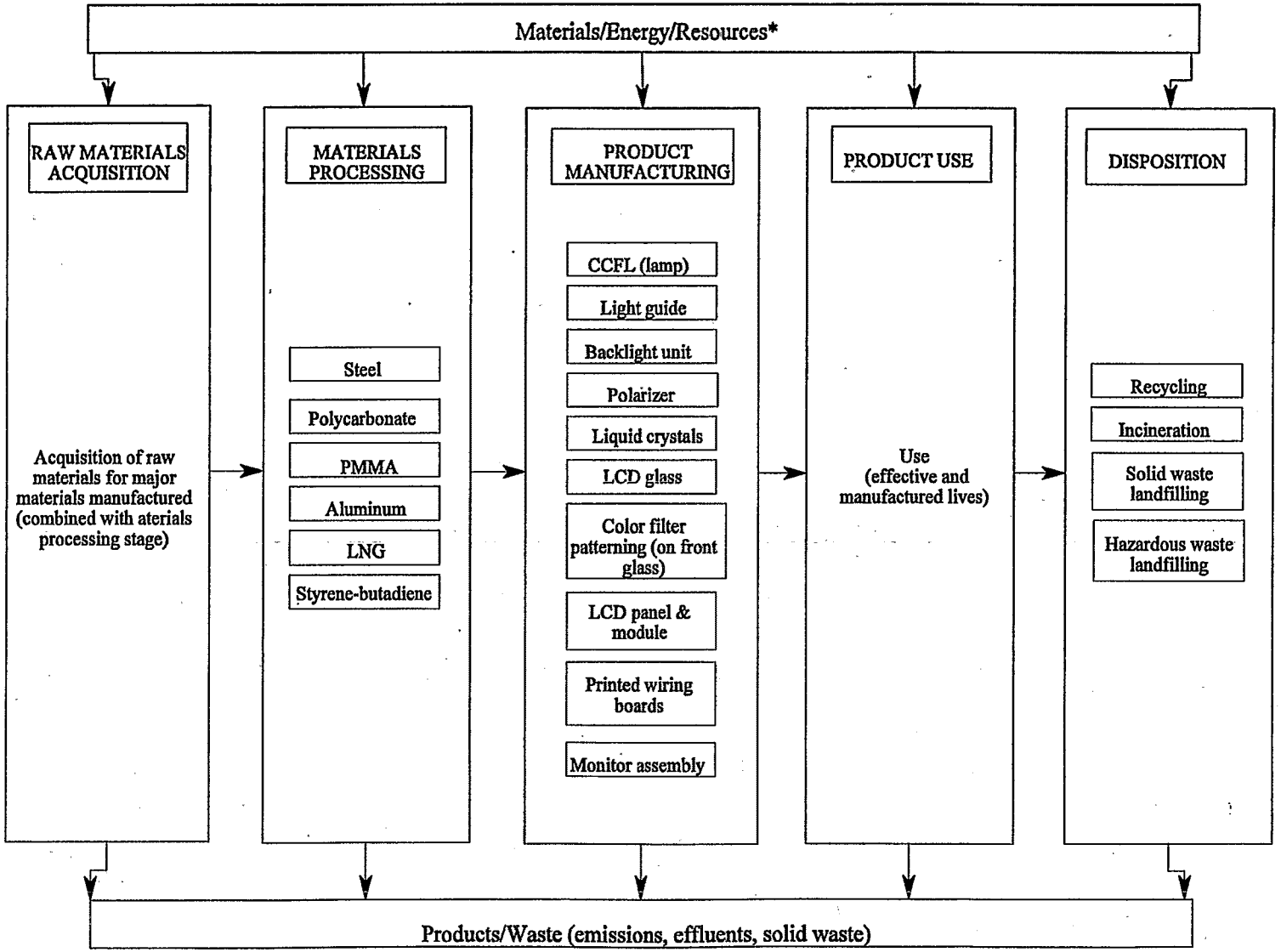
[a] In this study, worldwide boundaries were considered; however, the actual geographic locations for LC1 data are presented in Chapter 2 (Sections 2.2 and 2.3).

While the geographic boundaries show where impacts might occur for various life-cycle stages, traditional LCAs do not provide an actual spatial relationship of impacts. That is, particular impacts cannot be attributed to a specific location. Rather, impacts are generally presented on a global or regional scale.



Note: Arrows indicate flows between life-cycle stages. The arrows also represent transportation of materials required to get from one process to another.
* Electricity generation and fuel production (fuel oils, natural gas, and LPG) processes are not shown but were attached to those processes that consume energy resourcesthroughout the life-cycle

Figure 1-6. CRT Life-Cycle



Note: Arrows indicate flows between life-cycle stages. The arrows also represent transportation of materials required to get from one process to another.
* Electricity generation and fuel production (fuel oils, natural gas, and LPG) processes are not shown but were attached to those processes that consume energy resourcesthroughout the life-cycle

Figure 1-7. LCD Life-Cycle

This study addresses impacts from the life cycle of a desktop computer display manufactured using 1997-2000 technology. The use and disposition stages cover a period that represents the life of a display. Two lifespans are considered: (1) the "effective" life, defined as the period of time the display is in use by primary, secondary, or even tertiary users before reaching its final disposition; and (2) the "manufactured" life, defined as the designed durability of a display. The effective life is estimated based on past and current use patterns of displays and represents a realistic estimate of the lifespan. Because the effective life is subject to many variables, including fluctuating market trends, it is also necessary to evaluate the displays over their manufactured life. The manufactured life is estimated based on the manufacturer's estimated durability of the display. Because of quickly changing technologies in this industry, the effective life has been shorter than the manufactured life. The effective life, which is currently the more realistic scenario is used as the primary scenario in the final results presented in this study. However, the manufactured life is presented as an alternative scenario.

It is assumed that parameters that may change with time, such as available landfill space, will remain constant throughout the lifespan of the product system. If the lifespan is relatively short (i.e., within a timeframe where significant changes in landfill space would not occur), the preceding assumption is reasonable. If resources become more scarce within the lifespan, this assumption could underestimate the impacts.

1.4.3 General Exclusions

Impacts from the infrastructure needed to support the manufacturing facilities (e.g., maintenance of manufacturing plants) are beyond the scope of this study. However, maintenance of clean rooms used in the manufacturing of LCDs (and other components), which require substantial amounts of energy, are considered part of the manufacturing process.

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Chapter 2

LIFE-CYCLE INVENTORY

A life-cycle inventory (LCI) is the identification and quantification of the material and resource inputs and emission and product outputs from the unit processes in the life cycle of a product system (Figure 2-1). For the Design for the Environment (DfE) Computer Display Project (CDP), LCI inputs include materials used in the computer display product itself, ancillary materials used in processing and manufacturing of the displays, and energy and other resources consumed in the manufacturing, use, or final disposition of the displays. Outputs include primary products, co-products, air emissions, water effluents, and releases to land. Specific unit processes for CRTs and LCDs are represented by the boxes in Figures 1-6 and 1-7, and each unit process has inputs and outputs particular to that process. Figures 2-2 and 2-3 also show each unit process for both the CRT and LCD life cycles, and graphically displays how they are linked to subsequent processes. This figure will be referred to throughout this chapter in the discussion of each life-cycle stage.

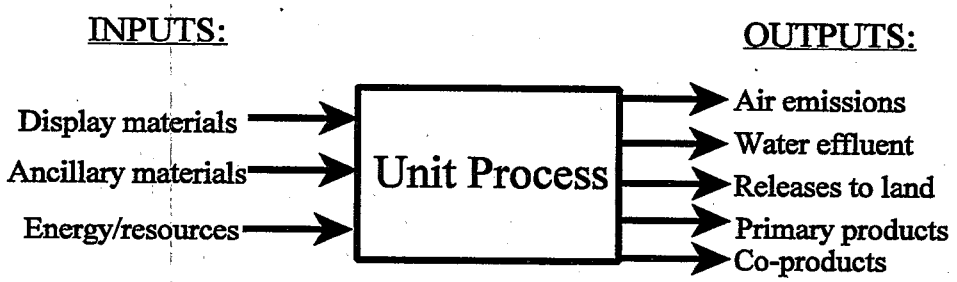

Figure 2-1. Unit process inventory conceptual diagram

This chapter describes the methods for collecting LCI data in the DfE CDP, and presents LCI results. Section 2.1 describes the general methodology for LCI data collection, while Sections 2.2 through 2.6 present the specific methodologies, data sources, data quality, limitations and uncertainties for each life-cycle stage. Section 2.7 then concludes with the combined LCI data for each monitor type.

More specifically, Section 2.2 presents the LCI methodology for the materials extraction and materials processing (i.e., "upstream") life-cycle stages, including electricity generation. Electricity is used in several processes throughout each monitor's life-cycle, and the electricity generating process is linked to the processes that use electricity. As a consequence, the inventory results from electricity generation are reported as part of the associated life-cycle stage for the process to which it is linked. For example, electricity used in manufacturing a product component is included in the manufacturing stage inventory, while electricity used during the use stage is included in the use stage inventory.

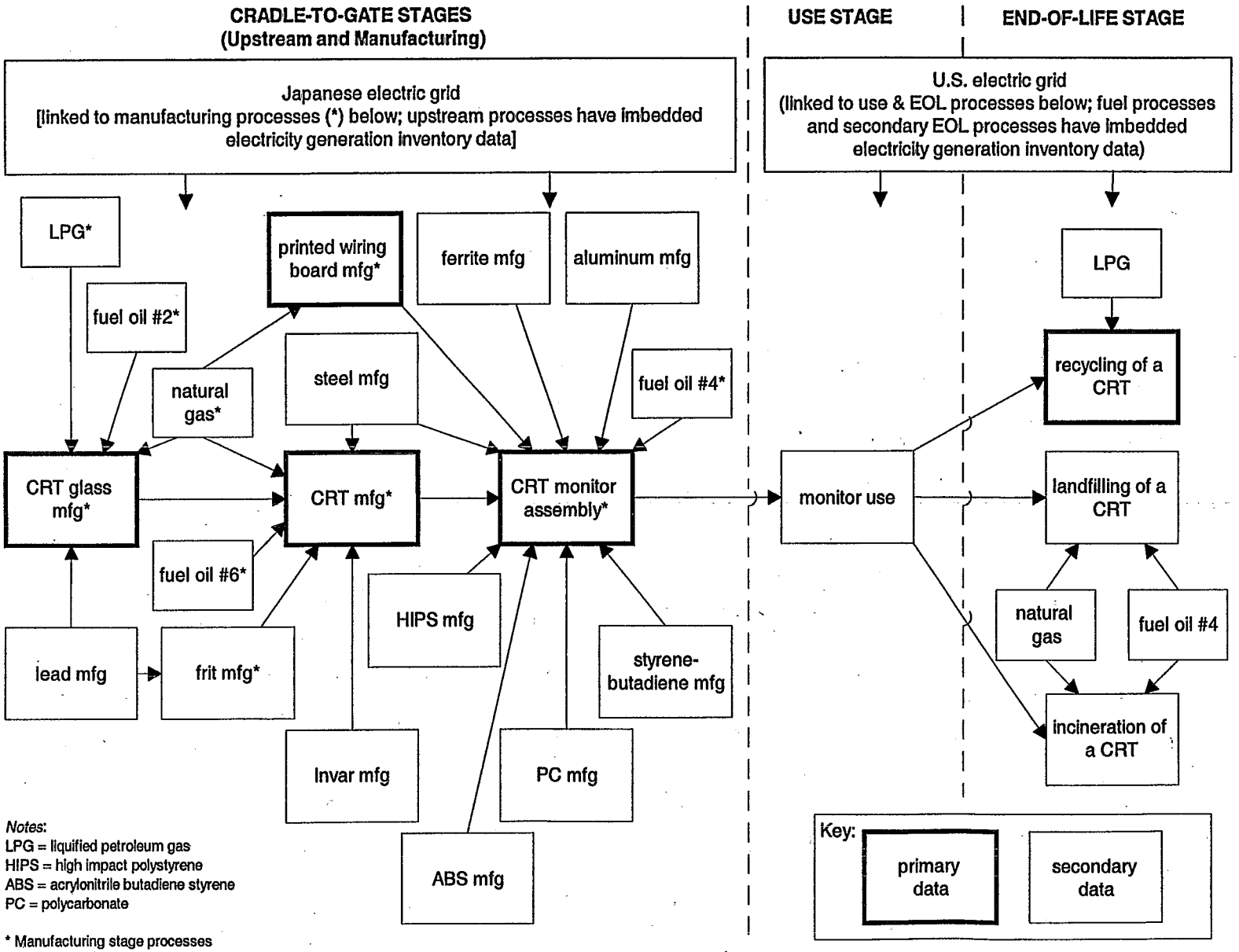

Figure 2-2. CRT linked processes

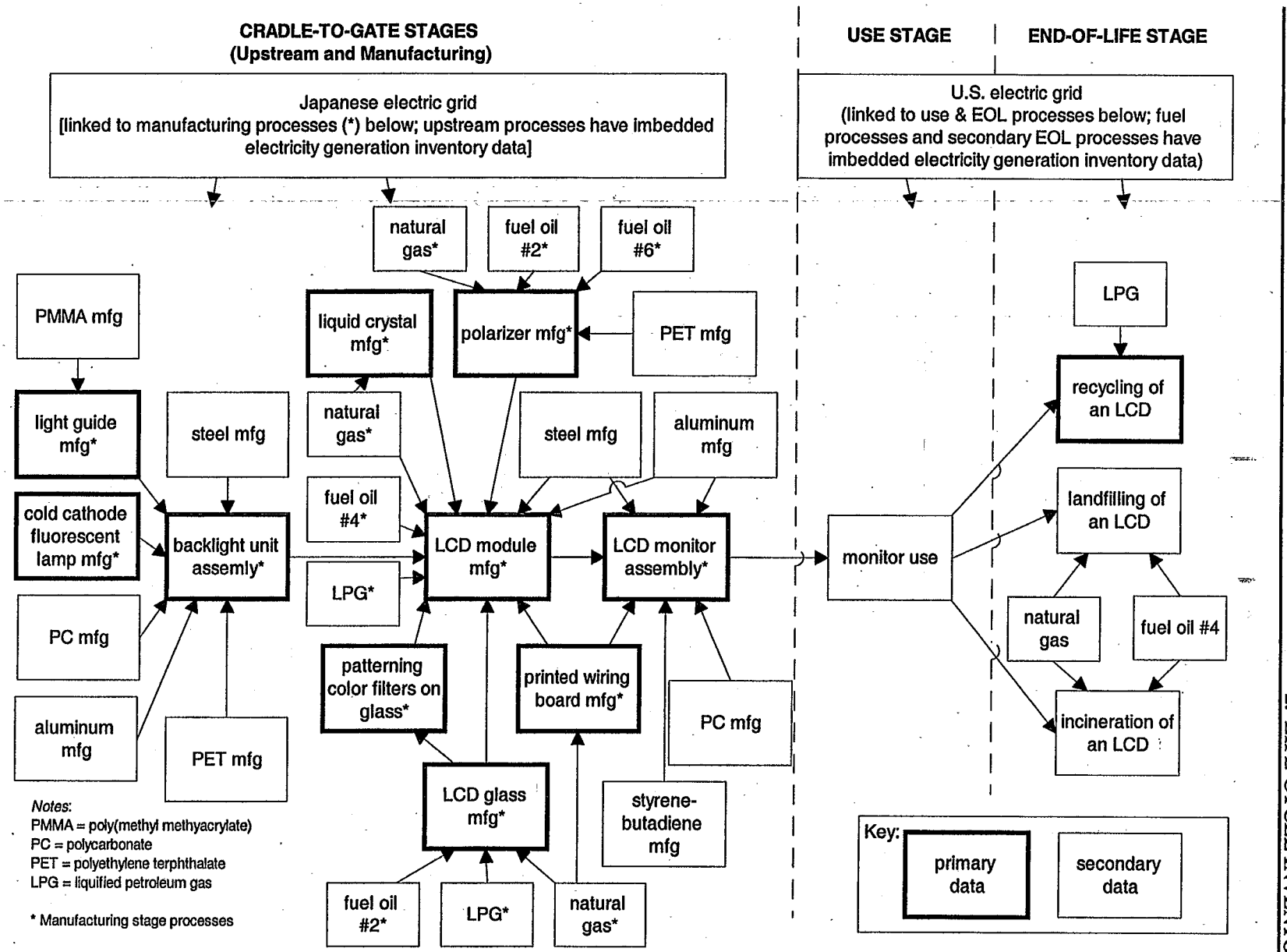

Figure 2-3. LCD linked processes

Section 2.3 presents the LCI methods for the product manufacturing life-cycle inventory, which was developed from primary data collected through questionnaires designed and sent to manufacturers for this study. Sections 2.4 and 2.5 present the methods for developing the use and end-of-life (EOL) life-cycle stage inventories, respectively. Transportation is another important aspect of a product life-cycle that can cause environmental impacts. Information related to the transport of materials, products, and wastes is presented in Section 2.6. As the final section of Chapter 2, Section 2.7, summarizes and discusses the entire inventory data over the life-cycles of the CRT and LCD computer monitors. Sensitivity analyses are also discussed in Section 2.7.

2.1 GENERAL METHODOLOGY

This section describes the data categories evaluated in the CDP LCI, the decision rules used to determine which materials extraction and materials processing life-cycle stages (e.g., "upstream" processes) to evaluate in the study, and data collection methods. It also describes procedures for allocating inputs and outputs from a process to the product of interest (e.g., a display or display component) when the process is used in the manufacture, recycle, or disposal of more than one product type at the same facility. Finally, it describes the data management and analysis software used for the project and methods for maintaining overall data quality and critical review.

2.1.1 Data Categories

Table 2-1 describes the data categories for which inventory data were collected, including material inputs, energy inputs, natural resource inputs, emission outputs, and product outputs. Inventory data were normalized to mass per functional unit (in the case of material and resource inputs and emission or material outputs), megajoules (MJ) per functional unit (in the case of energy inputs), or the number of components per functional unit (in the case of display components). As discussed in Section 1.3, the functional unit is one desktop computer display over its lifespan.

Data that reflected production for one year of continuous processes were scaled to one functional unit. Thus, excessive material or energy associated with startups, shutdowns, and changeovers were assumed to be distributed over time. Consequently, any environmental and exposure modeling associated with the impact assessment reflects continuous emissions such that equilibrium concentrations may be assumed. If the reporting year was less than one year for any inventory item, the analysis was adjusted as appropriate.

Table 2-1. LCI data categories

Data Category	Description
Material inputs (kg per functional unit)	
Primary materials	Actual materials that make up the final product for a particular process. These can be individual materials or a combination of materials that comprise a component part.
Ancillary (process) materials	Materials that are used in the processing of a product for a particular process. Process materials from monitor manufacturing could include, for example, etchants used during photolithography which are washed away and not part of the final product, but are necessary to manufacture the product.
Energy inputs (MJ per functional unit)	
Process energy	Energy consumed by any process in the life-cycle.
Precombustion energy	The energy expended to extract, process, refine, and deliver a usable fuel for combustion.
Transportation energy	Energy consumed in the transportation of the materials or products in the life cycle.
Natural resource inputs (kg per functional unit)	
Non-renewable resources	Materials extracted from the ground that are non-renewable, or stock, resources (e.g., coal).
Renewable resources (e.g., water)	Water or other renewable, or flow, resources (e.g., limestone) are included in the analysis. Renewable resource data values are presented in mass of water consumed for a particular process.
Emissions outputs (kg per functional unit)	
Air	Mass of a product or material that is considered a pollutant within each life-cycle stage. Air outputs represent actual gaseous or particulate releases to the environment from a point or diffuse source, after passing through emission control devices, if applicable.
Water	Mass of a product or material that is considered a pollutant within each life-cycle stage. Water outputs represent actual discharges to either surface or groundwater from point or diffuse sources, after passing through any water treatment devices.
Solid wastes	Mass of a product or material that is deposited in a landfill or deep well. Represents actual disposal of either solids or liquids that are deposited either before or after treatment (e.g., incineration, composting), recovery, or recycling processes.
Products (kg of material or number of components per functional unit)	
Primary products	Material or component outputs from a process that are received as input by a subsequent unit process within the display life cycle.
Co-products	Material outputs from a process that can be used, either with or without further processing, that are not used as part of the final functional unit product.

Data were also collected on the final disposition of emissions outputs, such as whether outputs are recycled, treated, and/or disposed. This information helps determine what impacts will be calculated for a particular inventory item. Methods for calculating impacts are discussed in Chapter 3, Life-Cycle Impact Assessment. The dispositions used for this project are as follows:

- air,
- surface water,
- landfill,
- land (other than landfill),
- treatment,
- recycling/reuse, and
- deep well injection.

Given the enormous amount of data involved in inventorying all of the inputs and outputs for a product system, life-cycle assessment (LCA) practitioners typically employ decision rules to make the data collection manageable and representative of the product system and its impacts. Section 2.1.2 discusses the decision rules used in the CDP LCI.

2.1.2 Decision Rules

In an LCA, the materials extraction and materials processing life-cycle stages (referred to as "upstream" life-cycle stages) include processes for extracting raw materials from the earth and processing those raw materials into the materials used in the manufacture of the product of interest. Examples of upstream processes include the mining of iron ore and its processing with other materials into steel sheet or the extraction of petroleum from underground reserves and its conversion into plastic pellets. A continuing challenge for LCA practitioners is to collect all the appropriate data for a product system, including data for these upstream processes as well as data for product manufacturing, use, and disposal processes. In this project, decision rules as to what inventories should be included as upstream processes in the overall modeled life-cycle are based on the materials used to manufacture the computer monitors. Also, which component parts to include in the model depends on these decision rules. In considering upstream materials, a combination of several factors, including availability of existing data were considered. For considering which component manufacturing processes to include, the decision rules, plus manufacturers willingness to participate, factored into our overall scope of what was included in the analysis.

To help determine which upstream processes to include in the CDP LCI, first the bill of materials (BOM) of the component parts and the materials that make up those parts (Tables 1-3 and 1-4) was reviewed. The quantities of those materials identified by MCC can be found in Industry Profile Document (MCC, 1998). Using the MCC BOM allowed work to begin on selecting and collecting upstream data before the actual BOM from the manufacturing stage was obtained from the project's primary data collection effort. Final decisions on which upstream processes to include were based on the BOM developed from data collected from manufacturers. Tables 2-2 and 2-3 list the BOMs of the primary material inputs from the manufacturing of the CRT and LCD, respectively. The mass quantities given in the tables are the primary material

inputs to the manufacturing process and would be equivalent to the amount of material in the final product plus excess or waste materials. While this is not exactly equivalent to the mass of each material that makes up a finished product, it does represent the mass of primary materials used to manufacture the finished product at participating facilities. Details of how these data were obtained are presented in Section 2.3, which describes the manufacturing stage inventory.

Table 2-2. Bill of primary material inputs for a 17" CRT monitor

Material/Component	Sub-component	Mass (kg) [a]		weight % of total inputs [a]	
Lead oxide glass		9.76		46.1%	
	Lead		0.45		2.1%
Steel		5.16		24.4%	
Plastics		3.04		14.4%	
	Polycarbonate (PC)		0.92		4.36%
	Styrene-butadiene co-polymer		0.83		3.91%
	Polyethylene ether (PEE)		0.74		3.47%
	Acrylonitrile-butadiene-styrene (ABS)		0.32		1.52%
	High-impact polystyrene (HIPS)		0.15		0.71%
	Triphenyl phosphate		0.05		0.25%
	Tricresyl phosphate		0.02		0.11%
	Phosphate ester		0.01		0.04%
Printed wiring boards (PWB) and components		0.85		4.00%	
Cables/wires		0.45		2.13%	
Aluminum (heat sink)		0.27		1.29%	
Nickel alloy (invar)		0.27		1.29%	
CRT shield assembly		0.24		1.14%	
Ferrite		0.17		0.80%	
Deflection yoke assembly		0.15		0.71%	
Demagnetic coil		0.13		0.60%	
Video cable assembly		0.11		0.54%	
Power cord assembly		0.11		0.54%	
Electron gun		0.10		0.47%	
CRT magnet assembly		0.08		0.36%	
Audio cable assembly		0.07		0.34%	
Frit		0.07		0.32%	
Solder		0.03		0.13%	
Phosphors		0.02		0.08%	
Aquadag		0.02		0.07%	
Other (misc.)		0.06		0.30%	
TOTAL		**21.16**		**100%**	

[a] Based on the primary material inputs to the manufacturing process, including material in the final product plus excess or waste materials.

Table 2-3. Bill of primary material inputs for a 15" LCD monitor

Material/Component		Mass (kg) [a]		weight % of total inputs [a]	
	Subcomponent				
Steel		2.53		44.12%	
Plastics		1.78		30.98%	
	Polycarbonate (PC)		0.52		9.00%
	Poly(methyl methacrylate) (PMMA)		0.45		7.80%
	Styrene-butadiene copolymer		0.36		6.31%
	Polyethylene ether (PEE)		0.30		5.23%
	Triphenyl phosphate		0.09		1.61%
	Polyethylene terephthalate (PET)		0.06		1.03%
Glass		0.59		10.31%	
Printed wiring boards (PWB) and components		0.37		6.52%	
Cables/wires		0.23		4.08%	
Aluminum (heat sink, transistor)		0.13		2.34%	
Solder (60% tin, 40% lead)		0.04		0.66%	
Color filter pigment		0.04		0.65%	
Polyvinyl alcohol (PVA) (for polarizer)		0.01		0.15%	
Liquid crystals, for 15" LCD, unspecified [b]		0.0023		0.04%	
Backlight lamp (cold cathode fluorescent lamp, CCFL)		0.0019		0.03%	
	Mercury		3.99E-06		0.0001%
Transistor metals, other (e.g., Mo, Ti, MoW)		0.0019		0.03%	
Indium tin oxide (ITO) (electrode)		0.0005		0.01%	
Polyimide alignment layer		0.0005		0.01%	
Other (e.g., adhesives, spacers, misc.)		0.0031		0.05%	
TOTAL		5.73		100%	

[a] Based on the primary material inputs to the manufacturing process, including material in the final product plus excess or waste materials.

[b] This does not include all liquid crystals, as those specified as individual chemicals are in very small amounts and included in the "other" category.

The decision rule process begins by assessing the materials and components in Tables 2-2 and 2-3 for the following attributes:

1. *The mass (M) contribution of each component and material in the display.* The mass is important in order to account for the majority of materials and components that make up a display, but also because the more significant the material or component by mass, the more materials and resources may be required to manufacture the material or component and thus it may have a significant environmental impact.

2. *Materials that are of known or suspected environmental (Env) significance (e.g., toxic).* As this is an environmental life-cycle assessment, consideration of materials or components that are known to or are suspected to exhibit an environmental hazard are also included to the extent feasible.

3. *Materials that are known or suspected to have a large energy (E) contribution to the systems energy requirements.* Energy impacts are of great interest to the use and manufacture of display monitors and, therefore, priorities were given to including materials or components that are known to or suspected to consume large amounts of energy.

4. *Materials or components that are functionally (F) significant to the display.* "Functionally significant" is defined as important to the technically successful operation of the display. For example, the liquid crystals in an AMLCD would be "functionally significant" while screws, gaskets, or the plastic cover would not be.

5. *Materials or components that are physically (P) unique in the CRT as compared to the LCD and vice versa.* The physical uniqueness of a material or component could be identified by chemical makeup or by size. An example of the latter would be if the plastic casing for the CRT and LCDs were made of the same material, but the CRT casing had substantially more material by weight.

The priority scheme depicted in Figure 2-4 provides guidelines for applying the CDP decision rules. Material or component inputs that account for more than five percent of the total mass of a display technology were given top priority for data collection, as were those of known or suspected environmental or energy significance and those that are functionally significant or physically unique. Of less emphasis in trying to obtain data, but still included if possible, were materials or components that are functionally significant but physically similar to those in the other technologies, and those that were between 1 and 5% of the total mass of the display. Recognizing the limitations of project resources, materials or components that account for less than one percent of total mass or are not otherwise significant or unique were excluded *a priori.*

Based on this hierarchy and on review of the preliminary BOMs, Tables 2-4 and 2-5 present how components were rated based on the priority scheme, and which ones were included in the analysis. If a material or component was included in the analysis as a separate process, it is listed in the last column of Tables 2-4 and 2-5 by what life-cycle stage that process is in (i.e., upstream or manufacturing process). If a material or component was only included as part of another process, and not as a separate process in the profile, the process in which that material or component is found is provided in the last column.

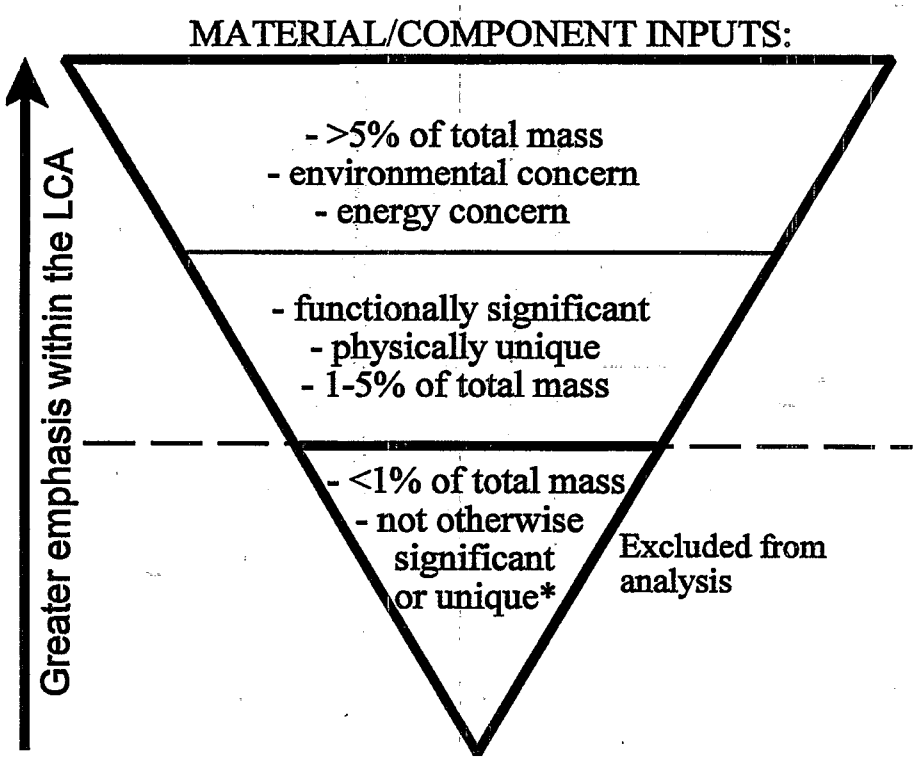

Figure 2-4. Decision rule guidelines

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

Table 2-4. Decision rule priorities and scope of analysis for the primary material inputs of the 17" CRT monitor

Material/Component		Decision rule	Included in analysis as:
	Sub-component		
Lead oxide glass		M, F, P, E, Env	manufacturing process
	Lead	P, Env	upstream process
Steel		M	upstream process
Plastics		---	-----
	Polycarbonate (PC)	M	upstream process
	Styrene-butadiene co-polymer	M	upstream process
	Polyethylene ether (PEE)	M	part of monitor assy. process
	Acrylonitrile-butadiene-styrene (ABS)	M	upstream process
	High-impact polystyrene (HIPS)	none	upstream process
	Triphenyl phosphate	none	part of monitor assy. process
	Tricresyl phosphate	P	part of monitor assy. process
	Phosphate ester	P	part of monitor assy. process
Printed wiring boards (PWB) and components		M, E, Env	manufacturing process
Cables/wires		none	part of monitor assy. process
Aluminum (heat sink)		M (<5%), E	upstream process
Nickel alloy (invar)		M (<5%), P	upstream process
CRT shield assembly		none	part of monitor assy. process
Ferrite		P	upstream process
Deflection yoke assembly		F, P	part of monitor assy. process
Demagnetic coil		F, P	part of monitor assy. process
Video cable assembly		none	part of monitor assy. process
Power cord assembly		none	part of monitor assy. process
Electron gun		F, P	part of tube mfg. process
CRT magnet assembly		P	part of monitor assy. process
Audio cable assembly		none	part of monitor assy. process
Frit		F, P, E, Env	manufacturing process
Solder		Env	part of monitor assy. process
Phosphors		F, P	part of tube mfg. process
Aquadag		F, P	part of tube mfg. process
Other (misc.)			miscellaneous

M = mass is greater than 1% of the total display weight; **Env** = environmental/toxic concern; **E** = energy concern; **F** = functional (technological) importance; **P** = physically unique.
Note: The CRT processes included in the CDP LCA were presented in Figures 1-6 and 2-2.

Table 2-5. Decision rule priorities and scope of analysis for the primary material inputs of the 15" LCD monitor

Material/Component		Decision rule	Included in analysis as:
	Sub-component		
Steel		M	upstream process
Plastics		---	-----
	Polycarbonate (PC)	M	upstream process
	Poly(methyl methacrylate) (PMMA)	M, P	upstream process
	Styrene-butadiene co-polymer	M	upstream process
	Polyethylene ether (PEE)	M	part of monitor assy. process
	Triphenyl phosphate	M (<5%)	part of monitor assy. process
	Polyethylene terephthalate (PET)	M (<5%), P	upstream process
Glass		M	manufacturing process
Printed wiring boards (PWB) and components		M, E, Env	manufacturing process
Cables/wires			part of monitor assy. process
Aluminum (heat sink, transistor)		M (<5%), E	upstream process
Solder (60% tin, 40% lead)		Env	part of monitor assy. & module mfg. processes
Color filter pigment		P	part of color filter patterning
Polyvinyl alcohol (PVA) (for polarizer)		none	part of polarizer mfg. process
Liquid crystals, for 15" LCD		F, P, Env	manufacturing process
Backlight lamp (cold cathode fluorescent lamp)		F, P, Env	manufacturing process
	Mercury	Env	part of backlight lamp process
Transistor metals, other (e.g., Mo, Ti, MoW)		F, P	part of module mfg. process
Indium tin oxide (ITO) (electrode)		F, P	part of module mfg. process
Polyimide alignment layer		F, P	part of module mfg. process
Other (e.g., adhesives, spacers, misc.)			miscellaneous

M = mass is greater than 1% of the total display weight; **Env** = environmental/toxic concern; **E** = energy concern; **F** = functional (technological) importance; **P** = physically unique.
Note: The LCD processes included in the CDP LCA were presented in Figures 1-7 and 2-3.

2.1.3 Data Collection and Data Sources

Data were collected from both primary and secondary sources. Primary data are directly accessible, plant-specific, measured, modeled, or estimated data generated for the particular project at hand. Secondary data are from literature sources or other LCAs, but are specific to either a product, material, or process used in the manufacture of the product of interest.

Table 2-6 lists the types of data (primary or secondary) used for each life-cycle stage in the CDP LCI. In general, greater emphasis was placed on collecting data and/or developing models for product manufacturing, use, and end-of-life. Primary data were collected from product and component manufacturers (in the U.S., Japan, and Korea), and CRT recyclers who voluntarily agreed to participate in the project. When proprietary data were involved, the University of Tennessee (UT) Center for Clean Products and Clean Technologies entered into

confidentiality agreements with the affected company. In addition, to both protect confidentiality and better represent the various manufacturing processes, data for particular processes that were collected from more than one company, where possible, and aggregated. Attempts were made to get at least two companies to contribute data for each particular process in the manufacturing life-cycle stage, which resulted in some process datasets being the aggregate of multiple (2-7) companies data. However, this was not feasible in every case and some datasets were simply the data of one company. Details of the data aggregation methods are provided in Section 2.3.

Data for the use stage were modeled specifically for this project by UT researchers, but were based on secondary data (i.e., secondary data were built upon to create the data used in the inventory for the use life-cycle stage). Data associated with the electricity generation were also based on secondary data, but modeled for this project. Transportation information (e.g., transportation mode and distances) were collected from the manufacturers that provided primary data. These data were linked to secondary data inventories of fuel inputs and emissions outputs for various types of transport vessels. Transportation data cover movement of materials and components both into and out of a facility, but do not include transportation of packaging or distribution of the finished display to the consumer. Finally, secondary data were used for upstream processes. More details on each of these data collection efforts are provided in subsequent sections of this chapter.

Table 2-6. Data types by life-cycle stage

Life-cycle stage	Data types
Upstream (materials extraction and processing)	Secondary data.
Product and component manufacturing	Primary data, except secondary data used for frit.
Use	Modeled using secondary data; maintenance and repair are not included in the analysis.
Final disposition (recycling and/or disposal)	Modeled using secondary data plus primary data from CRT recycling facilities.
Packaging, transportation, distribution	Primary data from product and component manufacturers for transport mode and distance; secondary data for fuel inputs and emissions outputs for the transport vessel. Packaging and distribution not included.

In some instances, neither primary nor secondary data were available. For example, CRTs are a much more mature technology than the LCD, and end-of-life (EOL) data are much less prevalent for the LCD than for the CRT. Where primary and secondary data are lacking, various assumptions and modeling serve as defaults.

2.1.4 Allocation Procedures

An allocation procedure is required when a process within a system shares a common management structure, or where multiple products or co-products are produced. In the CDP LCI allocation procedures are used when processes or services associated with the functional unit (e.g., a desktop computer display over its lifetime) are used in more than one product line at the

same facility (e.g., notebook computers, televisions). For example, transistors are used in LCD desktop computer displays, but also in other LCD technologies, such as notebook computer displays. If a facility uses a single process to manufacture transistors for both desktop and notebook computer display, inputs and outputs are allocated among the product lines to avoid over-estimating the environmental burdens associated with the product under evaluation.

The International Standards Organization (ISO, 1996) recommends that wherever possible, allocation should be avoided or minimized. This may be achieved by sub-dividing the unit process into two or more sub-processes, some of which can be excluded from the system under study. In the example above, if a manufacturer of transistors supplied only desktop computer LCD manufacturers, no allocation would be necessary from that manufacturer. However, it is more likely that the transistor manufacturer would have a larger customer base, including manufacturers of various products other than liquid crystal desktop computer displays. This requires allocation of flows from the manufacturing of transistors for several products to those associated only with desktop computer displays. As suggested by ISO, if sub-processes within the transistor facility can be identified that distinguish between transistors manufactured for LCDs and for other products, the latter sub-processes can be eliminated from the analysis, thus reducing allocation procedures.

In this study allocation procedures are used as follows:

- *Inventory data for utilities and services common to several processes are allocated to reflect the relative use of the service.* For example, fuel inputs and emission outputs from electric utility generation are allocated to a display or display component according to the actual or estimated electricity consumed during the manufacture, use, or final disposition of the product. Similarly, fuel inputs and emission outputs from commercial transport of a display component to a display assembler are allocated to the display component according to the mass of the component, the distance traveled, and the fraction of the transport vehicle's capacity occupied by the number of components shipped.
- *Where a unit process produces co-products, the burdens associated with the unit process are allocated to the co-product on a mass basis.* In the transistor example above, burdens are allocated according to the total mass of transistors used in desktop displays and the mass used in notebook computers. Total mass can be calculated from sales records which document the number of transistors delivered to different customers and measured mass of a set number of transistors.

Allocation is also necessary when a single process produces both energy and products. In this case, the inputs are partitioned among the energy and products, as appropriate, to avoid allocating inapplicable chemical burdens to energy production. However, this scenario was not encountered in the CDP LCI.

2.1.5 Data Management and Analysis Software

The data that were collected for this study were either obtained from questionnaires developed for this project, from existing databases, or from primary or secondary data collected by the UT Center for Clean Products and Clean Technologies. All these data were transferred to spreadsheets, which were then imported into a Life-Cycle Design Software Tool developed by

the Center for Clean Products and Clean Technologies with funding from the EPA Office of Research and Development and Saturn Corporation. The software tool was developed to store and organize life-cycle inventory data and to calculate life-cycle impacts for a product profile. Written using Microsoft FoxPro programming software, the tool is designed to allow flexibility in conducting life-cycle design and life-cycle assessment functions. It provides the means to organize inventory data, investigate alternative scenarios, evaluate impacts, and assess data quality.

The UT Life-Cycle Design Software Tool organizes data in such a way that each process inventory is independent. Customized "profiles" (e.g., the manufacture of a CRT or the whole life-cycle of an LCD) can be developed by linking processes together. The tool has the flexibility to modify or replace any particular process within a profile to evaluate potential alternatives. The data provided in this study may serve as a baseline to compare alternatives or modifications to particular processes. The models developed for the life-cycles of the CRT and LCD in this study can remain useful as many of the individual processes in the CRT and LCD life-cycles will likely remain constant (e.g., steel manufacturing, plastics manufacturing). Changes to specific processes can be made to conduct analyses of current or emerging process or technology changes. Relatively quick life-cycle analyses can be conducted on future product or process improvements, given the baseline data already available through this study.

2.1.6 Data Quality

LCI data quality can be evaluated based on the following data quality indicators (DQIs): (1) the source type (i.e., primary or secondary data sources); (2) the method in which the data were obtained (i.e., measured, calculated, estimated); and (3) the time period for which the data are representative. LCI DQIs are discussed further in *Life-Cycle Assessment Data Quality: A Conceptual Framework* (SETAC, 1994). CDP data quality for each life-cycle stage is discussed in detail in Sections 2.3 through 2.6 and summarized below.

For the primary data collected in this project, participating companies reported the method in which the data were obtained and the time period for which the data are representative. Data from the 1997-2000 time period were sought, with the most recent data preferred. Similarly, the time period of secondary data and method in which the data were originally obtained was also recorded, where available. Secondary data cover a broader time period, with data for most materials from the 1997 to 1998 time period, and data for most fuels from the 1983 to 1993 time period.

Anomalies and missing data are common hurdles in any data collecting exercise. Anomalies are extreme values within a given data set. Any anomaly identified during the course of this project that is germane to project results was highlighted for the project team and investigated to determine its source (e.g., mis-reported values). If the anomaly could be traced to an event inherently related to the process, it was left in the data set. If, however, the anomaly could not be accounted for, it was removed from the data set. Specific anomalies highlighted by the project team are discussed in Section 2.7, Summary of Life-Cycle Inventory Results.

We attempted to account for missing data by replacing it hierarchically. That is, if specific primary data were missing, secondary data were used. Where neither primary nor secondary data were available, such as data on the percent of LCD desktop displays recycled or remanufactured, assumptions were made and a sensitivity analysis was performed. In the cases

where no data were found or reasonable assumptions could not be made, these deficiencies are reported.

Any proprietary information required for the assessment was subject to confidentiality agreements between the Center for Clean Products and Clean Technologies and the participating company. Proprietary data are presented as aggregated data to avoid revealing the source. Further, any averaged process data obtained from fewer than three companies are also aggregated to avoid revealing individual inventory items from individual companies.

2.1.7 Critical Review

Critical review is a technique to verify whether an LCA has met the requirements of the study for methodology, data, and reporting, as defined in the goal definition and scoping phase. A critical review process was maintained in the CDP LCA to help ensure that the following criteria were met:

- the methods used to carry out assessments are consistent with the EPA, SETAC, and ISO assessment guidelines;
- the methods used to carry out assessments are scientifically and technically valid within the LCA framework;
- the data used are appropriate and reasonable in relation to the goals of the study;
- the interpretations reflect the limitations identified and the goals of the study; and
- the study results are transparent and consistent.

A project Core Group and Technical Work Group, both consisting of representatives from industry, academia, and government, and EPA's DfE Work Group provided critical reviews of the assessment. Members of these groups are listed in Appendix C, Critical Review. The Core Group served as the project steering committee and was responsible for approving all major scoping assumptions and decisions. The Technical Work Group and the DfE Work Group provided technical guidance and reviews of all major project deliverables including the final LCA report.

In addition to the critical review process, primary data collected were double-checked with the original source to ensure that their data are presented accurately. Additional details on the data verification process for primary data are presented in Sections 2.3 and 2.5.

2.2 MATERIALS EXTRACTION AND MATERIALS PROCESSING (UPSTREAM LIFE-CYCLE STAGES)

2.2.1 Methodology

The inventories included in the materials extraction and materials processing (upstream) life-cycle stages are those of the major primary materials found in the CRT or LCD monitor, as well as major ancillary materials required to manufacture the monitors. Inventories for electricity generation and fuels, which may be used in several life-cycle stages (e.g., to manufacture the products or to use the products), are also presented.

The inventories for extraction and processing of major materials were obtained from existing LCI databases. Electricity generation inventories were developed for this project from secondary sources that describe the distribution of fuels for different electric grids and the fuel inputs and emission outputs associated with different fuel types. The methodologies for developing these inventories are summarized below.

2.2.1.1 Upstream materials processes

Materials for which upstream processes were included in the CRT and LCD life-cycles were selected based on the decision rules described in Section 2.1.2, as well as the availability of secondary data for those materials. An attempt was made to include materials with a mass greater than or equal to one percent of the overall inputs to the product manufacture, or materials that may contribute to a large amount of energy use or have environmental concern. Tables 2-4 and 2-5 in Section 2.1.2 listed the decision criteria for primary materials/components that are included either as separate processes or as part of another process. The upstream materials processes for which inventory data were obtained for this project are presented in Table 2-7.

To determine which source or sources of secondary data to use, nine LCI databases were evaluated against 11 selection criteria in a technical memorandum presented to the project review teams (see Appendix D). Based on this analysis the project team chose the Environmental Information and Management Explorer (EIME) database and the Database for Environmental Analysis and Management (DEAM), two life-cycle inventory databases developed by the *Ecobilan* (Ecobalance) Group (*Ecobilan,* 1999). EIME was developed by *Ecobilan* specifically for electronics and the electronics industry and covers many of the materials specific to the CDP, while the DEAM database includes materials not covered by EIME. Combined, these databases contain detailed inventories of materials extraction and processing activities for most of the materials of interest in this project.

In the *Ecobilan* inventory for a particular material, the functional unit is a set mass of the material. Inputs and outputs are therefore given in terms of mass or other appropriate unit per unit mass of material. These data were imported into the UT Life-Cycle Design Software Tool discussed in Section 2.1.5, where they were linked to the mass of material used in the manufacture of a display monitor to develop inventories specific to the CDP. The associated amounts of each material were presented in Tables 2-2 and 2-3 in Section 2.1.2. How these materials are linked to other processes in the CRT and LCD profiles are shown in Figures 2-2 and 2-3 at the beginning of this chapter.

The materials inventories from *Ecobilan* also contain data for electricity generation, as appropriate, and in some cases, for transportation. Electricity generation and transportation data that were included in the *Ecobilan* inventories could not be separated from the inventory data for materials extraction and conversion processes. Therefore, when electricity generation and transport data were included in the *Ecobilan* inventories, the electricity and transport data collected specifically for this project were not used with the upstream process data.

Table 2-7. Materials having upstream processes included in the CDP LCA

Material	CRT	LCD
METALS		
aluminum	✓	✓
ferrite	✓	
lead	✓	
nickel alloy (invar)	✓	
steel	✓	✓
POLYMERS		
acrylonitrile-butadiene styrene (ABS)	✓	
high impact polystyrene (HIPS)	✓	
polycarbonate (PC)	✓	✓
polyethylene terphthalate (PET)		✓
poly(methyl methacrylate) (PMMA)		✓
styrene-butadiene co-polymer	✓	✓
ANCILLARY MATERIALS		
natural gas (used to represent LNG)		✓

2.2.1.2 Electric grids

Electricity is used in several processes throughout the life-cycle of the CRT and LCD monitors, and in some instances in large amounts. Therefore, the inventory for electricity generation is included in the scope of this project.

As described in Chapter 1, Section 1.4.2, the geographic boundaries of this project are worldwide for upstream and product manufacturing processes and limited to the United States for the use and end-of-life stages. In addition, most CRT and LCD manufacturing is done in Asia and most product manufacturing data collected in this study were from the United States or Japan, except for two LCD manufacturing data sets collected from Korean manufacturers. Therefore, the inventory associated with electricity generation during manufacturing was based on either the Japanese or U.S. electric grids, depending on the particular process or component being manufactured. Where data were obtained from more than one country for the same process, only one electric grid inventory could be used for a single process. In these cases, the Japanese electric grid was used since the majority of manufacturing data are from Japanese companies. The inventory for electricity generated during use and EOL processing was based on the U.S. electric grid.

The methodology and results for the electricity generation inventories are detailed in Appendix E, which presents the electric grid technical memorandum prepared for this project. The inventories were developed by first compiling U.S. inventory data for each of the major generation categories or fuel types, including electricity generated from coal, gas, petroleum, and nuclear fuels. These inventories were then combined with data on net electricity generation by fuel type in the U.S. and Japanese electric grids (Table 2-8) to develop the country-wide electric generation inventories. The inputs and outputs for the electricity generation inventories are presented in terms of mass or radioactivity per kWh of electricity generated. Inventories were not included for hydroelectric and renewable energy generation categories due to the scarcity of data on inputs and outputs for these categories. In addition, renewables account for only a small fraction of total U.S. electricity generation.

Table 2-8. Net electricity generation by fuel type

Fuel	Net electricity generation	
	United States (percent)	Japan (percent)
Coal	57	18
Gas	9	20
Petroleum	3	21
Nuclear	20	31
Hydro	11	9
Other	<1	1

Sources: U.S.: EIA, 1999a; Japan: EIA, 1997; FEPC, 1996.

Note that the Japanese grid inventory is based on the same fuel-specific inventories developed for the U.S. grid, but uses the average distribution of fuels for the Japanese grid (EIA, 1997, FEPC, 1996). This introduces some uncertainty into the Japanese electric grid since Japanese technologies, efficiencies, and pollution control techniques are likely to differ somewhat from their U.S. counterparts. However, the U.S. fuel-specific inventories were used to conserve project resources, rather than expending considerable effort on collecting inventory data from Japanese utilities.

The electricity generation inventories presented in Appendix E are shown as separate process inventories. However, in the overall analysis, they are linked to the manufacturing, use and EOL life-cycle stages, as appropriate. That is, where electricity is used in a process in any of those life-cycle stages, the inputs and outputs from generating the amount of electricity needed is allocated to that process. Note that the U.S. and Japanese electricity generation inventories developed for this project are not linked to the upstream life-cycle stages for materials used to manufacture CRT and LCD desktop computer displays. Electricity generation data were already included in the upstream material inventories received from *Ecobilan*.

2.2.1.3 Fuels

Several fuels are used in manufacturing and end-of-life processes during the life-cycle of the CRT and LCD monitors, and in some instances in large amounts.[1] Therefore, fuel production inventories are included in the scope of this project. These inventories are included in the life-cycle stage in which the fuels are actually consumed (e.g., product manufacturing or end-of-life) instead of in the upstream (materials processing) life-cycle stage. The following fuel inventories are included in both the CRT and LCD LCIs:

- natural gas (also used to represent LNG),
- liquified petroleum gas (LPG),
- fuel oil #2 (distillate),
- fuel oil #6 (residual), and
- fuel oil #4 (average of residual and distillate).

Fuel inventories were obtained from *Ecobilan*. In the *Ecobilan* inventories, the functional unit is a set mass of the material, with inputs and outputs given in terms of mass or other appropriate unit per mass of material (product) produced. These data were imported into the UT Life-Cycle Design software tool where they were linked to the mass of fuel used in different processes in the life-cycle of a display. How the fuel processes are linked to other processes in the CRT and LCD profiles was shown in Figures 2-2 and 2-3.

2.2.2 Data Sources and Data Quality

2.2.2.1 Upstream material and fuel processes

Table 2-9 summarizes data source and data quality information for the data received from *Ecobilan*, which are all secondary data for the purposes of the CDP. In addition to information about CDP data quality indicators (e.g., original source of data, year of data, method in which data were obtained, and geographic boundaries), the table lists whether or not electricity generation or transport data were included in the inventories. This information is important because: (1) electricity generation and transportation data are not from the same sources and therefore are not necessarily consistent among data sets; and (2) transportation data are not included in several of the upstream processes, and are thus a data gap for those processes.

As revealed in Table 2-9, the *Ecobilan* data were derived from various sources, including European data sources and U.S. data sources. In addition, the temporal boundaries of the data vary, with some data being as recent as 1998 but others being from as early as 1975. Electricity generation data are included in all of the inventories, but transportation data are only included in six of 16 data sets. All of these factors create some inconsistencies among the data sets and reduce the data quality when used for the purposes of the CDP. However, this is a common difficulty with LCA, which often uses data from secondary sources for upstream processes to avoid the tremendous amount of time and resources required to collect all the needed data.

[1] Fuels are also used in the materials processing life-cycle stage, but fuel production processes should already be accounted for in the materials inventories obtained from *Ecobilan*.

Table 2-9. Data sources and data quality for the *Ecobilan* inventories [a]

Material	Electricity generation included?	Transport included?	Year of data	Original source [b]
METALS				
aluminum	Y	--	--	ETH
ferrite	Y	--	--	not provided
lead	Y	--	Unknown	ETH
nickel-alloy (invar) [c]	Y	Y (nickel)	1991 (nickel)	ETH
steel	Y	--	1975-1990 [d]	FOEFL, others [d]
POLYMERS				
acrylonitrile-butadiene styrene (ABS)	Y	Y [e]	1997	Boustead
high impact polystyrene (HIPS)	Y	Y [e]	1997	Boustead
polycarbonate (PC)	Y	Y [e]	1997	Boustead
polyethylene terphthalate (PET)	Y	Y [e]	1998	Boustead
poly(methyl methacrylate) (PMMA)	Y	Y [e]	1997	Boustead
styrene-butadiene co-polymer [f]	Y	Y [e]	1997	Boustead
FUELS				
natural gas	Y	Y	1987-98	six sources cited
liquified petroleum gas (LPG)	Y	Y	1983-93	seven sources cited
fuel oil #2	Y	Y	1983-93	seven sources cited
fuel oil #6	Y	Y	1983-93	seven sources cited
fuel oil #4 [g]	Y	Y	1983-93	seven sources cited

Y: yes, included in inventory.
-- : not included in inventory.

[a] In general, the *Ecobilan* inventories provide descriptions of data quality but often do not report how data were collected (e.g., measured, estimated, etc.). Therefore, information on the data collection method is not presented here.

[b] *Sources*: ETH (EidgenÖssische Technische Hochschule): Data from the ETH (Swiss Federal Institute of Technology) (*Ecobilan*, 1999). FOEFL (Swiss Federal Office of Environment, Forests and Landscape): Data from the Eco-inventory of Packaging published by the Swiss FOEFL; FOEFL is also known as BUWAL, the acronym in German (*Ecobilan*, 1999). Boustead: LCI database developed by Boustead Consulting (*Ecobilan*, 1999).

In general, the geographic boundaries for different sources are as follows: (1) ETH and FOEFL data are from Europe; (2) Boustead data are from Europe and/or the United States; and (3) miscellaneous sources may be European or U.S. data.

[c] The invar inventory is a combination of 36% of the nickel inventory and 64% of the ferrite inventory.

[d] The steel inventory was originally provided by *Ecobilan* without detailed documentation; however, DEAM data that were received later have inventories for several steel production processes. The sources listed here are for the DEAM data.

[e] Boustead addresses transportation; however, the extent to which it is included in a particular process inventory is uncertain.

[f] The styrene-butadiene process is the 50/50 average of the styrene and butadiene processes.

[g] The fuel oil #4 process is the 50/50 average of the fuel oil #2 and fuel oil #6 processes.

2.2.2.2 Electric grids

Several sources of data were consulted to generate the fuel-specific inventories that were used to create the overall electricity generation inventories. Table 2-10 summarizes the data sources and some of the data quality indicators for these inventories. Appendix E discusses the data sources and data quality in detail.

As shown in Table 2-10, the electricity generation data were obtained primarily from secondary sources and include data from the mid-1990s as well as data from an unknown time frame. Most are based on measured data collected by the original source, although some are estimated or the data collection method is unknown. Finally, most of the fuel-specific inventories are based on U.S. data, indicating these data are probably less representative and thus of lower quality when applied to the Japanese electric grid.

Table 2-10. Data sources and data quality indicators for the electric generation inventories

Type of data	Source	Year of publication	Data collection method	Geographic boundaries
Net electricity generation by fuel	U.S. Energy Information Administration (EIA)	1997	Measured	U.S. and Japan
Primary inputs (Fuel)	EIA	1997	Measured	U.S.
Ancillary inputs	EIA, California Energy Commission, utility contacts	Varies	Varies [a]	U.S.
Air emissions	Primarily AP-42 plus other sources [b]	Varies, but mostly AP-42 data from 1995	Varies [a]	U.S.
Water releases	Oak Ridge National Laboratory (ORNL) [c]	1994	Unknown	U.S.
Radioactive air and water releases	ORNL [d]	1995	Measured	U.S.
Solid wastes	ORNL [e]	1994	Unknown	U.S.

[a] Includes emission factors from measured and estimated data, plus data where data collection methods were not reported.
[b] AP-42 is the U.S. EPA's compilation of Air Pollutant Emissions Factors (EPA, 1996).
[c] Coal-fired water release data from ORNL report addressing the externalities of coal fuel cycles (ORNL, 1994).
[d] From ORNL report addressing the externalities of nuclear fuel cycles (ORNL, 1995).
[e] Coal-fired solid waste data from ORNL report addressing the externalities of coal fuel cycles (ORNL, 1994); radioactive solid waste data from ORNL report addressing the externalities of nuclear fuel cycles (ORNL, 1995).

2.2.3 Limitations And Uncertainties

The limitations and uncertainties associated with the upstream materials, fuels, and electricity generation inventories are primarily due to the fact that these inventories were derived from secondary sources and thus are not tailored to the specific goals and boundaries of the CDP. Because the data are based on a limited number of facilities and have different geographic and temporal boundaries, they are not necessarily representative of current industry practices or of industry practices in the geographic and temporal boundaries defined for the CDP (see

Section 1.4). These are common limitations and uncertainties of LCA, which strives to evaluate the life-cycle environmental impacts of entire product systems and is therefore limited by resource constraints which do not allow the collection of original, measured data for every unit process within a product life cycle. Despite these limitations and uncertainties inherent in LCA methodology itself, LCA remains useful and, indeed is increasingly used by industry, governments, and other stakeholders as part of a comprehensive decision-making process or to understand broad or general environmental trade-offs.

2.2.3.1 Upstream material and fuel processes

Because they are derived from secondary sources, the upstream materials and fuels inventories used in the CDP do not precisely meet the geographic and temporal boundaries outlined for the CDP. Some data are from Europe, some from the United States, and some a combination of both. The manufacturing data for this project were collected from companies in the United States, Japan, and Korea (see Section 2.3), and the available upstream data may not represent the exact location or type of processing represented in the upstream data inventories. This is a limitation to using secondary data; however, the upstream data are only one portion of the overall inventory of the product systems being evaluated, and the project partners chose to focus on collecting primary data for the product manufacturing life-cycle stage, since those data had not been previously compiled.

Another limitation of the upstream inventory data is the lack of transportation data for some processes. These data become particularly important when, for example, raw materials are uncommon and must be transported long distances for processing or when the particular transport mode used for a particular material tends to have high environmental impacts. However, the original data sources used in the *Ecobilan* inventories (see Table 2-9) are among the most used LCI databases in the world (*Ecobilan,* 1999), which suggests the lack of transportation data for upstream processes is not unique to the CDP LCI, but a common limitation of other LCIs as well.

2.2.3.2 Electricity generation data

The limitations to the electricity generation inventory data are provided in Appendix E, Section 6. As another limitation, the Japanese grid was chosen when manufacturing data were from more than one country. Appendix E also describes how the U.S. fuel-specific inventories are applied to the Japanese grid, although technologies, efficiencies, etc. used in Japan are likely to differ from those in the United States. Furthermore, U.S. fuel-specific inventories were derived from secondary sources which did not necessarily meet our temporal boundaries, but did meet geographic boundaries for the U.S. inventory.

2.3 PRODUCT MANUFACTURING

2.3.1 Methodology

2.3.1.1 Identification of processes and manufacturers

Through literature research and contacts with industry experts, the manufacturing processes and the component parts of a CRT and an LCD computer monitor were identified. The major manufacturing processes and components, in terms of resources used, and potential importance to environmental impacts, were selected for inclusion in our primary data collection effort.

Once the components and processes were chosen, companies who might supply manufacturing data for the project needed to be identified. In order to identify those manufacturers, the DfE project's Core and Technical Work Groups were consulted. These groups consist of parties interested in the project results and willing to provide technical assistance throughout the project, including identifying contacts in manufacturing facilities. Manufacturing of CRTs, LCDs, and their component parts is done all over the world. Some manufacturers are in the United States; however, most manufacturers of desktop computer monitors and their components are in Asia. Where available, U.S. industry partners provided contacts at U.S. as well as some Japanese manufacturing facilities and questionnaires were sent to those contacts.

To assist in the collection of data in Asia, UT subcontracted with the Asian Technology Information Program (ATIP) to identify company contacts, and to distribute and collect questionnaires from Asian manufacturers. ATIP acted as a liaison between UT and Japanese and Korean companies that participated in the study.

Participation in the study was completely voluntary. Companies were provided with the goals of the study and the potential benefits of their participation. Once a company chose to participate, they were sent data collection questionnaires to complete information about their manufacturing process and to provide their inventory of process inputs and outputs. A copy of the manufacturing data collection questionnaire that was developed for and used in this study is provided in Appendix F.

The manufacturing processes for which primary data were collected are listed below. In parenthesis are the number of individual data sets collected for each process:

CRT monitor:

- CRT monitor assembly (3)
- CRT (tube) manufacturing (3)
- CRT leaded glass manufacturing (3)

LCD monitor:

- LCD monitor assembly (2)
- LCD panel and module manufacturing (7)
- LCD glass manufacturing (1)[2]
- color filter patterning on front glass (1)
- liquid crystal manufacturing (2)
- polarizer manufacturing (1)
- backlight unit assembly (3)
- backlight light guide manufacturing (1)
- cold cathode fluorescent lamp (CCFL) manufacturing (1)

How these processes are linked to one another in the CRT and LCD life-cycles is presented in Figures 2-2 and 2-3, respectively. The companies that provided data for the foregoing processes are listed in Table 2-11.

Table 2-11. Companies that provided primary manufacturing data for the CRT and/or LCD

Company	Technology	Company	Technology
American Video Glass Company	CRT	Nippon Denyo Co., Ltd.	LCD
T. Chatani and Co., Ltd.	LCD	Nippon Electric Glass Co., Ltd.	CRT
Chisso Corporation	LCD	Polaroid Corporation	LCD
Eizo Nanao Corporation	CRT, LCD	Samsung Electronics	LCD
Harison Electric Co., Ltd.	LCD	Sharp Corporation	LCD
Hoshiden and Philips Display Corporation	LCD	Sony Corporation (Japan)	CRT
Hyundai Electronics Industries Co., Ltd.	LCD	Sony Electronics Inc. (U.S.)	CRT
Iiyama Electric Co., Ltd.	CRT, LCD	Stanley Electric Co., Ltd.	LCD
Matsushita Electric Industrial Co., Ltd.	LCD	Techneglas	CRT
Merck Japan Ltd.	LCD	Toppan Printing Co., Ltd.	LCD
Mitsubishi Electronic Co., Ltd.	LCD	Toshiba Display Technology Co., Ltd.	CRT, LCD

Another process that was included in the CRT manufacturing stage data was frit manufacturing. We were not able to obtain primary data for this process; therefore, secondary data were collected from EPA documentation and personal contacts (see Appendix G). An inventory for printed wiring boards (PWBs) was also developed and included in the manufacturing stage analysis. The PWB inventory is based on manufacturing of the electronic boards, and does not include the components on the PWBs. The PWB data were obtained from an industry representative who was able to provide general data not necessarily from one facility,

[2] LCD glass manufacturing data were derived from the three sets of CRT leaded glass manufacturing data (modified to remove lead from the inventory).

but from a combination of facilities, based on his experience (Sharp, 2000). More details about PWB data collection are provided in Appendix G.

The manufacture of some components were not included in the scope of this study because they were either deemed to be of less significance to the overall product inventories, or data could not be obtained. However, all components were included as part of the final assembled monitor even when individual manufacturing inventories were not. For the CRT, the manufacture of the electron gun, deflection yoke, and phosphors were not included as separate processes, and for the LCD, the transistor metals/materials, spacers, drivers/driver ICs, and color filters were not included.

2.3.1.2 Data collection questionnaires

Data collection questionnaires were developed by the UT research team and approved by the Technical Work Group to most efficiently collect inventory data needed for the LCA. Appendix F provides a copy of the questionnaire given to product and component manufacturers. The data that were collected include brief process descriptions; primary and ancillary material inputs; utility inputs (e.g., electricity, fuels, water); air, water and waste outputs; product outputs; and associated transportation. Quantities of inputs and outputs provided by companies were converted to mass per unit of product. Transport of materials to and products or wastes from the manufacturing facility were also reported. Details of the transportation analysis for this project are presented in Section 2.6.

A total of 27 product manufacturing questionnaires were collected for 11 different processes. The corresponding countries and the number of data sets from each country are listed in Table 2-12.

Table 2-12. Location of companies and number of process data sets

Process	Country of origin of data (# of data sets)
CRT monitor assembly	Japan (2), U.S. (1)
CRT (tube) manufacturing	Japan (2), U.S. (1)
CRT leaded glass manufacturing	Japan (1), U.S. (2)
CRT frit manufacturing	generic secondary data from the U.S.
LCD monitor assembly	Japan (2)
LCD panel and module manufacturing	Japan (5), Korea (2)
LCD - glass manufacturing	Japan and U.S. (1)*
LCD - color filter patterning on front glass	Japan (1)
LCD - liquid crystal manufacturing	Japan (2)
LCD - polarizer manufacturing	Japan (1)
LCD - backlight unit assembly	Japan (3)
LCD - backlight light guide manufacturing	Japan (1)
LCD - cold cathode fluorescent lamp (CCFL) manufacturing	Japan (1)
PWB manufacturing (for CRT and LCD monitors)	generic secondary data from the U.S.

* Average of three data sets for CRT leaded glass manufacturing modified to remove lead from the inventory.

2.3.1.3 Allocation

Data provided by manufacturers may need to be allocated to the products of interest (i.e., 17" CRT or 15" LCD) in three situations:

- data are provided for more than the defined functional unit;
- data are provided on a rate basis instead of per functional unit (product); and
- data are provided for monitors/components of more than one size (i.e., not only 17" CRTs or 15" LCDs).

In some cases, allocation was not required, as the inventory data collected were for one unit of the product, defined as the functional unit. The three cases where allocation was necessary are briefly described below.

In the first case, simple scaling was required when data were provided for all 17" CRT or 15" LCD monitors produced at a plant, as opposed to only one monitor. This simply requires dividing the inventory mass by the number of monitors produced.

In the second case, data were provided over a certain amount of time. The inventory data were then scaled to represent the functional unit. For example, if it was reported that x kilograms of a material are used *per year* to produce one 17" or 15" monitor, and y number of products are produced per year, then the amount of that material per functional unit is x/y.

In the third situation, allocation was also necessary for a company that manufactured more than just the product or component of interest for this study. For example, a monitor manufacturer may assemble various sized monitors, in addition to 15" LCDs or 17" CRTs. Therefore it was necessary to allocate the process inventory to only our product of interest. We used the difference in mass between the product of interest and other co-products and the difference in the number of each product produced to allocate the inventory to the functional unit.

2.3.1.4 Aggregating manufacturing data

After one set of data from one company is allocated to one monitor, processes for which we collected more than one company's data were averaged together. Once the inventory data for a process were averaged, the electricity consumption from that process was linked to the appropriate electric grid inventory (i.e., Japanese or U.S.). All the manufacturing processes were linked to the Japanese grid, with the exception of frit and PWB manufacturing, both of which were based on data collected in the United States. Where process data were represented by companies in more than one country, the countries in which the majority of facilities were located was used for the basis of which electric grid to use. An exception is the polarizer data, which was from the United States, but the manufacturing was only a pilot plant and not producing a product in the open market. Therefore, it was assumed that polarizer manufacturing, as with most other LCD components, was done in Japan. Once each manufacturing process inventory for each monitor type was complete (i.e., an averaged inventory with an associated electric grid), each was aggregated with the rest of the manufacturing stage processes to comprise the inventory for the manufacturing stage for a monitor. This manufacturing stage inventory was then combined with the other life-cycle stages to represent the full LCI for each monitor type.

2.3.2 Data Sources and Data Quality

While manufacturers worldwide were offered the opportunity to participate in this project, only manufacturing data from Japan, Korea, and the United States were collected. The quality of the data can be evaluated against two factors: (1) the date of the data; and (2) the type of data (i.e., measured, calculated or estimated). An understanding of how data were collected and data verification steps should also be considered when evaluating the data quality. The data collection phase of this project began in 1997 and extended through 2000. Some processes are more sensitive to production dates than others. Most processes included in this analysis are mature technologies and are not expected to differ significantly between the years 1997 and 2000. However, an exception is LCD panel manufacturing, which is an evolving and rapidly advancing process and has seen changes between these years. The countries and dates from which data for each process were obtained are presented in Table 2-13. For the LCD panel and module manufacturing process, most data were from 1998 and 1999.

In the data collection questionnaires, companies identified whether the quantity of each inventory item was a measured, calculated, or estimated value. These identifiers were referred to as the "data quality indicator" (DQI) in the manufacturing questionnaire. The breakdown of DQIs for the inventory items in the CRT and LCD processes are presented in Tables 2-14 and 2-15, respectively. The last line in each table shows overall averages weighted by the number of inventory items in each data set. For the CRT, 43% of the data were measured, 34% calculated, 13% estimated, and 10% were not classified. For the LCD, a similar distribution shows 33% measured, 30% calculated, 23% estimated, and 14% not classified.

Table 2-13. Applicable years of primary data sets

Process	# of data sets	Dates of inventory for each data set
CRT monitor assembly	3	1997, 1998-9, 1999
CRT (tube) manufacturing	3	1997, 1998, 1998
CRT leaded glass manufacturing	3	1998, 2000, 2000
LCD monitor assembly	2	1998, 1999
LCD panel and module manufacturing	7	1997-8, 1998, 1998, 1998-9, 1999, 1999, 1999-2000
LCD - color filter patterning on front glass	1	1998
LCD - glass manufacturing*	1	1998-2000
LCD - liquid crystal manufacturing	2	1998, 1998
LCD - polarizer manufacturing	1	1997
LCD - backlight unit assembly	3	1998, 1999, 1999
LCD - backlight light guide manufacturing	1	1999
LCD - cold cathode fluorescent lamp (CCFL) manufacturing	1	1998-9

* Primary data, but developed from the CRT glass manufacturing data.

Data quality can also be reviewed in terms of data collection methods. Much effort was given to collecting primary data from manufacturers in this study. Questionnaires were sent out and follow-up communication was conducted to verify data gaps or discrepancies. Twelve companies were visited directly to clarify data and telephone or electronic communication followed-up those and the remaining companies that were providing data for the study. Where data could not be confirmed, additional literature research and discussions with other industry experts were conducted.

Table 2-14. Data quality indicator percentages for the CRT processes

Process	% of inventory items that are:			
	Measured	Calculated	Estimated	Not reported
CRT monitor assembly				
Data set 1 (22 inventory items)	9%	64%	27%	0%
Data set 2 (11 inventory items)	9%	83%	0%	9%
Data set 3 (33 inventory items)	3%	0%	0%	97%
total inventory items = 66	wt. avg = 6%	wt. avg = 35%	wt. avg = 9%	wt. avg = 50%
CRT (tube) manufacturing				
Data set 1 (69 inventory items)	91%	1%	4%	3%
Data set 2 (51 inventory items)	45%	55%	0%	0%
Data set 3 (83 inventory items)	21%	78%	1%	0%
total inventory items = 203	wt. avg = 51%	wt. avg = 46%	wt. avg = 2%	wt. avg = 1%
CRT leaded glass manufacturing				
Data set 1 (43 inventory items)	9%	3%	86%	2%
Data set 2 (45 inventory items)	91%	7%	0%	2%
Data set 3 (2 inventory items)	100%	0%	0%	0%
total inventory items = 90	wt. avg = 52%	wt. avg = 5%	wt. avg = 41%	wt. avg = 2%
Overall weighted average for CRT (359 items)	**43%**	**34%**	**13%**	**10%**

Table 2-15. Data quality indicator percentages for the LCD processes

Process	% of inventory items that are:			
	Measured	Calculated	Estimated	Not reported
LCD monitor assembly				
Data set 1 (36 inventory items)	5%	78%	17%	0%
Data set 2 (10 inventory items)	10%	80%	10%	0%
total inventory items = 46	wt. avg = 6%	wt. avg = 78%	wt. avg = 16%	wt. avg = 0%
LCD panel and module manufacturing				
Data set 1 (71 inventory items)	80%	17%	0%	3%
Data set 2 (39 inventory items)	0%	100%	0%	0%
Data set 3 (45 inventory items)	40%	32%	17%	11%
Data set 4 (139 inventory items)	55%	38%	0%	7%
Data set 5 (53 inventory items)	43%	0%	36%	21%
Data set 6 (86 inventory items)	0%	0%	24%	76%
Data set 7 (32 inventory items)	0%	0%	97%	3%
total inventory items = 465	wt. avg = 37%	wt. avg = 26%	wt. avg = 17%	wt. avg = 20%
LCD - glass manufacturing* (83 inventory items)	0%	0%	100%	0%
LCD - color filter patterning on front glass (29 inventory items)	97%	0%	3%	0%
LCD - liquid crystal manufacturing				
Data set 1 (41 inventory items)	22%	64%	7%	7%
Data set 2 (6 inventory items)	0%	0%	0%	100%
total inventory items = 47	wt. avg = 19%	wt. avg = 56%	wt. avg = 6%	wt. avg = 19%
LCD - polarizer manufacturing (30 inventory items)	57%	17%	20%	6%
LCD - backlight unit assembly				
Data set 1 (20 inventory items)	0%	90%	0%	10%
Data set 2 (12 inventory items)	50%	0%	8%	42%
Data set 3 (12 inventory items)	0%	92%	8%	0%
total inventory items = 44	wt. avg = 14%	wt. avg = 66%	wt. avg = 4%	wt. avg = 16%
LCD - backlight light guide manufacturing (5 inventory items)	40%	40%	20%	0%
LCD - cold cathode fluorescent lamp (CCFL) manufacturing (36 inventory items)	58%	39%	0%	3%
Overall average for LCD (785 items)	**33%**	**30%**	**23%**	**14%**

* Data based on CRT leaded glass manufacturing data.

2.3.3 Limitations and Uncertainties

The limitations and uncertainties associated with the manufacturing stage are related to the following categories:

- the product system boundaries (scope),
- the data collection process, and
- the data.

Specific limitations/uncertainties for each of these categories are briefly described below.

2.3.3.1 Product system boundary uncertainties

The scope of the analysis included the major monitor components; however, it excluded certain components, such as column and row driver ICs for the LCD and the electron gun for the CRT. The components that were thought to possibly have an effect on the inventory were the column and row drivers, as IC manufacturing is known to be energy intensive and use various process chemicals. Based on some back-of-the-envelope calculations, the exclusion of the manufacturing of the column and row driver ICs is not expected to have a large impact on the inventory or impact results due to the small size of the drivers. Therefore, it is assumed that the exclusion of the column and row drivers will not have a significant impact on the study results.

The scope of the analysis in this study was also dependent on whether companies were willing to provide data. LCD glass manufacturing data from a primary source are not included in the inventory because no companies were willing to supply the data. For example, one manufacturer chose not to provide data because LCD glass manufacturing technology is still developing and is expected to improve from current low yields and high waste generation. However, because glass is an important component by weight of the LCD, we chose to modify the CRT glass manufacturing data to represent LCD glass manufacturing.

Both CRT and LCD glass are considered to be "specialty glasses" in the glass industry and a limited number of companies produce these products. Consequently, there are limited public data available on the production of these glasses. (One major difference between the CRT glass and the LCD glass is that CRT glass contains lead oxide while LCD glass does not.) Therefore, the primary data collected for this study for CRT glass manufacturing was modified by removing inputs and outputs containing lead, and used to represent LCD glass manufacturing. The remaining inputs and outputs were assumed to be the same per kilogram of glass produced. Further research was conducted to confirm whether this was a valid assumption for the energy used in production. Consultation with experts in the field revealed differing estimates between energy used to produce a kilogram of CRT glass and a kilogram of LCD glass. Estimates ranged from an equal amount of energy per kilogram for CRT and LCD glass production, to twice as much energy per kilogram of LCD glass compared to CRT glass. With an assumption of equal or greater energy use for the LCD (call that quantity of energy X), the proportion of that energy (X) that is electrical energy and fuel energy was assumed to be the same as that given in the primary data for CRT glass production (if the portion of energy X for the CRT was 30% electrical and 70% fuel energy, those same proportions were used for the LCD's breakdown of energy X).

Uncertainty in the differences between energy used for CRT versus LCD glass production are related to production yield and melting point. The melting point of LCD glass is greater than that of CRT glass; however, the difference in the production yield is uncertain compared to the difference in melting point. The production yield for CRT and LCD depends on whether one considers the surface area or the volume of the glass. LCD glass is a flat glass product and excess glass is cut off the ends to obtain the final product. CRT glass manufacturing drops molten glass into a mold and glass is not cut off of a flat piece of glass as in LCD production, but excess glass may be produced during the molding process. Another factor in the difference in energy used for CRT and LCD glass is that the LCD glass must meet high specification standards for use as a substrate for the transistors to be patterned on the glass. Additional finishing steps are required and the process is conducted in clean rooms (described in Section 1.3.3.2, LCD manufacturing). The assumption that the same amount of energy is used for CRT glass and LCD glass production takes into account each of these factors. The baseline analysis in this study assumes the energy use per kilogram of LCD glass is equivalent to that of CRT glass. The uncertainty associated with the glass manufacturing data is a limitation to the manufacturing inventory data set. Additional limitations from the glass manufacturing data are discussed below with other "data uncertainties" in Section 2.3.3.3.

2.3.3.2 Data collection process uncertainties

Limitations and uncertainties related to the data collection process include the fact that companies were self-selected, which could lead to selection bias (e.g., those companies that are more advanced in terms of environmental protection might be more willing to supply data than those that are less progressive). Also, the data were supplied by companies whose vested interest is to have their product look more desirable, which could result in biased data being provided. However, multiple sets of data were obtained for this project, where possible, so that average processes could be developed in an attempt to avoid biased data. The peer review process and employment of the Core and Technical Work Groups as reviewers in this project is intended to help reduce or identify any such bias. Further, several companies were visited and contacted for verification of data.

Other data collection-process limitations resulted from the difficulty in obtaining and verifying data over long distances (i.e., Japan and Korea to United States) as well as from the language barrier. The use of ATIP as the Asian Liaison aided in reducing this limitation; however, there were still language barriers that had to be overcome with ATIP, as well as through direct communication with several companies.

2.3.3.3 Data uncertainties

Additional limitations to the manufacturing stage inventory are related to the data themselves. Several attempts were made to verify or eliminate outliers in the data; however, uncertainty in some data remained due to large data ranges and outliers. Specific data with the greatest uncertainty include: (1) CRT glass manufacturing energy inputs (mentioned above in Section 2.3.3.1); (2) the distribution of fuel/electricity inputs for LCD module manufacturing; and (3) the use of a large amount of liquified natural gas (LNG) as an "ancillary material" and not a fuel.

In addition to the uncertainty in the difference between energy used to manufacture CRT glass and LCD glass, the energy reported to produce a kilogram of CRT glass varied greatly between the data sets. Consultation with experts in the glass industry confirmed that the average energy consumption derived from the primary data sets, although it appeared to be high, could be possible. The total energy inputs per kilogram of glass from the primary data sets used in the analysis, ranged over a factor of approximately 150 (i.e., the largest total energy value in the data was about 150 times that of the smallest value). Due to this large discrepancy, the glass energy data is the subject of sensitivity analyses in this study. The high energy use values were mostly a function of liquified petroleum gas (LPG) used as a fuel.

Other data for which large ranges were found, and which could be important to the results, are the energy use from LCD panel/module manufacturing. Energy data were provided by six of the seven companies supplying LCD panel/module data. The percent of energy from electricity ranged from approximately 3% to 87%. Three of the companies had the electrical energy component contributing greater than 50% of the total energy use, and the other three companies listed other fuels [e.g., LPG, LNG] as contributing greater than 50% to the total energy use. Another large discrepancy was the total energy use for panel/module manufacturing. Four of the six companies had energy use per panel between approximately 440 MJ/panel and 940 MJ/panel, while the two remaining companies had approximately 4,100 and 7,000 MJ/panel. The average per panel was approximately 2,270 MJ/panel and the standard deviation was about 2,910 MJ/panel.

Given the wide variability in the data and large standard deviation, CDP researchers evaluated the data for outliers by breaking the total energy data points into quartile ranges. Minor outliers are then those within a certain range of multipliers beyond the middle 50% of the distribution. That is, the interquartile range (IQR) (i.e., the range of values representing the middle 50%) multiplied by 1.5 is the lower bound of the minor outlier and the IQR multiplied by three is the upper bound. Anything beyond the IQR times three is a major outlier. Using this approach, one data set was found to be a minor outlier and another was found to be a major outlier. These outliers were excluded from the averages used in the baseline analysis, but included in the averages used in a sensitivity analysis (see Section 2.7.3.3).

Finally, the average amount of LNG used as an ancillary material (not a fuel) in LCD panel/module manufacturing was reported as 194 kg per functional unit. This data point remained in the inventory data set for LCD manufacturing, and was assumed to indeed be an ancillary material, and not a fuel. LNG was also reported as a fuel as a separate input (approximately 3.22 kg/functional unit). Keeping the LNG ancillary material in the inventory will not affect the energy impact results, since LNG used as an ancillary material is only linked to the production of that material, and not to the use of it as a fuel. It will, however, affect upstream impacts from the production of the material. Note that the natural gas process was used as a surrogate for the production of LNG, as inventory data was not available for the latter.

2.4 PRODUCT USE

2.4.1 Methodology

The methods for developing the use stage inventory are presented in Appendix H and summarized here. CRTs and LCDs use different mechanisms to produce images on screen, which result in different energy use rates. These energy use rates (e.g., kW) can be combined with the time a desktop monitor is on during its lifespan (hours/life) to calculate the total quantity of electrical energy consumed during the use life-cycle stage (e.g., kWh/life). In this project, two lifespan scenarios are considered:

- *Effective life* - the actual amount of time a monitor is used, by one or multiple users, before it is disposed of, recycled, or re-manufactured. Reuse of a monitor by a subsequent user is considered part of its effective life. Recycling, on the other hand, is the reuse of parts or materials that require additional processing after disassembly, and it is not considered part of the use stage.
- *Manufactured life* - the amount of time either an entire monitor or a single component will last before reaching a point where the equipment no longer functions, independent of user choices.

These two scenarios are considered in this project in order to account for potential differences between how consumers *currently* use the equipment and how consumers could use the equipment. Currently, consumers often replace monitors before they physically break down. This behavior results in a lifespan that is not solely dependent on the monitor technology itself. The manufactured life, on the other hand, is based on the technology and represents how consumers could potentially use the equipment. If the lifespans are significantly different, the difference could have a large impact on how the use stage compares to the other life-cycle stages in this study. The baseline analyses in this project use the effective life scenario and the manufactured life will be part of the sensitivity analyses.

2.4.1.1 Energy use rate

Most desktop monitors manufactured today are built to use several different power consumption modes during normal operation. There are often up to four different power consumption modes that can be used by a monitor in going from a state of active use to a state of almost complete shut-down. These four modes, from greatest power consumption to least, are typically entitled "full-on" or active use, "standby," "suspend," and "active-off." For this report, manufacturers' data on these power modes were collected from company contacts and Internet sites for 35 different 17" CRT monitors and 12 different 15" LCD monitors. The complete list of these data is presented in Appendix H, Attachment A, Table A1.

For the purposes of this study, the power consumption modes have been categorized into two modes: "full-on" and "low." The "low" power mode is an average of the three low power modes typically provided by the manufacturers (i.e., standby, suspend, and active-off). These three categories were averaged to create one "low" power consumption mode because hours per use data (needed for calculations in this study) are only available for a "full-on" and a reduced power mode. The low mode value for the CRT is the average of the three modal averages of

standby, suspend, and active-off. For the LCD, data on only two low-power modes (standby and active-off) were provided by manufacturers (see Appendix H, Attachment A, Table A2), and therefore, the low mode value is an average of those two modal averages. Table 2-16 presents the average values for full-on and low power modes that were used for subsequent calculations in this analysis.

Table 2-16. Average energy use rates [a]

Monitor type	Full-on power mode [kilowatts (std. dev.)]	Low power mode [b] [kilowatts (std. dev.)]
17" CRT	0.113 (0.015 SD)	0.013 (0.005 SD)
15" LCD	0.040 (0.007 SD)	0.006 (0.003 SD)

[a] See Appendix H, Attachment A, Table A1 for source data.
[b] An average of company-reported values for standby, suspend and active-off (see Appendix H, Attachment A, Table A1).
Note: 1 kW = 1000 Watts = 1000 J/sec.

2.4.1.2 Effective life (baseline lifespan calculation)

The effective life scenario attempts to model the actual quantity of hours that an average monitor spends in each of the two primary power consumption modes (full-on and a lower power state) during its lifetime. The effective life of an average monitor is based on the following information:

- the proportion of computers that are used in an office environment versus a home environment, to account for different use rates in these two basic user environments;
- the amount of time in a year a typical monitor spends in full-on power mode and in a lower power-consuming mode for both office and home environments; and
- the number of years a typical monitor is used during its lifespan for both office and home environments, not including years in storage before a monitor is replaced or discarded (as it is not consuming power during storage).

Under the effective life scenario, we assume there is no difference in the amount of time a CRT or LCD monitor is operating. That is, the hours per life for the effective life calculation is not technology-dependent. Therefore, the same set of hours-per-life values are used to calculate the kWhs used per effective lifetime for a CRT and an LCD. The remainder of this section discusses the data and methods used to calculate the hours-per-life values used in the effective life scenario. More details are also provided in Appendix H.

Percentages of Office- and Home-Environment Users

Home and office users of computer equipment do not follow the same use patterns. Thus, data are needed on the percent of users in each environment to determine the use pattern of an "average" computer monitor. It is assumed that 65% of computers are in office environments and 35% in home environments, based on data available through the Computer Industry Almanac (CIA, 1997) and the Energy Information Administration (EIA, 1999b) (see Appendix H, Section 2.2.2.1 for more details).

Note that an "office" environment may be a school, hospital, or other commercial environment, and the computers they use may follow widely varying degrees of use. For example, computers (and thus monitors) in a school may only be used a few hours in a day, while hospitals might operate theirs nearly constantly. For this study, it is assumed that on average, typical office use patterns (to be presented below, and in Appendix H, Section 2.2.2.2) are representative of all non-home environment users.

Operating Pattern (average hours in use per year)

In order to determine the amount of electricity consumed during a monitor's effective life, we need to know the use operating patterns for both the office and home environments. The "operating pattern" is defined here as the number of hours per year spent in each power mode. The average number of hours per mode per year will be the weighted average of the two user environments (i.e., 65% office, 35% home).

A literature search for computer monitor operating patterns was conducted for both office and home environments and a summary of literature reviewed is presented in Appendix H, Attachment A, Table A3. Based on the literature (Nordman *et al.*, 1996, Fanara, 1999, EIA, 1999b) and other assumptions presented in Appendix H, Section 2.2.2.2, we assume the number of hours per year that office and home monitors are used in each mode are as follows:

- Office:

Full-on power mode:	1,095 hrs/yr
Low power mode:	2,263 hrs/yr
Total:	3,358 hrs/yr

- Home:

Full-on power mode:	522 hrs/hr
Low power mode:	793 hrs/yr
Total:	1,315 hrs/yr

Average Years Per Life

The number of years per life, multiplied by the operating patterns in hours per year (listed above), will result in the hours per effective life. A monitor may be reused in multiple "lives" before reaching its end-of-life. The end-of-life is defined as the point at which the monitor is no longer used for its intended purpose in the physical form in which it was originally manufactured. End-of-life options include indefinite storage (in which case it is not reused after storage), de-manufacturing, recycling, or disposal. A monitor may be stored before being reused; however, this storage time will not affect our use calculations since no electricity is required to operate the monitor during this storage. After its first life as used by the original owner, a monitor might be used by different people and with different PC systems in subsequent lives.

For data on the number of years of use that are in a monitor's lifetime, several sources of information were reviewed (see Appendix H). Based on a recent study by the National Safety Council (NSC, 1999), we assumed that a monitor is used for 4 years in its first life and 2.5 years for its second or subsequent lives. The operating patterns (in hours/year) presented above are

assumed to be the same for all of the 6.5 years of the total effective life. However, in the lives subsequent to the first life, the hours per year values are reduced by the fraction of monitors assumed to be reused. Matthews *et al.* (1997) estimated that 45% of PCs are reused after a first life; thus, the effective life operating pattern values in years of life after the first life are 45% of the values in the first life.

Lifespan estimates from the National Safety Council (NSC, 1999) were specific to CRT monitors; however, they were not specific to LCD desktop monitors. The NSC data did contain estimates of a "Notebook PC," which were two to three years for the first life and one to two years for the remaining lives; however, we expect that desktop LCD monitors will more closely mirror the lifetime estimates of a desktop CRT monitor than that of a notebook PC. Consequently, it was assumed that LCD desktop monitors also spend four years in their first life and 2.5 years in their subsequent lives. Additionally, the NSC document did not attempt to separate those computer systems or monitors that are used in an office versus a home environment. Thus, it was assumed that the same years per life are realized for office and home environments.

Effective Life Estimates (hours per life)

The data presented above are summarized in Table 2-17 and used to estimate the total hours per effective life. The values for hours per year per power mode are assumed to be the operating pattern throughout the first life (first four years). In the remaining lives, the annual operating hours decrease to 45% of the hours in operation during each year in the first life, with the remaining lives lasting a total of 2.5 years. Table 2-17 also presents the total hours per effective life per mode, based on percentage in office and home environments. These values are in bold in Table 2-17 (4,586 and 8,961 hrs per effective life) and will be multiplied by the energy use rates per mode (presented in Table 2-16), to calculate the total energy consumption per effective life for each monitor type.

Table 2-17. Effective life values

User environment	Power mode	First life (4 years)		Remaining lives (2.5 years)		Model totals [b] (hr/effective life)
		Operating pattern (hr/yr)	Total (hr/4 yrs)	Operating pattern (hr/yr) [a]	Total (hrs/2.5 yrs)	
Office (65%)	Full-on	1,095	4,380	493	1,233	5,613
	Low	2,263	9,052	1,018	2,545	11,597
Home (35%)	Full-on	523	2,092	235	588	2,680
	Low	793	3,172	357	893	4,065
Weighted average [c]	Full-on	---	---	---	---	**4,586**
	Low	---	---	---	---	**8,961**

[a] The remaining lives operating pattern is 45% of first life operating pattern, based on 45% of monitors that are reused (Matthews *et al.*, 1997).

[b] Modal totals calculated as [(Total for first 4 years) + (Total for remaining 2.5 years)].

[c] The weighted averages shown for full-on and low power modes are based on the assumption that 65% of users operate in an office environment and 35% operate in a home environment.

Effective Life Total Energy Consumption (kWh/life)

In order to calculate the total kWhs consumed, first, the energy use rates (kW) were multiplied by the lifespans (hours per life) for each mode and each monitor type. They were then summed for the two power modes to obtain a total kWh/life for each monitor type (Table 2-18).

Table 2-18. Effective life electricity consumption

Monitor type	Power mode	Energy use rate (kW)	EL calculated lifespan (hours/life)	EL energy consumption (kWh/life)
17" CRT	Full-on	0.113	4,586	518
	Low	0.013	8,961	116
	Total	---	13,547	634
15" LCD	Full-on	0.040	4,586	183
	Low	0.006	8,961	54
	Total	---	13,547	237

2.4.1.3 Manufactured life (alternative lifespan calculation)

Due to the uncertainty and assumptions associated with the effective life scenario, an alternative scenario is also considered. The manufactured life is defined here as the length of time a monitor is designed to operate effectively for the user. It is the number of hours a monitor would function as manufactured, and is independent of user choices or actions. One way to estimate this manufactured life is to use the mean-time-before-failure (MTBF) specification of a monitor or its components. The CRT MTBF specification dictates the amount of time the display must operate before it reaches its brightness "half-life," or the ability to produce 50% of its initial, maximum brightness. The MTBF value, generally provided in total hours per life of a monitor, is what most final manufacturers or assemblers of personal computer (PC) equipment, including monitor assemblers, typically specify for a component. To meet the specification, suppliers typically calculate the MTBF (a military-based specification) based on component data. Suppliers' test results are usually called the "calculated" MTBF. The MTBF value also depends on which combination of power modes are used during testing, which is referred to as the "duty cycle" and each supplier may use a different duty cycle to test their component.

Additionally, monitor assemblers will often perform their own testing, typically entitled "demonstrated" MTBF. The testing includes sequences where the monitor is "stressed" by quickly switching back and forth from an all black picture to an all white one, or quickly switching individual pixels either on and off or through multiple colors or black and white. Manufacturers typically find that their demonstrated MTBF is on the order of twice as long as the calculated MTBF (McConnaughey, 1999; Douglas, 1999). However, it should be noted that the demonstrated MTBF is not a real-time testing method, as the testing data is used in a complex equation to calculate that "demonstrated" value.

From review of the information obtained on CRT-based monitors (see Appendix H, Attachment A, Table A2), it appears that the CRT (the tube) itself is the limiting component, or the component that 99% of the time determines whether the entire monitor has reached its end-of-life. Thus, from the limited information that was obtained on CRTs, and the limited

confidence that can be instilled in those data, an average of the two ranges obtained on the estimated lifetime of CRTs (10,000 and 15,000 hours) was used as the CRT manufactured lifetime (12,500 hours) (Goldwassar, 1999; Douglas, 1999).

For active matrix LCDs, the components that have the greatest potential to fail first are the display panel itself (including the liquid crystals and thin-film transistors), backlights, driver integrated circuit (IC) tabs, and other smaller components. The backlights and driver IC tabs can be field-replaced, thus their failure does not necessarily represent the end of the monitor's life. However, failure of the liquid crystals or transistors, which would require replacement of the display panel itself, would most likely mean that the monitor cannot be cost-effectively repaired. The MTBFs of all these components appear to have a broad range. For example, different backlight manufacturers reported from as few as 15,000 hours to as many as 50,000 hours (Douglas, 1999; Tsuda, 1999; VP150, 1999). However, it appears that those components that are not field-replaceable (e.g., the LCD panel) have MTBFs in the range of 40,000 to 50,000 hours (Tsuda, 1999; Young, 1999). Thus in this study, the amount of time an LCD monitor would operate during its manufactured life is assumed to be the average of the two non field-replaceable values, or 45,000 hours. In order for a monitor to operate for 45,000 hours, any major field-replaceable parts that have MTBFs less than 45,000 hours will need to be accounted for in this LCA project. For example, assuming the backlights last on average 32,500 hours (the average of the values obtained for backlights), more than one (approximately 1.4, on average) would be needed for every panel during its lifetime. Therefore, in the final CDP LCA, the manufacturing of extra backlights would need to be included in the inventory.

Little information is available on the duty cycles that component manufacturers use to test components. Thus, it is assumed that the average duty cycle used in testing components is 50% of the time tested in full-on mode and 50% in a lower power mode. Table 2-19 shows the values that are used in this study for the hours per manufactured life for the CRT and LCD. Some sensitivity analyses were done and presented in Socolof *et al.* (2000).

Table 2-19. Manufactured life values

Monitor type	Total hours (hours/life)	Mode	Duty cycle (% time spent in each mode during testing)	Hours per mode (hours/life)
17" CRT	12,500	Full-on	50%	6,250
		Low	50%	6,250
15" LCD	45,000	Full-on	50%	22,500
		Low	50%	22,500

To calculate the manufactured life electricity consumption (kWh/life), the energy use rate (kW) is multiplied by the lifespan (hours/life) for each monitor in each power mode (Table 2-20). The LCD manufactured life (45,000 hours) is 3.6 times greater than the CRT manufactured life (12,500 hours). In an LCA, comparisons are made based on functional equivalency. Therefore, if one monitor will operate for a longer period of time than another, impacts should be based on an equivalent use. Therefore, based on equivalent use periods, 3.6 CRTs would need to be manufactured for every LCD. This will be incorporated into the profile analysis for the comparative manufactured life LCA.

Table 2-20. Manufactured life electricity consumption

Monitor type	Power mode	Energy use rate (kW)	ML calculated lifespan (hours/life)	ML energy consumption (kWh/life)
17" CRT	Full-on	0.113	6,250	706
	Low	0.013	6,250	81
	Total	----	12,500	787
15" LCD	Full-on	0.040	22,500	900
	Low	0.006	22,500	135
	Total	----	45,000	1,035

2.4.1.4 Effective life versus manufactured life

For the CRT monitor, the effective life total hours are 13,547 versus the manufactured life total of 12,500. While this suggests that a CRT can be used longer than is physically possible, it simply reveals our low confidence in these numbers and some of their supporting values, with less confidence in the manufactured life data than the effective life estimates. A more complete discussion of the data quality is presented in Section 2.4.2 and Appendix H.

Assumptions were required several times that could bias these numbers in either direction; however, it is thought that the manufactured life estimate is most likely low based on the other estimates for the overall CRT monitor (see Appendix H, Attachment A, Table A2). However, there was no sound basis for assuming a lower value and thus the above hours per life values were used. It should also be stated that while these numbers are different, they are within an 8% error range of one another, and can be taken to be a near 1:1 ratio, indicating a similar potential lifespan.

For LCDs, the comparison across lifespan scenarios is more consistent with what one would expect, with the manufactured life value of 45,000 hours per life being much greater than the effective life value of 13,547 hours per life. The effective life value reflects the assumption that a user's use habits are not technology-dependent, and would seem to reveal that LCDs are not being used as long as they can physically be (less than a third as long).

The difference between the effective and manufactured lives are important when evaluating all the life-cycle stages for a particular monitor type. If the manufactured life is significantly greater than the effective life, the use stage will have greater impacts, as compared to other life-cycle stages. Therefore, it is important to focus on the lifetime scenario that is most realistic, while still recognizing the potential impacts from another feasible lifespan scenario.

In this project, we will use the effective life as the primary basis for the use stage inventory due to the fact that the effective life data are attempting to obtain a more realistic value for electricity consumed per lifetime, and that we currently have greater confidence in those data versus the manufactured life data. The manufactured life data will be used in one sense as a sensitivity analysis and to discuss potential differences in the use stage impacts based on this alternative lifetime scenario.

2.4.2 Data Sources and Data Quality

Source and quality information for the use stage data are detailed in Appendix H, Table 11. We assigned four categories of data quality ratings: excellent, average, poor, and unknown. In general, data assigned higher quality ratings were directly measured and represent 1998 data. As data required more calculation or estimation, or were found from a previous year, the data quality rating was reduced.

The overall level of use stage data quality is between average and excellent (Appendix H, Table 11). However, a distinct difference can be seen in the average data quality ratings given to manufactured life data (average) and the effective life data (excellent). This implies that greater confidence can be placed in the effective life data than in the manufactured life data. Additionally, the energy use rate data appears to be of average quality.

2.4.3 Limitations and Uncertainties

Details of the limitations and uncertainties associated with the energy use rate, the effective life, and the manufactured life estimates are presented in Appendix H, Section 5.

2.5 END-OF-LIFE

2.5.1 Methodology

A Technical Memorandum, attached as Appendix I, was prepared for this project that provides background on the EOL issues for the CRT and LCD. It also provides details on the methodology used in this project for the EOL life-cycle inventory. This section summarizes the salient points from that memorandum needed to understand the EOL methodology and results. For the EOL analysis, a monitor is assumed to have reached EOL status when:

- it has served its useful life;
- is no longer functional; and/or
- is rendered unusable due to technological obsolescence.

Each of these situations is addressed by either the manufactured or effective lives (defined in Section 2.4).

2.5.1.1 EOL disposition options

The major EOL dispositions considered in this analysis are as follows:

- recycling - including disassembly and materials recovery;
- landfilling - including hazardous (Subtitle C) and non-hazardous (Subtitle D) landfills;
- remanufacturing - including refurbishing or reconditioning (to make usable again); and
- incineration - waste to energy incineration.

See Appendix I for further descriptions of these dispositions. Note that reuse is considered part of the use stage and not included as an EOL disposition.

The functional unit in this analysis is one monitor; therefore, the different EOL dispositions were allocated as a probability of one monitor going to a certain EOL disposition. Data were somewhat scarce on the percent of monitors going to each disposition, especially for the LCD monitors. After literature research and consultation with the project's Technical Work Group, as well as various other industry experts, project partners chose best estimates of disposition distributions. Table 2-21 presents the assumptions used for the EOL life-cycle stage dispositions for the CRT and LCD, respectively. An explanation of the assumptions and the sources of the data are presented in Appendix I.

The values in Table 2-21 have been used in the baseline scenarios for the CRT and LCD LCIs. To address the uncertainty in the LCD estimates, a sensitivity analysis was conducted (which is discussed in Section 2.7.3).

Table 2-21. Distribution of EOL disposition assumptions for the CRT and LCD

Disposition	CRT	LCD
Incineration	15%	15%
Recycling	11%	15%
Remanufacturing	3%	15%
Hazardous waste landfill	46%	5%
Solid waste landfill	25%	50%

Sources: NSC, 1999; EPA, 1998; Vorhees, 2000; CIA, 1997; EIA, 1999b

2.5.1.2 Data collection

Inventory data were needed for each of the EOL dispositions to be included in the life-cycle profiles. Primary data were collected for CRT recycling from three companies. Hazardous/solid waste landfilling and incineration were developed from secondary data obtained from *Ecobilan*. In attempts made to obtain remanufacturing data, it was found that remanufacturing processes span a wide range of activities, from as little as replacing button tops to as extensive as testing and replacing PWBs or transformers. Given the broad range of possibilities, no single set of operations could be identified to adequately represent remanufacturing activities that could be incorporated in our model. Remanufacturing data were, therefore, excluded from the assessment.

Recycling

Companies willing to provide CRT recycling data were given EOL questionnaires, which are similar to the manufacturing questionnaires, but modified as appropriate for the EOL life-cycle stage (see Appendix I). The questionnaires were used as a guide for collecting inventory data. The companies agreed to provide inventory data through personal meetings and telephone conversations rather than completing the detailed questionnaire. As a result, the most critical data were identified by the research team to prioritize data needs, and all the details in the questionnaire may not have been provided.

The three companies contacted were: (1) DMC Recycling; (2) A & B Recycling; and (3) The Oak Ridge National Recycle Center (TORNRC). DMC shreds the complete monitor up and separates the recovered materials into three major material streams: ferrous, silica-based, and copper-based. The ferrous metals are sent to steel mills for recycling, while the other streams are sent to lead and copper smelters, respectively. A & B Recycling performs a partial disassembly of the casing and other materials outside the CRT. These materials (namely, HIPS, steel, aluminum, and copper wiring) are sent for recycling, while the CRT itself is shipped to Envirocycle (a CRT recycler in Pennsylvania), where the glass is recovered and sent for recycling back into CRT glass, and the other materials are also recovered for recycling. TORNRC conducts complete monitor disassembly (which includes the CRT recycling process similar to the one performed at Envirocycle), and recovers the individual materials for subsequent recycling.

None of the recycling companies contacted have yet encountered end-of-life LCDs in any appreciable quantities that would justify the development of a separate recycling process for them. Whatever sporadic quantities of LCDs that they do receive (mainly notebook computer

displays) are either sent for refurbishing/resale or are processed along with other electronic equipment, by recovering different materials from them, such as metals, glass, plastics, etc. In the absence of actual data for LCD recycling, the shredding-and-materials-recovery process followed by DMC Recycling for CRTs was assumed to be suitable for recovering materials from LCDs as well, and was therefore used to model LCD recycling.

Landfilling and Incineration

Generic secondary data were used for the incineration and landfilling processes because when monitors are disposed of, they are combined with multiple waste streams, and data for monitors alone are not readily available. Although data specific to landfilling and incineration operations for monitors alone were not available, DEAM inventories from *Ecobilan* were available for landfilling and incinerating the following major monitor materials (by weight): steel, glass, plastic, and aluminum. These inventories were combined, based on the approximate proportion of each material in a CRT and an LCD, to create individual processes for landfilling and for incineration (for each monitor type). The proportions of these materials in a CRT and an LCD, presented in Table 2-22, are estimates of the final assembled monitor based on the manufacturing inventory data. Note that these proportions are slightly different from the proportion of total inputs per functional unit presented in Section 2.1.2, Tables 2-2 and 2-3 because materials efficiency during production is not accounted for here (in Table 2-22). The majority of the assembled monitors by weight is accounted for in the overall incineration and landfilling processes, as seen in the totals in Table 2-22.

It should be noted that some of the DEAM inventories associated with incineration or landfilling are for generic materials (i.e., glass, plastic), and may not accurately represent the makeup of the material used in the monitors. For example, the glass is not leaded glass, and the plastics may not represent the exact breakdown of plastics in the monitors being modeled in this study (see Section 2.5.3, Limitations and Uncertainties for further discussion).

Table 2-22. Percent contribution of major materials in the final product

Material	CRT	LCD
Glass	43% (9.48 kg)	9% (0.585 kg)
Steel	30% (6.61 kg)	47% (3.055 kg)
Plastic	17% (3.75 kg)	40% (2.60 kg)
Aluminum	2% (0.441 kg)	1% (0.065 kg)
Total	**92% (22.043 kg)**	**97% (6.5 kg)**

2.5.1.3 Assumptions

The assumptions used in the EOL life-cycle stage include the percentage breakdown of each EOL disposition option (see Table 2-21), the breakdown of materials for the incineration and landfilling inventories (Table 2-22), as well as those listed in Section 2.2 of Appendix I.

2.5.2 Data Sources and Data Quality

Primary CRT recycling data collected were collected from three companies: A & B Recycling, DMC Recycling, and TORNRC. Efforts were made to collect all data in the questionnaires; however, priority was given to obtaining the inventory data. The companies, preferring to provide data over the phone or during personal meetings, were able to provide the inventory data required for the analyses in this study.

Specific DQIs, such as those reported for the manufacturing data (see Section 2.3.2, Tables 2-14 and 2-15), were not obtained. The data from these companies represent facility operations ranging from October 1999 to February 2000. Also, while the data obtained are from three recycling facilities that may have different operations, the averaged inventory data are intended to be representative of various recycling activities in the industry.

Data for the EOL life-cycle stage are a combination of primary data, for which we do not have specific DQI, and secondary data, with limited data quality information. The overall data quality for this life-cycle stage may therefore be limited, and in relative terms, is lower quality than the manufacturing stage data.

Sources of data for EOL distribution assumptions include the National Safety Council (NSC, 1999), EPA (1998), CIA (1997), EIA (1999b) and Vorhees (2000). These are discussed in Appendix I.

2.5.3 Limitations and Uncertainties

Assumptions of the disposition percentages for CRTs and LCDs may not be truly representative of actual dispositions. Recycling technologies are not yet standardized for the sorting, separation, and processing of different types of CRT glass, metals, and plastics. The methods currently employed by a few large-volume recyclers who have been in the CRT recycling business for some years were used in this study and represent "state-of-the-art" in the CRT recycling industry. The LCD recycling process used was based on a CRT recycling process employed by one of the recycling companies contacted, as it was considered general enough to be applicable to LCDs. In the future, when greater numbers of LCDs begin to arrive at recycling facilities, more standardized processes for handling LCDs specifically might be developed.

Limitations for the incineration and landfilling inventories are that incineration and landfilling of the materials were for generic materials and not specific to actually incinerating or landfilling a CRT or LCD monitor. For the CRT, the glass incineration portion of the monitor is for generic, non-leaded glass. The plastics are also generic plastics (mainly those used for packaging that ultimately end up in municipal solid waste, such as HDPE, LDPE, and PET) and may not account for the flame retardants that might be in the plastics, for example. Also, only a few of the major materials by weight are included in the modeled CRT and LCD that are incinerated (listed in Table 2-22).

2.6 TRANSPORTATION

2.6.1 Methodology

Transportation of materials, products, and wastes throughout a product's life-cycle has environmental impacts and should be included in a comprehensive LCA. However, complete transportation data for all life-cycle stages is often difficult to obtain. Only six of the 16 upstream data sets used for this study explicitly stated that transportation was included. An additional six upstream processes are assumed to have considered transportation (Table 2-9). In the manufacturing stage, transportation data were collected in the questionnaires that were distributed to manufacturers. Some transportation data were provided by manufacturers on materials received by their facility and products and wastes shipped from their facility. Data were not obtained on transportation during the use stage because distributing questionnaires and collecting primary data for the use stage were not within the boundaries and scope of the LCA. Consequently, individual consumer transport to pick up purchased monitors and to send to a secondary user or to a recycling/disposal facility were not accounted for. Similarly, EOL data, either from CRT recyclers, or secondary data for incineration and recycling did not include transportation data. Therefore, the transportation data collected in this study may only represent a small portion of the overall transport in the life of a monitor.

The manufacturing data collection questionnaires (Appendix F) provided space for companies to identify transportation information for each material input, product output, or waste output. The questionnaire asked for the distance traveled, mode of transport (i.e., vehicle type), number of trips per year, and percent capacity of the vehicle containing a particular material of interest. Given this information, the project researchers calculated the total distance traveled for a transportation mode per functional unit.

In order to determine the environmental effects of transport, the total distance traveled must be linked to an inventory associated with a transport mode on a per-distance-traveled basis. *Ecobilan's* DEAM data provided inventories for several vehicles either on a per-distance-traveled basis or a per mass-load, per-distance-traveled basis. Given the maximum load of the vehicle, the latter figures can also be used with the transportation data collected in the manufacturing questionnaires to estimate the total distance traveled per mode per functional unit.

2.6.2 Questionnaire Results

In many cases, companies completing the questionnaires provided partial transportation data. For the CRT processes, manufacturers supplied adequate transportation data for 66% of the materials that are expected to have transportation data. For the LCD processes, 73% of the materials had adequate transportation data to determine the total distance traveled per mode per functional unit. Of the transportation data that were provided, Table 2-23 lists the distribution of transport modes for the CRT and LCD manufacturers. To complete the LCI, transport data from the questionnaires would have to be linked to vehicle inventories, which were available through the DEAM data. However, the vehicle inventories were not linked to the questionnaire data because the questionnaire asked for percent capacity, but did not couple that with the load capacity of the vehicle. As a result, the data were inconsistent and could not accurately be used in the overall product LCI.

Table 2-23. Distribution of transport modes and total distances per mode

Transport mode	CRT		LCD	
	Distribution of modes	Approx. normalized [a] distance traveled per functional unit	Distribution of modes	Approx. normalized* distance traveled per functional unit
Large diesel truck	61%	3 km	58%	3 km
Small diesel or gas truck	21%	<1 km	35%	<1 km
Ocean	16%	37 km	3%	<1 km
Rail	2%	<1 km	2%	<1 km
Air	0%	0	2%	52 km
Total	100%	40 km	100%	56 km

[a] Normalized by the percent capacity of a vehicle carrying the material of interest.
Note: 1 km = 0.6215 miles.

In order to use the vehicle inventory data, it would have to be assumed that the load capacity assumed by manufacturers when providing the percent capacity was consistent with that in the DEAM vehicle inventory data. However, conducting a review of the DEAM data versus the questionnaire data showed that this was not consistent. The greatest difference (based on relatively crude averages of all the transport data provided) appeared to be for the ocean transport, where the discrepancy was on the order of tens of millions of times different. The other modes appeared to be between 22,000 to 660,000 times. These huge discrepancies puts the linked transportation data into question, making it unreliable for use in this study. When the transportation impacts were run in the analysis, and these factors applied, the transportation impacts appeared to be small compared to the other life-cycle stages, but no real reliable information can be gleaned from these data. Further work is needed in this area to understand the true transportation impacts. For this report, the transportation-related inventories are not included.

Transportation data that can be used from the questionnaires include the modes of transport used and the total distances traveled per functional unit (by mode). These are presented in Table 2-23. The "normalized" distance is the total distance traveled for each material multiplied by the percent capacity of the vehicle that was carrying the particular material of interest. This was done to allocate a portion of the vehicle (and thus a portion of the associated inputs and outputs for transport in a particular vehicle) to the transport of the material of interest. It should be noted that these percent capacities were assumptions made by the manufacturers who completed the questionnaires and the percent capacity assumptions could have been inconsistently interpreted. Not only are the distances modified to represent only the product of interest, they are scaled to represent one functional unit (i.e., the material, product, or waste associated with one monitor). Thus, the total normalized distance for the CRT is 40 kilometers (km) per functional unit and 56 km per functional unit for the LCD. These numbers are normalized with the intention of linking them to the individual vehicle inventories, but as stated above, this has not been done due to data inconsistencies.

The most frequently used mode of transport for both the CRT and LCD is the large diesel truck, followed by the small gas or diesel truck. However, the largest normalized distance traveled for the CRT is via ocean transport and for the LCD is via air transport. Worth noting again is that these distances were calculated by normalizing the capacity of the vehicle, as

assumed by the manufacturer. Although the transport data represent transport of several materials, products, and wastes into and out of manufacturing facilities, the majority of the distances traveled are from the transport of the final assembled monitors. Of all the reported transportation for the manufacturing stage, the distance traveled of a final assembled CRT monitor via the ocean represents 80% of the total distance traveled. For the LCD, 90% of all reported kilometers traveled are for transport of the final assembled LCD monitor via airplane. Transport of the final assembled CRT monitor for all transport modes is 86% of all kilometers traveled per functional unit. Similarly, for the final assembled LCD monitor, approximately 92% of all manufacturing transportation reported is for the final assembled monitor.

2.6.3 Data Sources and Data Quality

Primary data were derived from manufacturing questionnaires and inventory data for transport vehicles were available through DEAM data. However, inconsistencies between the data made it impossible to accurately apply the DEAM inventories to the questionnaire data. Therefore, the data quality is very low and complete transportation inventory data are excluded from the analysis results.

2.6.4 Limitations and Uncertainties

Inconsistencies between data collected in questionnaires and DEAM data made it impossible to use the transportation inventory data as part of the overall life-cycle. From rough estimates based on data received, it is possible that the transportation impacts are not driving overall life-cycle impacts, however, this would need to be investigated further to confirm such a conclusion.

2.7 SUMMARY OF LIFE-CYCLE INVENTORY RESULTS

2.7.1 Baseline LCI

This section presents the baseline inventory data for the life-cycles of the CRT and LCD monitors. The baseline scenario meets the following conditions:

- uses the effective life use stage scenario;
- uses the average value of all the energy inputs from the primary data for glass manufacturing;
- assumes LCD glass manufacturing processes use the same amounts of energy as CRT glass manufacturing per kilogram of glass produced;
- excludes two outliers from the average of the energy inputs in the LCD panel/module manufacturing inventory;
- excludes transportation in the manufacturing stage, but includes any transportation embedded in upstream data sets; and,
- includes the manufacturing process of materials used as fuels (e.g., natural gas, fuel oils) in the life-cycle stage in which they are consumed instead of in the materials processing stage. In cases where materials normally considered to be fuels are used as ancillary materials their manufacturing processes are included with other upstream processes.

Inventory data presented here are used to calculate impacts in the impact assessment (Chapter 3), which translates inventory items into impacts. Note that only limited conclusions can be made based on the inventory alone.

Table 2-24 presents the total quantity of inputs and outputs for the entire life-cycles of the CRT and LCD based on input and output types. Definitions of the input and output types were presented in Table 2-1 in Section 2.1.1. Graphs depicting selected input and output types, derived from the values in Table 2-24, are in Figures 2-5, 2-6, and 2-7. Complete inventory tables for each input and output type by life-cycle stage for the CRT and LCD are provided in Appendix J. The inventories presented in Appendix J list each individual input or output alphabetically for a particular input or output type. The individual inputs or outputs may be the sum of that material for several processes.

The total inventory results for life-cycle inputs reveal that more primary materials,[3] water, fuels, electricity, and total energy (i.e., fuel energy plus electricity) are used throughout the CRT life-cycle while more ancillary materials are used throughout the LCD life-cycle. For the life-cycle outputs, the CRT releases more air emissions; water pollutants; hazardous, solid, and radioactive waste; and radioactivity than the LCD. The LCD releases more total wastewater than the CRT. The data that comprise the inventory totals presented in Table 2-24 are listed in Appendix J and broken down by life-cycle stage. Further details on the inventory are provided for each monitor type below.

[3] Note that the total mass of primary materials includes the inputs to each process, which may duplicate materials used in processes subsequent to other processes. For example, the primary materials used in steel production are added to the steel used as a primary material for monitor assembly.

Table 2-24. Total life-cycle inventory summary - baseline analysis

Inputs	CRT	LCD	Units
Primary materials	**6.53e+02**	3.63e+02	kg/functional unit
Ancillary materials	1.98e+01	**2.08e+02**	kg/functional unit
Water	**1.31e+04**	2.82e+03	kg (or L)/functional unit
Fuels	**4.33e+02**	3.86e+01	kg/functional unit
Electricity	**2.49e+03**	1.20e+03	MJ*/functional unit
Total energy	**2.08e+04**	2.84e+03	MJ*/functional unit
Outputs			
Air pollutants	**6.64e+02**	3.46e+02	kg/functional unit
Wastewater	1.52E+03	**3.13e+03**	kg (or L)/functional unit
Water pollutants	**2.09E+01**	1.68e+00	kg/functional unit
Hazardous waste	**9.46e+00**	6.29e+00	kg/functional unit
Solid waste	**1.72e+02**	5.23e+01	kg/functional unit
Radioactive waste	**2.90e-03**	1.48e-03	kg/functional unit
Radioactivity	**8.98e+07**	4.01e+07	Bq/functional unit

* 3.6 MJ = 1 kWh

Note: Bold indicates the larger value when comparing the CRT and LCD.

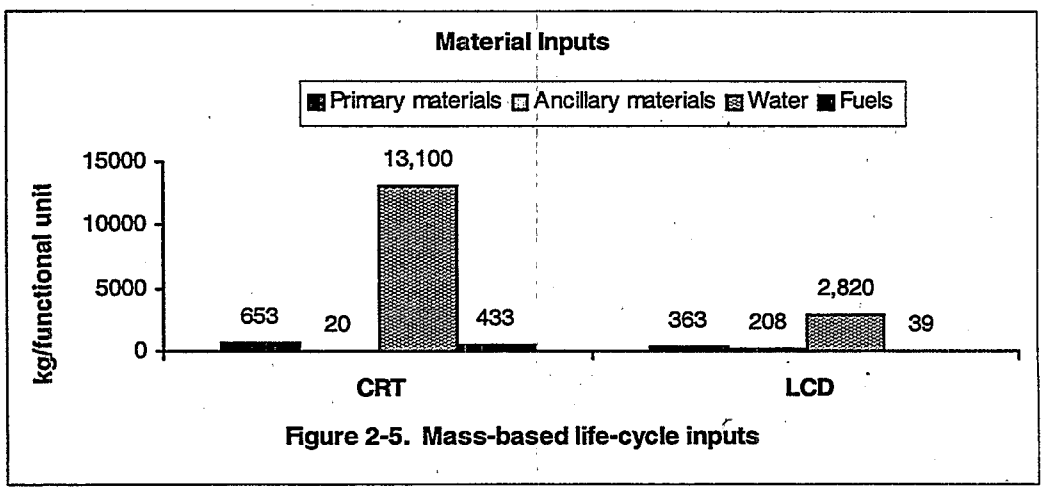

Figure 2-5. Mass-based life-cycle inputs

Table 2-26. Top 99% of CRT primary materials inputs (kg/functional unit)

Material	Upstream	Mfg	Use	EOL	Total	% of total
Petroleum (in ground)	1.32E+00	3.72E+02	3.80E+00	-1.52E+00	3.75E+02	54.17%
Coal, average (in ground)	3.57E+00	5.15E+00	1.79E+02	1.79E-02	1.88E+02	27.15%
Assembled CRT monitor	0	0	2.20E+01	0	2.20E+01	3.38%
Natural gas	0	1.47E+00	1.40E+01	-8.88E-02	1.54E+01	2.36%
Cathode ray tube (CRT)	0	1.07E+01	0	0	1.07E+01	1.64%
CRT glass, unspecified	0	9.76E+00	0	0	9.76E+00	1.50%
Iron (Fe, ore)	6.90E+00	0	0	0	6.90E+00	1.06%
Steel	2.48E-06	5.16E+00	0	0	5.16E+00	0.79%
Natural gas (in ground)	8.41E-01	3.27E+00	0	-1.64E+00	2.47E+00	0.38%
Sand	0	2.40E+00	0	0	2.40E+00	0.37%
Recycled CRT Glass	0	2.06E+00	0	0	2.06E+00	0.32%
Bauxite (Al2O3, ore)	1.37E+00	0	0	0	1.37E+00	0.21%
Iron scrap	9.46E-01	0	0	0	9.46E-01	0.14%
Polycarbonate resin	0	9.23E-01	0	0	9.23E-01	0.14%
PWB-laminate	0	8.47E-01	0	0	8.47E-01	0.13%
Printed wiring board (PWB)	0	8.47E-01	0	0	8.47E-01	0.13%
Styrene-butadiene copolymers	0	8.27E-01	0	0	8.27E-01	0.13%
PPE	0	7.35E-01	0	0	7.35E-01	0.11%

See Appendix J for complete inventory table.

Table 2-27. Top 99% of CRT ancillary materials inputs (kg/functional unit)

Material	Upstream	Mfg	Use	EOL	Total	% of total
Clay (in ground)	4.49e-03	0	0	8.19e+00	8.19e+00	41.35%
Sand (in ground)	5.85e-02	2.74e-02	0	2.71e+00	2.80e+00	14.13%
Limestone	0	6.91e-02	2.41e+00	2.41e-04	2.48e+00	12.51%
Limestone (CaCO3, in ground)	8.60e-01	1.08e+00	0	-2.39e-01	1.70e+00	8.58%
Lime	0	3.04e-02	1.06e+00	1.06e-04	1.09e+00	5.49%
Sodium chloride (NaCl, in ground or in sea)	7.61e-01	1.26e-02	0	-3.07e-05	7.73e-01	3.90%
Sulfuric acid	0	2.38e-01	0	0	2.38e-01	1.20%
Hydrochloric acid	0	2.36e-01	0	0	2.36e-01	1.19%
Sodium hydroxide	0	1.98e-01	0	0	1.98e-01	1.00%
Pyrite (FeS2, ore)	1.94e-01	0	0	0	1.94e-01	0.98%
Nitric acid	0	1.44e-01	0	0	1.44e-01	0.73%
Ferric chloride	0	1.37e-01	0	0	1.37e-01	0.69%
Calcium Chloride	0	1.27e-01	0	0	1.27e-01	0.64%
Calcium hydroxide	0	9.54e-02	0	0	9.54e-02	0.48%
Hydrofluoric acid	0	8.65e-02	0	0	8.65e-02	0.44%
Hydrogen peroxide	0	8.45e-02	0	0	8.45e-02	0.43%
Ammonium hydroxide	0	7.90e-02	0	0	7.90e-02	0.40%
Pumice	0	7.86e-02	0	0	7.86e-02	0.40%
Ammonium chloride	0	7.76e-02	0	0	7.76e-02	0.39%

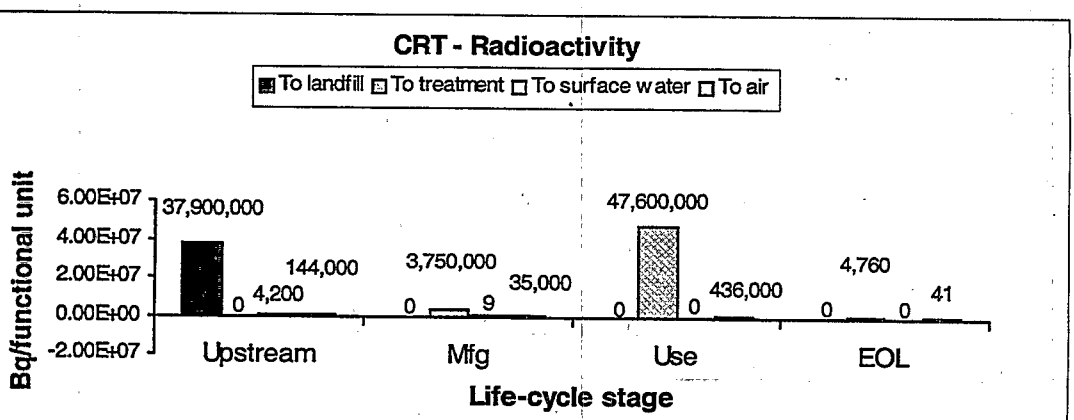

Figure 2-23. CRT radioactivity outputs by life-cycle stage

CRT Primary Inputs

Beginning with the primary data inputs, Figure 2-11 shows that most primary materials are from the manufacturing and use life-cycle stages. To better understand what some of the top contributing materials are to those life-cycle stage totals, Table 2-26 shows the top 99% of the materials contributing to the total CRT primary input inventory. As shown in Table 2-26, the largest material contributor is petroleum, which is about 54% of all the primary CRT inputs. The petroleum is mostly (>98%) from the LPG production process, which relates back to the LPG needed as a fuel in glass production. The other major contributor to primary material inputs is coal (~27%) which is used to produce electricity consumed in the use stage. More detail on the processes that contribute greatest within the manufacturing stage will be presented below after brief discussions of the life-cycle stage breakdowns for each inventory type. For the complete list of primary materials in the CRT inventory, the total mass, and the mass contribution of each life-cycle stage, see Appendix J-1, Table J-1.

CRT Ancillary Inputs

Observing Figure 2-12, the mass of ancillary CRT inputs in the EOL life-cycle stage was greatest (11 kg/functional unit). The upstream stages had the lowest mass of ancillary inputs compared to the other life-cycle stages. To better understand the materials contributing to those totals, Table 2-27 shows that clay is the greatest contributor by mass at 41% of the total CRT ancillary inputs. Clay is used predominately during EOL incineration and landfilling. See Table J-2 in Appendix J for the complete list of ancillary materials in the CRT inventory.

Table 2-27. Top 99% of CRT ancillary materials inputs (kg/functional unit)

Material	Upstream	Mfg	Use	EOL	Total	% of total
Alkali cleaning agent	0	7.72e-02	0	0	7.72e-02	0.39%
Iron (Fe, ore)	7.23e-02	0	0	3.41e-03	7.57e-02	0.38%
Potassium peroxymonosulfate	0	7.06e-02	0	0	7.06e-02	0.36%
Sulfuric acid, aluminum salt	0	6.75e-02	0	0	6.75e-02	0.34%
Alkali soda (to neutralize acid waste water)	0	5.45e-02	0	0	5.45e-02	0.28%
Polyethylene glycol	0	5.04e-02	0	0	5.04e-02	0.25%
Bauxite (Al2O3, ore)	1.10e-03	4.47e-02	0	-1.14e-04	4.57e-02	0.23%
Nitrogen	0	4.57e-02	0	0	4.57e-02	0.23%
PWB-solder mask solids	0	4.37e-02	0	0	4.37e-02	0.22%
Potassium hydroxide	0	4.27e-02	0	0	4.27e-02	0.22%
Lubricant (unspecified)	4.11e-02	0	0	0	4.11e-02	0.21%
Chlorine	0	4.03e-02	0	0	4.03e-02	0.20%
Zinc (Zn, ore)	3.79e-02	0	0	0	3.79e-02	0.19%
Aluminum Oxide	0	3.37e-02	0	0	3.37e-02	0.17%
Oil (in ground)	0	0	0	3.35e-02	3.35e-02	0.17%
Sodium Carbonate	0	3.22e-02	0	0	3.22e-02	0.16%
Tin (Sn, ore)	2.43e-02	0	0	0	2.43e-02	0.12%

See Appendix J for complete inventory table.

CRT Utility Inputs

Utility inputs in the CRT life-cycle are presented in the inventory in Table 2-28 and include fuel (kg/functional unit), electricity (MJ/functional unit), and water (kg or L/functional unit) inputs. Figures 2-13, 2-14, and 2-15 show the total fuels, water, and electricity inputs, respectively. The fuel and electricity inputs have also been combined into a total energy input category, shown in Figure 2-16. This is also considered one of the impact categories of the LCIA that will be presented in Chapter 3. Therefore, more details on how it is calculated are available in Chapter 3. Briefly, the mass of the fuels are converted to units of energy and added to the electrical energy quantities (in units of MJ).

Table 2-28. CRT utility inputs

Material	Upstream	Mfg	Use	EOL	Total	% of total
Fuels (kg/functional unit):						
LPG	0	3.51E+02	0	3.03E-03	3.51E+02	81.10%
Natural gas (in ground)	2.76E+00	4.56E+01	0	-2.09E-01	4.82E+01	11.14%
Coal, average (in ground)	2.25E+00	1.36E+01	0	-1.16E-02	1.58E+01	3.66%
Petroleum (in ground)	2.02E+00	9.71E+00	0	-5.77E-02	1.17E+01	2.70%
Fuel oil #6	0	3.68E+00	0	0	3.68E+00	0.85%
Fuel Oil #2	0	1.16E+00	0	0	1.16E+00	0.27%
Natural gas	0	2.44E+00	0	-1.30E+00	1.14E+00	0.26%
Coal, lignite (in ground)	9.73E-01	0	0	0	9.73E-01	0.22%
LNG	0	3.35E-01	0	0	3.35E-01	0.08%
Uranium (U, ore)	1.21E-04	2.29E-04	0	-1.99E-07	3.49E-04	<0.01%
Fuel oil #4	0	1.37E-01	0	-1.38E+00	-1.24E+00	-0.29%
Total fuels	8.00E+00	4.28E+02	0	-2.95E+00	4.33E+02	100.00%
Electricity (MJ/functional unit):						
Electricity	7.32E+01	1.29E+02	2.29E+03	2.29E-01	2.49E+03	
Water (kg or L/functional unit):						
Water	5.54E+02	1.14E+04	1.14E+03	-2.73E+01	1.31E+04	
Total energy (fuels and electricity, MJ/functional unit):						
Energy	3.66E+02	1.83E+04	2.29E+03	-1.28E+02	2.08E+04	

Table 2-28 shows that LPG used in the manufacturing stage dominates the fuel inputs. LPG from the manufacturing stage is equal to about 81% of all the fuel inputs in the CRT life-cycle. More detail into the process-specific contributions within the manufacturing stage will be presented below at the end of this section. Electricity inputs, however, are dominated by the use stage (~92% of all electricity throughout the CRT life-cycle). When fuel energy and electrical energy are combined into a total energy input value, the overall energy from manufacturing greatly exceeds that from the use stage (18,300 MJ/functional unit versus 2,290 MJ/functional unit). This is depicted in Figure 2-16.

The other utility listed in Table 2-28 is water. Nearly 87% of the water inputs in the CRT life-cycle are from the manufacturing processes; and nearly 80% are from LPG production alone. The life-cycle stage contributing the next most is the use stage at 8.7%. This is from the water used to generate electricity used during the use stage. The upstream stages only contribute about 4% to the total water inputs for the CRT life-cycle. Table J-3 in Appendix J provides the complete list of inventory items for the CRT.

CRT Air Outputs

Air emissions from the CRT life cycle are dominated from the use stage as seen in Figure 2-17. This indicates that most air emissions by mass are from the generation of electricity used by consumers of the monitors. Nearly 68% of the total life-cycle air emissions by mass (or 450 kg/functional unit) are from the use stage. Carbon dioxide (CO_2) alone constitutes 445

kg/functional unit (or about 66% of all air emissions by mass in the life-cycle and nearly 99% of the use stage air emissions). Table 2-29 reveals the individual contribution of CO_2 and other inventory items that contribute to the top 99.99% of air emissions. (See Appendix J for complete inventory table.) These are organized from the air emissions that are the largest contributors to those that are the smaller contributors. Table J-4 in Appendix J shows the contribution of every air emission in the inventory, organized alphabetically. The next largest air emissions, by life-cycle stage, are emitted during the manufacturing stage, which contribute about 28% to the total life-cycle air emissions. Almost 85% of that is air emissions from the LPG production process. All the air emissions in the CRT inventory are designated as direct emissions to the ambient environment.[5]

Table 2-29. Top 99.99% of CRT air pollutant emissions (kg/functional unit)

Material	Upstream	Mfg	Use	EOL	Total	% of total
Carbon dioxide	2.92e+01	1.79e+02	4.45e+02	2.59e+00	6.55e+02	98.68%
Sulfur dioxide	3.37e-01	1.26e-01	2.49e+00	8.30e-04	2.96e+00	0.45%
Nitrogen oxides	6.99e-03	6.95e-01	1.18e+00	-1.90e-02	1.86e+00	0.28%
Methane	6.40e-02	9.08e-01	6.45e-01	-4.30e-02	1.57e+00	0.24%
Sulfur oxides	5.71e-03	8.20e-01	0	-2.97e-02	7.96e-01	0.12%
Carbon monoxide	4.18e-02	4.58e-01	8.09e-02	-4.17e-03	5.76e-01	0.09%
PM	1.28e-01	1.31e-01	0	-1.88e-02	2.40e-01	0.04%
Nonmethane hydrocarbons, remaining unspeciated	9.97e-02	1.10e-01	0	-1.91e-03	2.08e-01	0.03%
Hydrocarbons, remaining unspeciated	1.28e-02	1.58e-01	0	-6.12e-04	1.70e-01	0.03%
Hydrochloric acid	2.39e-03	1.12e-02	1.08e-01	-1.04e-03	1.20e-01	0.02%
Other organics	5.60e-04	7.83e-02	0	-3.65e-03	7.52e-02	0.01%
PM-10	0	3.15e-03	5.78e-02	4.78e-06	6.09e-02	0.01%
Nitrogen dioxide	5.76e-02	0	0	1.85e-03	5.95e-02	0.01%

CRT Water Outputs

The volume (or mass) of wastewater released throughout the CRT life-cycle is approximately 1,520 L (kg) per functional unit. Approximately 6% of that is sent to treatment as opposed to direct discharge to surface water (Figure 2-18). The mass of chemical pollutants within the wastewater streams was calculated separately. The total mass of these water pollutants released, presented by life-cycle stage, is shown in Figure 2-19. The manufacturing life-cycle stage contributes the greatest mass of water pollutants with approximately 20 kg per functional unit. This is about 96% of all the water pollutants for the entire life-cycle. The upstream stages have the second greatest mass of water pollutants at nearly 1 kg/functional unit (just under 4%). The use and EOL stages are small contributors, with the EOL being negative

[5] Note that some companies may not have reported inventory items associated with all output dispositions, as only some dispositions are used for impact calculations. For example, outputs that are treated or recycled and not directly released to the environment are not used in calculating impacts and may not have been reported. This could be applicable to all output inventories.

due to recovery processes within the EOL stage. Table 2-30 shows the major contributors to the water pollutant quantities, and reveals that sodium ion, chloride ions and dissolved solids contribute nearly 85% of all the water pollutants to the entire life-cycle. Greater than 95% of the sodium ion outputs are from LPG production and greater than 78% of the chloride ions are from LPG production. As with other input/output types, LPG production used in glass manufacturing has a large impact on the CRT inventory. For the complete inventory, listing water pollutants alphabetically and subtotaled for each life-cycle stage, see Appendix J, Table J-5. Further details on the manufacturing stage will be provided later.

Table 2-30. Top 99.9% of CRT water pollutant outputs (kg/functional unit)

Material	Disposition	Upstream	Mfg.	Use	EOL	Total	% of total
Sodium (+1)	surface water	2.90e-01	7.04e+00	0	-3.08e-02	7.30e+00	34.94%
Chloride ions	surface water	4.29e-01	6.48e+00	0	-2.39e-02	6.88e+00	32.95%
Dissolved solids	surface water	5.30e-03	3.62e+00	0	-8.77e-05	3.62e+00	17.36%
COD	surface water	1.00e-02	1.60e+00	0	-3.94e-03	1.61e+00	7.71%
Suspended solids	surface water	7.72e-03	8.69e-01	0	-2.11e-03	8.74e-01	4.19%
BOD	surface water	3.93e-04	1.95e-01	0	-4.65e-04	1.95e-01	0.93%
Waste oil	surface water	3.65e-03	1.01e-01	0	-3.13e-04	1.04e-01	0.50%
Dissolved solids	treatment	0	8.01e-02	0	0	8.01e-02	0.38%
Sulfate ion (-4)	treatment	0	1.09e-03	6.84e-02	6.84e-06	6.95e-02	0.33%
Sulfate ion (-4)	surface water	3.75e-02	9.61e-04	0	-1.85e-06	3.84e-02	0.18%
Ammonia ions	surface water	3.54e-06	2.76e-02	0	-6.63e-05	2.75e-02	0.13%
Metals, remaining unspeciated	surface water	6.74e-04	9.75e-03	0	-3.42e-05	1.04e-02	0.05%
COD	treatment	0	8.33e-03	0	0	8.33e-03	0.04%
Oil & grease	surface water	0	7.46e-03	0	0	7.46e-03	0.04%
Nitrogen	surface water	4.46e-05	7.18e-03	0	0	7.23e-03	0.03%
Calcium (+2)	surface water	4.96e-03	0	0	0	4.96e-03	0.02%
Carbonate ion	surface water	4.83e-03	0	0	0	4.83e-03	0.02%
Phenol	surface water	6.25e-05	3.63e-03	0	-9.41e-06	3.68e-03	0.02%
Fluoride	surface water	1.89e-05	3.45e-03	0	0	3.47e-03	0.02%
Salts (unspecified)	surface water	1.71e-03	1.62e-03	0	-4.21e-06	3.33e-03	0.02%
Suspended solids	treatment	0	1.29e-03	1.78e-03	1.78e-07	3.07e-03	0.01%
Fluorides (F-)	surface water	9.63e-05	2.97e-03	0	-7.72e-06	3.06e-03	0.01%

CRT Hazardous Waste Outputs

The total mass of hazardous waste generated throughout the life-cycle of the CRT (Figure 2-20) is mostly from the amount of the monitor that is assumed to be placed in a hazardous waste landfill (Table 2-31). This 7.2 kg is based on the proportion of monitors assumed to be hazardous waste as determined in Section 2.5 (EOL) and is approximately 87% of the hazardous waste generated in the EOL stage. Compared to the total mass of hazardous wastes produced throughout the CRT life-cycle, the EOL stage contributes about 88%. The disposition of the waste will be used to determine how impacts are calculated in Chapter 3. Figure 2-20 shows what portion of hazardous wastes are reported as being landfilled, recycled/reused, or treated.

The amount of hazardous waste from the upstream and manufacturing stages are negligible, by comparison. Table 2-31 and Table J-6 in Appendix J list the hazardous wastes and where each hazardous waste is disposed.

Table 2-31. Top 99.9% of CRT hazardous waste outputs (kg/functional unit)

Material	Disposition	Upstream	Mfg	Use	EOL	Total	% of total
EOL CRT monitor, landfilled	landfill	0	0	0	7.20E+00	7.20E+00	76.1%
Hazardous waste	landfill	3.85E-04	6.15E-01	0	-1.50E-03	6.14E-01	6.49%
CRT glass, cullet	R/R	0	0	0	4.84E-01	4.84E-01	5.12%
CRT glass, funnel	R/R	0	0	0	2.29E-01	2.29E-01	2.42%
Transformer	R/R	0	0	0	2.28E-01	2.28E-01	2.41%
PWB-waste cupric etchant	R/R	0	2.25E-01	0	0	2.25E-01	2.38%
Printed wiring board (PWB)	R/R	0	0	0	1.46E-01	1.46E-01	1.54%
General hazardous waste	treatment	0	1.24E-01	0	0	1.24E-01	1.31%
PWB-solder dross	R/R	0	6.70E-02	0	0	6.70E-02	0.71%
General hazardous waste	landfill	4.85E-02	0	0	-9.61E-05	4.84E-02	0.51%
PWB-decontaminating debris	treatment	0	1.55E-02	0	0	1.55E-02	0.16%
PWB-route dust	R/R	0	1.20E-02	0	0	1.20E-02	0.13%
PWB-lead contaminated waste oil	treatment	0	1.16E-02	0	0	1.16E-02	0.12%
Chrome liquid waste (D007 waste)	R/R	0	9.80E-03	0	0	9.80E-03	0.10%
Cinders from CRT glass mfg (70% PbO)	landfill	0	8.26E-03	0	0	8.26E-03	0.09%
Unspecified sludge	R/R	0	5.56E-03	0	0	5.56E-03	0.06%
Unspecified sludge	landfill	0	5.22E-03	0	0	5.22E-03	0.06%
CRT glass funnel EP dust (Pb) (D008 waste)	R/R	0	5.01E-03	0	0	5.01E-03	0.05%
Waste acid (mostly 3% HCl solution)	R/R	0	3.93E-03	0	0	3.93E-03	0.04%
Frit	landfill	0	2.99E-03	0	0	2.99E-03	0.03%
Slag and ash	landfill	0	2.47E-03	0	0	2.47E-03	0.03%
Broken CRT glass	landfill	0	1.88E-03	0	0	1.88E-03	0.02%
Hydrofluoric acid	landfill	0	1.78E-03	0	0	1.78E-03	0.02%

R/R: recycling/reuse.
See Appendix J for complete inventory table.

CRT Solid Waste Outputs

Figure 2-21 shows that both the manufacturing and use stages contribute significant amounts of solid waste by mass to the CRT life-cycle. The majority of the solid waste is landfilled. In terms of mass, the greatest contributor to the solid waste outputs for the CRT life-cycle is coal waste that is a result of generating electricity (Table 2-32). Therefore, coal waste is predominately in the use stage, which uses the most electricity, but also in the manufacturing stage, and to a much lesser degree in the EOL stage. Note that the electricity generation processes that support the secondary data used were derived from a different source (i.e., *Ecobilan*) and do not include coal waste as an output; however, the equally large amount of solid waste generated from those processes is listed as "slag and ash" in the upstream and

manufacturing inventories. Overall, the top 80% of solid waste generated in the CRT life-cycle is from coal waste, slag and ash, dust/sludge, and fly/bottom ash. Note that different inventories used in this project have varying nomenclature and some of these solid wastes may indeed overlap. Note also that the mass of a CRT monitor that is assumed to be landfilled at the EOL (3.9 kg/functional unit) is only approximately 2% of the total mass of solid waste in the CRT life-cycle. See Appendix J, Table J-7 for the complete CRT solid waste inventory.

Table 2-32. Top 99% of CRT solid waste outputs (kg/functional unit)

Material	Disposition	Upstream	Mfg	Use	EOL	Total	% of total
Coal waste	landfill	0	1.46E+00	5.09E+01	5.09E-03	5.23E+01	30.37%
Slag and ash	landfill	9.65E-02	6.66E+01	0	-1.49E+01	5.18E+01	30.06%
Dust/sludge	landfill	0	5.64E-01	1.97E+01	1.97E-03	2.02E+01	11.75%
Fly/bottom ash	landfill	0	3.65E-01	1.27E+01	1.27E-03	1.31E+01	7.59%
Unspecified solid waste	landfill	4.94E+00	0	0	-7.86E-01	4.15E+00	2.41%
EOL CRT Monitor, landfilled	landfill	0	0	0	3.91E+00	3.91E+00	2.27%
Unspecified solid waste	treatment	0	3.66E+00	0	0	3.66E+00	2.12%
Unspecified solid waste	recycle/reuse	3.07E+00	4.33E-01	0	0	3.50E+00	2.03%
Unspecified waste	landfill	0	3.38E+00	0	-1.49E-02	3.36E+00	1.95%
EOL CRT Monitor, incinerated	treatment	0	0	0	3.31E+00	3.31E+00	1.92%
Iron scrap	recycle/reuse	3.43E-01	0	0	2.50E+00	2.85E+00	1.65%
EOL CRT Monitor, recycled	recycle/reuse	0	0	0	2.42E+00	2.42E+00	1.40%
Broken CRT glass	recycle/reuse	0	1.08E+00	0	0	1.08E+00	0.62%
Mixed industrial (waste)	landfill	4.87E-02	1.00E+00	0	-5.12E-04	1.05E+00	0.61%
Slag and ash	recycle/reuse	0	6.85E-01	0	-3.01E-03	6.82E-01	0.40%
EOL CRT Monitor, remanufactured	recycle/reuse	0	0	0	6.60E-01	6.60E-01	0.38%
Mining waste	landfill	4.48E-01	0	0	-1.90E-06	4.48E-01	0.26%
Mineral waste	landfill	4.42E-01	2.61E-03	0	-6.76E-06	4.44E-01	0.26%
Carbon Steel Scrap	recycle/reuse	0	0	0	4.10E-01	4.10E-01	0.24%
flame retardant high-impact polystyrene (HIPS)	recycle/reuse	0	0	0	4.03E-01	4.03E-01	0.23%
Waste water treatment (WWT) sludge	recycle/reuse	0	3.72E-01	0	0	3.72E-01	0.22%
Ferric chloride	recycle/reuse	0	3.69E-01	0	0	3.69E-01	0.21%
CRT glass, faceplate	recycle/reuse	0	0	0	3.54E-01	3.54E-01	0.21%

CRT Radioactive Waste Outputs

Radioactive waste outputs in the CRT inventory are found only in the electricity generation and cold-rolled steel production process. Therefore, radioactive wastes will be found wherever electricity is used in a process in the CRT life-cycle. Only very small amounts (approximately 0.003 kg/functional unit) of radioactive waste are generated over the entire life-cycle of the CRT (Figure 2-22 and Table 2-33). As expected, the majority of this is linked to the use stage, where most electricity is used in the CRT life-cycle. Low-level radioactive waste (79%) and depleted uranium (20%) are most of the waste, with very small amounts of highly radioactive waste and some unspecified radioactive waste in the inventory. The inventory of radioactive waste outputs is small, and therefore, Table 2-33 lists all material outputs associated

with radioactive waste, in descending order of quantity. Table J-8 in Appendix J lists these in alphabetical order.

Table 2-33. CRT radioactive waste outputs (kg/functional unit)

Material	Disposition	Upstream	Mfg	Use	EOL	Total	% of total
Low-level radioactive waste	landfill	4.11E-04	1.38E-04	1.76E-03	1.76E-07	2.31E-03	79.5%
Uranium, depleted	landfill	0	4.15E-05	5.27E-04	5.27E-08	5.69E-04	19.6%
Radioactive waste (unspecified)	landfill	1.88E-05	0	0	0	1.88E-05	0.6%
Highly radioactive waste (Class C)	landfill	8.65E-06	0	0	0	8.65E-06	0.3%
Total radioactive wastes		4.39E-04	1.80E-04	2.28E-03	2.29E-07	2.90E-03	100.0%

CRT Radioactivity Outputs

Radioactivity is also inventoried in this project as isotopes that are released to the environment. Radioactivity is measured in Bequerels and may be released to air, water, or land. The quantity of radioactivity for each life-cycle stage and different dispositions is presented in Figure 2-23. Table 2-34 shows the top 99.9% of the radioactivity outputs.

Table 2-34. Top 99.9% of CRT radioactivity outputs (Bq/functional unit)

Material	Disposition	Upstream	Mfg	Use	EOL	Total	% of total
Molybdenum-99 (isotope)	treatment	0	3.72e+06	4.73e+07	4.73e+03	5.10e+07	56.75%
Plutonium-241 (isotope)	landfill	3.74e+07	0	0	0	3.74e+07	41.67%
Xenon-133 (isotope)	air	2.43e+03	6.28e+03	3.12e+05	3.12e+01	3.21e+05	0.36%
Tritium-3 (isotope)	treatment	0	2.20e+04	2.80e+05	2.80e+01	3.02e+05	0.34%
Plutonium-240 (isotope)	landfill	1.62e+05	0	0	0	1.62e+05	0.18%
Cesium-135 (isotope)	landfill	1.46e+05	0	0	0	1.46e+05	0.16%
Radon-222 (isotope)	air	1.37e+05	0	0	0	1.37e+05	0.15%
Plutonium-239 (isotope)	landfill	1.14e+05	0	0	0	1.14e+05	0.13%
Xenon-133 (isotope)	treatment	0	3.48e+03	4.43e+04	4.43e+00	4.78e+04	0.05%
Tritium-3 (isotope)	air	3.47e+02	2.95e+03	3.74e+04	3.75e+00	4.07e+04	0.05%
Xenon-133M (isotope)	air	0	1.99e+04	2.07e+04	2.07e+00	4.06e+04	0.05%
Krypton-85 (isotope)	air	1.73e+02	2.08e+03	2.65e+04	2.65e+00	2.87e+04	0.03%

See Appendix J for complete inventory table.

Radioactivity outputs are related to the generation of electricity and therefore the greatest quantity of radioactivity is from the use stage, as expected. Table J-9 in Appendix J lists the complete inventory.

CRT Manufacturing Stage

The inventory tables that show the specific materials (i.e., those in Appendix J and Tables 2-26 through 2-34) are the sums of the materials from one or more processes within a life-cycle stage. To burrow down deeper into the data, the manufacturing stage inventory data are broken

down by process or group of processes. Groups of processes were combined when fewer than three companies provided data for a process or when confidentiality agreements precluded presenting individual process data. The manufacturing process groups are presented in Table 2-35. Also for confidentiality purposes, upstream and EOL data (derived from *Ecobilan's* data) were not broken down by process. Burrowing further into the contributing processes or process groups is necessary for future manufacturing improvement assessments. Burrowing further into process-specific data at the use stage is not necessary because electricity generation is the only process in the use stage.

Table 2-35. CRT process groups

Process group	Process(es) included
Monitor assembly	monitor assembly
Tube	CRT (tube) manufacturing
Glass/frit	CRT glass manufacturing, frit manufacturing
PWB	PWB manufacturing
Japanese grid	electricity generation - Japanese electric grid
U.S. grid	electricity generation - U.S. electric grid
Fuels	production of fuel oils #2, #4 and #6, LPG, and natural gas

Tables 2-36 through 2-44 list the specific inventories for each process group in the manufacturing stage for each input and output type. Figures 2-24 through 2-34 graph the total inventories for each process group for each input and output type. It should be noted that the input/output type that had the greatest contribution in the manufacturing stage compared to other stages was fuel inputs, which also translated into total energy inputs being greatest in the manufacturing stage. Nonetheless, for purposes of showing more detail in the manufacturing stage and allowing for improvement assessments for manufacturers, the individual material contributions for each manufacturing process group are presented below.

Of the total 421 kg of primary materials per functional unit in the manufacturing stage, fuels production contributes the greatest (374 kg/functional unit), followed by monitor assembly (20.1 kg/functional unit), and then tube manufacturing (11.9 kg/functional unit) (Figure 2-24). The specific material contributions are presented in Table 2-36. Only small amounts of ancillary materials are used in the CRT life cycle and the manufacturing stage only contributed a small percentage of the overall ancillary materials in the life-cycle. However, within the manufacturing life-cycle stage, fuels production and PWB manufacturing had the greatest amount of ancillary materials (1.16 kg/functional unit each) (Figure 2-25).

Table 2-36. CRT manufacturing stage primary material inputs

Material	Quantity (kg/ (functional unit)	% of process group total	% of grand total
Process group			
Monitor assembly			
ABS resin	4.24e-01	2.11%	
Aluminum (elemental)	3.60e-01	1.79%	
Audio cable assembly	9.45e-02	0.47%	
Cables/wires	6.12e-02	0.31%	
Cables/wires	3.33e-01	1.66%	
Cathode ray tube (CRT)	1.07e+01	53.30%	
Connector	5.67e-02	0.28%	
CRT magnet assembly	7.56e-02	0.38%	
CRT shield assembly - ASTM A366/CC#2	2.42e-01	1.21%	
Deflection Yoke assembly	1.51e-01	0.75%	
Demagnetic coil - PU coated paper	1.26e-01	0.63%	
Ferrite	1.70e-01	0.85%	
Phosphate ester	8.31e-03	0.04%	
Polycarbonate resin	9.23e-01	4.60%	
Polystyrene (PS, high impact)	1.51e-01	0.75%	
Power cord assembly	1.13e-01	0.57%	
PPE	7.35e-01	3.66%	
Printed wiring board (PWB)	8.47e-01	4.22%	
Solder, unspecified	2.67e-02	0.13%	
Steel	3.45e+00	17.21%	
Styrene-butadiene copolymers	8.27e-01	4.13%	
Tricresyl phosphate	2.30e-02	0.11%	
Triphenyl phosphate	5.29e-02	0.26%	
Video cable assembly	1.13e-01	0.57%	
Total	**2.01e+01**	100.00%	**4.76%**
Tube			
Amyl acetate (mixed isomers)	1.20e-03	0.01%	
Aquadag	2.06e-02	0.17%	
Blue Phosphor (ZnS)	3.84e-03	0.03%	
Blue Phosphor (ZnS.Ag.Al)	1.67e-03	0.01%	
CRT glass, unspecified	9.76e+00	81.70%	
Electron gun	1.01e-01	0.84%	
Frit	6.67e-02	0.56%	
Green Phosphor (ZnS)	3.34e-03	0.03%	
Green Phosphor (ZnS.Cu.Al)	1.34e-03	0.01%	
Nickel Alloy (invar)	2.72e-01	2.28%	
Red Phosphor (Y2O2S)	4.65e-03	0.04%	
Red Phosphor (Y2O2S.Eu)	1.33e-03	0.01%	
Steel	1.71e+00	14.30%	
Total	**1.19e+01**	100.00%	**2.84%**

Table 2-36. CRT manufacturing stage primary material inputs

Material	Quantity (kg/ (functional unit)	% of process group total	% of grand total
Process group			
Glass/frit			
Barium Carbonate	2.97e-01	4.52%	
Glass, unspecified	4.91e-02	0.75%	
Lead	4.47e-01	6.82%	
Potassium Carbonate	3.78e-01	5.76%	
Recycled CRT Glass	2.06e+00	31.37%	
Sand	2.40e+00	36.57%	
Sodium Carbonate	4.88e-01	7.43%	
Strontium Carbonate	3.31e-01	5.05%	
Zircon Sand	5.43e-02	0.83%	
Borax	8.00e-03	0.12%	
Lead	4.67e-02	0.71%	
Silica	5.33e-03	0.08%	
Total	**6.56e+00**	100.00%	**1.56%**
PWB			
PWB-laminate	8.47e-01	94.35%	
Solder (63% tin; 37% lead)	5.08e-02	5.66%	
Total	**8.98e-01**	100.00%	**0.21%**
Japanese grid			
Coal, average (in ground)	2.28e+00	47.41%	
Natural gas	1.25e+00	25.89%	
Petroleum (in ground)	1.29e+00	26.69%	
Uranium, yellowcake	3.04e-04	0.01%	
Total	**4.82e+00**	100.00%	**1.14%**
U.S. grid			
Coal, average (in ground)	2.86e+00	90.97%	
Natural gas	2.23e-01	7.10%	
Petroleum (in ground)	6.07e-02	1.93%	
Uranium, yellowcake	7.74e-05	<0.01%	
Total	**3.15e+00**	100.00%	**0.75%**
Fuels			
Petroleum (in ground)	3.70e+02	99.12%	
Natural gas (in ground)	3.27e+00	0.88%	
Total	**3.74e+02**	100.00%	**88.74%**
Grand Total	**4.21e+02**		**100.00%**

Table 2-37. CRT manufacturing stage ancillary material inputs

Material	Quantity (kg/ (functional unit)	% of process group total	% of grand total
Process group			
Monitor assembly			
2,2,4-trimethylpentane	1.50e-04	0.72%	
Cyclohexane	1.88e-04	0.90%	
Fluorocarbon resin	3.75e-05	0.18%	
Isopropyl alcohol	1.94e-02	93.40%	
Surfactant, unspecified	1.42e-04	0.68%	
Synthetic resin, unspecified	8.53e-04	4.10%	
Total	**2.08e-02**	**100.00%**	**0.59%**
Tube			
Acetone	3.17e-04	0.04%	
Acrylic Polymer, unspecified	9.13e-03	1.02%	
Alkali cleaning agent	7.72e-02	8.61%	
Alkali soda (to neutralize acid waste water)	5.45e-02	6.08%	
Ammonia	1.19e-04	0.01%	
Ammonium bifluoride	2.04e-03	0.23%	
Ammonium Dichromate	3.50e-05	<0.01%	
Ammonium fluoride	8.91e-04	0.10%	
Ammonium hydroxide	1.41e-03	0.16%	
Ammonium Oxalate	8.92e-05	0.01%	
Ammonium Oxalate Monohydrate	3.16e-04	0.04%	
Boric acid	4.73e-03	0.53%	
Calcium Chloride	1.27e-01	14.18%	
Calcium hydroxide	9.54e-02	10.64%	
Chlorine	4.03e-02	4.50%	
Chromium (VI)	7.63e-05	0.01%	
Dimethyl Formamide	4.36e-05	<0.01%	
Ferric chloride	1.37e-01	15.32%	
HV Carbon (paste)	1.14e-05	<0.01%	
Hydrochloric acid	4.39e-02	4.89%	
Hydrofluoric acid	7.39e-03	0.82%	
Hydrogen peroxide	5.34e-02	5.96%	
Isopentylacetate	1.74e-03	0.19%	
Muratic Acid (drum)	1.87e-03	0.21%	
Nitric acid	8.17e-03	0.91%	
Nitrogen	4.57e-02	5.10%	
Oxalic acid	5.35e-05	0.01%	
Oxygen (Liquid)	7.57e-03	0.84%	
Periodic Acid	2.26e-04	0.03%	
Polyvinyl alcohol	8.11e-03	0.90%	
Polyvinyl Pyrrolidone (PVP)	2.41e-02	2.69%	
Sodium Dichromate	1.05e-04	0.01%	

Table 2-37. CRT manufacturing stage ancillary material inputs

Material	Quantity (kg/ (functional unit)	% of process group total	% of grand total
Process group			
Sodium Dichromate Dihydrate (VI)	3.10e-05	<0.01%	
Sodium hydroxide	3.52e-03	0.39%	
Sodium Hypochlorite	9.25e-05	0.01%	
Sodium Metabisulfite	4.67e-03	0.52%	
Sodium Persulfate	3.54e-04	0.04%	
Sulfuric acid	5.58e-02	6.23%	
Sulfuric acid, aluminum salt	6.75e-02	7.53%	
Toluene	4.80e-03	0.54%	
unspecified CRT process material	5.77e-03	0.64%	
Xylene (mixed isomers)	4.80e-04	0.05%	
Total	**8.97e-01**	**100.00%**	**25.36%**
Glass/frit			
Aluminum Oxide	3.37e-02	17.30%	
Cerium Oxide	3.28e-03	1.68%	
Chromium Oxide	5.62e-05	0.03%	
Hydrofluoric acid	7.91e-02	40.61%	
Pumice	7.86e-02	40.37%	
Total	**1.95e-01**	**100.00%**	**5.51%**
PWB			
Ammonium chloride	7.76e-02	6.68%	
Ammonium hydroxide	7.76e-02	6.68%	
Formaldehyde	6.60e-03	0.57%	
Glycol ethers	2.35e-02	2.03%	
Hydrochloric acid	1.92e-01	16.51%	
Hydrogen peroxide	3.10e-02	2.67%	
Nitric acid	1.36e-01	11.70%	
Polyethylene glycol	5.04e-02	4.34%	
Potassium hydroxide	4.27e-02	3.68%	
Potassium permanganate	1.16e-03	0.10%	
Potassium peroxymonosulfate	7.06e-02	6.08%	
PWB-solder mask solids	4.37e-02	3.76%	
Sodium Carbonate	3.22e-02	2.77%	
Sodium hydroxide	1.94e-01	16.71%	
Sulfuric acid	1.83e-01	15.72%	
Total	**1.16e+00**	**100.00%**	**32.84%**
Japanese grid			
Lime	1.35e-02	30.57%	
Limestone	3.06e-02	69.43%	
Total	**4.41e-02**	100.00%	**1.25%**
U.S. grid			
Lime	1.69e-02	30.52%	

Table 2-37. CRT manufacturing stage ancillary material inputs

Material	Quantity (kg/ (functional unit)	% of process group total	% of grand total
Process group			
Limestone	3.85e-02	69.48%	
Total	**5.53e-02**	100.00%	**1.57%**
Fuels			
Bauxite (Al2O3, ore)	4.47e-02	3.85%	
Limestone (CaCO3, in ground)	1.08e+00	92.71%	
Sand (in ground)	2.74e-02	2.36%	
Sodium chloride (NaCl, in ground or in sea)	1.26e-02	1.08%	
Total	**1.16e+00**	100.00%	**32.89%**
Grand Total	**3.54e+00**		**100.00%**

Table 2-38. CRT manufacturing stage utility inputs

Material	Quantity	% of process group total	% of grand total
Process group			
Fuels (kg/functional unit):			
Monitor assembly			
Fuel oil #4	**1.37e-01**		**0.03%**
Tube			
Fuel oil #6	3.68e+00	75.86%	
LNG	3.35e-01	6.91%	
Natural gas	8.37e-01	17.23%	
Total	**4.86e+00**	100.00%	**1.14%**
Glass/frit			
Fuel oil #2	1.16e+00	0.33%	
Liquified petroleum gas (LPG)	3.51e+02	99.33%	
Natural gas	1.21e+00	0.34%	
Total	**3.53e+02**	100.00%	**82.62%**
PWB			
Natural gas	**3.91e-01**		**0.09%**
Fuels			
Coal, average (in ground)	1.36e+01	19.71%	
Natural gas (in ground)	4.56e+01	66.20%	
Petroleum (in ground)	9.71e+00	14.08%	
Uranium (U, ore)	2.29e-04	<0.01%	
Total	**6.89e+01**	100.00%	**16.12%**
Grand Total	**4.28e+02**		**100.00%**
Electricity (MJ/functional unit):			
Monitor assembly	1.33e+01		10.27%
Tube	3.19e+01		24.68%
Glass/frit	7.40e+01		57.27%
PWB	1.00e+01		7.77%
Total	**1.29e+02**		**100.00%**
Water (kg or L/functional unit):			
Monitor assembly	3.51e+01		0.31%
Tube	8.11e+02		7.09%
Glass/frit	0		0.00%
PWB	4.22e+01		0.37%
Japanese grid	4.43e+01		0.39%
U.S. grid	1.82e+01		0.16%
Fuels	1.05e+04		91.69%
Total	**1.14e+04**		**100.00%**
Total energy (fuels and electricity, MJ/functional unit):			
Monitor assembly	1.90e+01		0.10%
Tube	2.37e+02		1.29%

Table 2-38. CRT manufacturing stage utility inputs

Material	Quantity	% of process group total	% of grand total
Process group			
Glass/frit	1.52e+04		83.23%
PWB	2.74e+01		0.15%
Fuels	2.79e+03		15.22%
Total	**1.83e+04**		**100.00%**

Table 2-39. CRT manufacturing stage air emissions

Material	Quantity (kg/ (functional unit)	% of process group total	% of grand total
Process group			
Tube			
Carbon monoxide	1.70E-02	50.61%	
Dimethyl Formamide	3.49E-05	0.10%	
Nitrogen oxides	2.17E-03	6.48%	
Nonmethane hydrocarbons, remaining unspeciated	1.59E-04	0.47%	
Sulfur oxides	9.96E-03	29.73%	
Toluene	3.84E-03	11.46%	
Xylene (mixed isomers)	3.84E-04	1.15%	
Total	**3.35E-02**	100.00%	**0.02%**
Glass/frit			
Barium	9.33E-10	<0.01%	
Carbon dioxide	2.85E+00	98.45%	
Carbon monoxide	1.64E-04	0.01%	
Chromium	1.39E-07	<0.01%	
Cobalt	1.43E-10	<0.01%	
Copper	6.33E-10	<0.01%	
Fluorides (F-)	2.93E-05	<0.01%	
Lead	3.22E-07	<0.01%	
Manganese	4.67E-10	<0.01%	
Nickel	5.33E-10	<0.01%	
Nitrogen oxides	4.47E-02	1.54%	
PM	1.10E-04	<0.01%	
Sulfur oxides	5.08E-05	<0.01%	
Zinc (elemental)	4.67E-09	<0.01%	
Total	**2.90E+00**	100.00%	**1.59%**
PWB			
Formaldehyde	**3.88E-05**		**0.00%**
Japanese grid			
1,1,1-Trichloroethane	6.46E-08	<0.01%	
1,2-Dichloroethane	4.57E-08	<0.01%	
2,3,7,8-TCDD	1.68E-14	<0.01%	
2,3,7,8-TCDF	5.84E-14	<0.01%	
2,4-Dinitrotoluene	3.19E-10	<0.01%	
2-Chloroacetophenone	8.00E-09	<0.01%	
2-Methylnaphthalene	2.38E-10	<0.01%	
5-Methyl chrysene	2.51E-11	<0.01%	
Acenaphthene	4.32E-09	<0.01%	
Acenaphthylene	3.29E-10	<0.01%	
Acetaldehyde	6.52E-07	<0.01%	
Acetophenone	1.71E-08	<0.01%	
Acrolein	3.31E-07	<0.01%	

Table 2-39. CRT manufacturing stage air emissions

Material	Quantity (kg/ (functional unit)	% of process group total	% of grand total
Process group			
Anthracene	4.55E-10	<0.01%	
Antimony	9.50E-07	<0.01%	
Arsenic	7.01E-07	<0.01%	
Barium	5.18E-07	<0.01%	
Benzene	1.52E-06	<0.01%	
Benzo[a]anthracene	8.00E-10	<0.01%	
Benzo[a]pyrene	4.35E-11	<0.01%	
Benzo[b,j,k]fluoranthene	3.89E-10	<0.01%	
Benzo[g,h,i]perylene	4.30E-10	<0.01%	
Benzyl chloride	8.00E-07	<0.01%	
Beryllium	3.23E-08	<0.01%	
Biphenyl	1.94E-09	<0.01%	
Bromoform	4.46E-08	<0.01%	
Bromomethane	1.83E-07	<0.01%	
Cadmium	1.41E-07	<0.01%	
Carbon dioxide	1.54E+01	99.14%	
Carbon disulfide	1.49E-07	<0.01%	
Carbon monoxide	2.80E-03	0.02%	
Chloride ions	6.14E-05	<0.01%	
Chlorobenzene	2.51E-08	<0.01%	
Chloroform	6.74E-08	<0.01%	
Chromium (III)	5.52E-07	<0.01%	
Chromium (VI)	1.34E-07	<0.01%	
Chrysene	5.35E-10	<0.01%	
Cobalt	1.18E-06	<0.01%	
Copper	3.18E-07	<0.01%	
Cumene hydroperoxide	6.06E-09	<0.01%	
Cyanide (-1)	2.86E-06	<0.01%	
Di(2-ethylhexyl)phthalate	8.34E-08	<0.01%	
Dibenzo[a,h]anthracene	2.96E-10	<0.01%	
Dichloromethane	3.31E-07	<0.01%	
Dimethyl sulfate	5.49E-08	<0.01%	
Dioxins, remaining unspeciated	7.46E-13	<0.01%	
Ethyl Chloride	4.80E-08	<0.01%	
Ethylbenzene	1.19E-07	<0.01%	
Ethylene dibromide	1.37E-09	<0.01%	
Fluoranthene	1.75E-09	<0.01%	
Fluorene	1.83E-09	<0.01%	
Fluorides (F-)	6.60E-06	<0.01%	
Formaldehyde	1.02E-05	<0.01%	
Furans, remaining unspeciated	1.19E-12	<0.01%	

Table 2-39. CRT manufacturing stage air emissions

Material	Quantity (kg/ (functional unit)	% of process group total	% of grand total
Process group			
Hexane	7.66E-08	<0.01%	
Hydrochloric acid	1.37E-03	<0.01%	
Hydrofluoric acid	1.71E-04	<0.01%	
Indeno(1,2,3-cd)pyrene	4.48E-10	<0.01%	
Isophorone	6.63E-07	<0.01%	
Lead (Pb, ore)	4.41E-07	<0.01%	
Magnesium	1.26E-05	<0.01%	
Manganese (Mn, ore)	1.09E-06	<0.01%	
Mercury	1.18E-07	<0.01%	
Methane	8.13E-05	<0.01%	
Methyl chloride	6.06E-07	<0.01%	
Methyl ethyl ketone	4.46E-07	<0.01%	
Methyl hydrazine	1.94E-07	<0.01%	
Methyl methacrylate	2.29E-08	<0.01%	
Methyl tert-butyl ether	3.99E-08	<0.01%	
Molybdenum	1.55E-07	<0.01%	
Naphthalene	2.21E-07	<0.01%	
Nickel	1.47E-05	<0.01%	
Nitrogen oxides	4.07E-02	0.26%	
Nitrous oxide	1.12E-04	<0.01%	
o-xylene	1.93E-08	<0.01%	
Phenanthrene	5.21E-09	<0.01%	
Phenol	1.83E-08	<0.01%	
PM-10	2.00E-03	0.01%	
Propionaldehyde	4.34E-07	<0.01%	
Pyrene	1.26E-09	<0.01%	
Selenium	1.61E-06	<0.01%	
Styrene	2.86E-08	<0.01%	
Sulfur dioxide	8.62E-02	0.56%	
Tetrachloroethylene	4.92E-08	<0.01%	
TOCs, remaining unspeciated	1.97E-04	<0.01%	
Toluene	1.43E-06	<0.01%	
Vanadium	5.71E-06	<0.01%	
Vinyl acetate	8.67E-09	<0.01%	
Xylene (mixed isomers)	4.23E-08	<0.01%	
Zinc (elemental)	5.15E-06	<0.01%	
Total	**1.55E+01**	100.00%	**8.50%**
U.S. grid			
1,1,1-Trichloroethane	3.06E-08	<0.01%	
1,2-Dichloroethane	5.73E-08	<0.01%	
2,3,7,8-TCDD	2.05E-14	<0.01%	

Table 2-39. CRT manufacturing stage air emissions

Material	Quantity (kg/ (functional unit)	% of process group total	% of grand total
Process group			
2,3,7,8-TCDF	7.30E-14	<0.01%	
2,4-Dinitrotoluene	4.01E-10	<0.01%	
2-Chloroacetophenone	1.00E-08	<0.01%	
2-Methylnaphthalene	4.26E-11	<0.01%	
5-Methyl chrysene	3.15E-11	<0.01%	
Acenaphthene	9.06E-10	<0.01%	
Acenaphthylene	3.60E-10	<0.01%	
Acetaldehyde	8.16E-07	<0.01%	
Acetophenone	2.15E-08	<0.01%	
Acrolein	4.15E-07	<0.01%	
Anthracene	3.11E-10	<0.01%	
Antimony	6.96E-08	<0.01%	
Arsenic	5.99E-07	<0.01%	
Barium	3.28E-08	<0.01%	
Benzene	1.86E-06	<0.01%	
Benzo[a]anthracene	1.48E-10	<0.01%	
Benzo[a]pyrene	5.44E-11	<0.01%	
Benzo[b,j,k]fluoranthene	1.70E-10	<0.01%	
Benzo[g,h,i]perylene	5.75E-11	<0.01%	
Benzyl chloride	1.00E-06	<0.01%	
Beryllium	3.05E-08	<0.01%	
Biphenyl	2.43E-09	<0.01%	
Bromoform	5.58E-08	<0.01%	
Bromomethane	2.29E-07	<0.01%	
Cadmium	7.69E-08	<0.01%	
Carbon dioxide	7.10E+00	98.98%	
Carbon disulfide	1.86E-07	<0.01%	
Carbon monoxide	1.29E-03	0.02%	
Chloride ions	2.90E-06	<0.01%	
Chlorobenzene	3.15E-08	<0.01%	
Chloroform	8.45E-08	<0.01%	
Chromium (III)	3.88E-07	<0.01%	
Chromium (VI)	1.15E-07	<0.01%	
Chrysene	1.63E-10	<0.01%	
Cobalt	1.94E-07	<0.01%	
Copper	1.59E-08	<0.01%	
Cumene	7.59E-09	<0.01%	
Cyanide (-1)	3.58E-06	<0.01%	
Di(2-ethylhexyl)phthalate	1.04E-07	<0.01%	
Dibenzo[a,h]anthracene	1.40E-11	<0.01%	
Dichloromethane	4.15E-07	<0.01%	

Table 2-39. CRT manufacturing stage air emissions

Material	Quantity (kg/ (functional unit)	% of process group total	% of grand total
Process group			
Dimethyl sulfate	6.87E-08	<0.01%	
Dioxins, remaining unspeciated	9.33E-13	<0.01%	
Ethyl Chloride	6.01E-08	<0.01%	
Ethylbenzene	1.35E-07	<0.01%	
Ethylene dibromide	1.72E-09	<0.01%	
Fluoranthene	1.07E-09	<0.01%	
Fluorene	1.34E-09	<0.01%	
Fluoride	3.12E-07	<0.01%	
Formaldehyde	1.35E-06	<0.01%	
Furans, remaining unspeciated	1.49E-12	<0.01%	
Hexane	9.59E-08	<0.01%	
Hydrochloric acid	1.72E-03	0.02%	
Hydrofluoric acid	2.15E-04	<0.01%	
Indeno(1,2,3-cd)pyrene	1.05E-10	<0.01%	
Isophorone	8.30E-07	<0.01%	
Lead	2.04E-07	<0.01%	
Magnesium	1.57E-05	<0.01%	
Manganese	7.28E-07	<0.01%	
Mercury	1.20E-07	<0.01%	
Methane	1.03E-02	0.14%	
Methyl chloride	7.59E-07	<0.01%	
Methyl ethyl ketone	5.58E-07	<0.01%	
Methyl hydrazine	2.43E-07	<0.01%	
Methyl methacrylate	2.86E-08	<0.01%	
Methyl tert-butyl ether	5.01E-08	<0.01%	
Molybdenum	9.32E-09	<0.01%	
Naphthalene	2.92E-08	<0.01%	
Nickel	1.09E-06	<0.01%	
Nitrogen oxides	1.88E-02	0.26%	
Nitrous oxide	5.42E-05	<0.01%	
o-xylene	9.11E-10	<0.01%	
Phenanthrene	4.00E-09	<0.01%	
Phenol	2.29E-08	<0.01%	
Phosphorus (yellow or white)	7.91E-08	<0.01%	
PM-10	9.22E-04	0.01%	
Propionaldehyde	5.44E-07	<0.01%	
Pyrene	5.32E-10	<0.01%	
Selenium	1.87E-06	<0.01%	
Styrene	3.58E-08	<0.01%	
Sulfur dioxide	3.98E-02	0.56%	
Tetrachloroethylene	6.16E-08	<0.01%	

Table 2-39. CRT manufacturing stage air emissions

Material	Quantity (kg/ (functional unit)	% of process group total	% of grand total
Process group			
TOCs, remaining unspeciated	9.19E-05	<0.01%	
Toluene	4.06E-07	<0.01%	
Vanadium	2.81E-07	<0.01%	
Vinyl acetate	1.09E-08	<0.01%	
Xylene (mixed isomers)	5.30E-08	<0.01%	
Zinc (elemental)	2.43E-07	<0.01%	
Total	**7.17E+00**	100.00%	**3.93%**
Fuels			
1,1,1-Trichloroethane	1.36E-07	<0.01%	
1,2-Dichloroethane	2.71E-07	<0.01%	
1,4-Dichlorobenzene	3.06E-07	<0.01%	
2,4-Dinitrotoluene	1.90E-09	<0.01%	
2-Chloroacetophenone	4.75E-08	<0.01%	
2-Methylnaphthalene	6.11E-09	<0.01%	
3-Methylcholanthrene	4.59E-10	<0.01%	
5-Methyl chrysene	1.49E-10	<0.01%	
Acenaphthene	5.31E-09	<0.01%	
Acenaphthylene	2.17E-09	<0.01%	
Acetaldehyde	3.86E-06	<0.01%	
Acetophenone	1.02E-07	<0.01%	
Acrolein	1.97E-06	<0.01%	
Aldehydes	1.52E-03	<0.01%	
Aluminum (elemental)	1.98E-05	<0.01%	
Ammonia	2.35E-03	<0.01%	
Anthracene	2.12E-09	<0.01%	
Antimony	6.36E-07	<0.01%	
Aromatic hydrocarbons	5.29E-08	<0.01%	
Arsenic	1.41E-05	<0.01%	
Barium	3.33E-07	<0.01%	
Benzene	1.57E-02	0.01%	
Benzo[a]anthracene	1.27E-09	<0.01%	
Benzo[a]pyrene	6.94E-10	<0.01%	
Benzo[b,j,k]fluoranthene	7.46E-10	<0.01%	
Benzo[b]fluoranthene	5.07E-10	<0.01%	
Benzo[g,h,i]perylene	5.63E-10	<0.01%	
Benzo[k]fluoranthene	5.07E-10	<0.01%	
Benzyl chloride	4.75E-06	<0.01%	
Beryllium	1.42E-06	<0.01%	
Biphenyl	1.15E-08	<0.01%	
Bromoform	2.64E-07	<0.01%	
Bromomethane	1.08E-06	<0.01%	

Table 2-39. CRT manufacturing stage air emissions

Material	Quantity (kg/ (functional unit)	% of process group total	% of grand total
Process group			
Butane	5.35E-04	<0.01%	
Cadmium	8.20E-07	<0.01%	
Calcium	1.72E-05	<0.01%	
Carbon dioxide	1.54E+02	97.92%	
Carbon disulfide	8.81E-07	<0.01%	
Carbon monoxide	4.36E-01	0.28%	
Chloride ions	3.39E-05	<0.01%	
Chlorine	5.84E-09	<0.01%	
Chlorobenzene	1.49E-07	<0.01%	
Chloroform	4.00E-07	<0.01%	
Chromium (III)	2.13E-05	<0.01%	
Chromium (VI)	2.13E-05	<0.01%	
Chrysene	1.22E-09	<0.01%	
Cobalt	2.54E-06	<0.01%	
Copper	1.57E-06	<0.01%	
Cumene	3.59E-08	<0.01%	
Cyanide (-1)	1.69E-05	<0.01%	
Di(2-ethylhexyl)phthalate	4.95E-07	<0.01%	
Dibenzo[a,h]anthracene	3.61E-10	<0.01%	
Dichloromethane	1.97E-06	<0.01%	
Dimethyl sulfate	3.25E-07	<0.01%	
Dimethylbenzanthracene	3.82E-09	<0.01%	
Dioxins, remaining unspeciated	1.10E-10	<0.01%	
Ethane	7.90E-04	<0.01%	
Ethyl Chloride	2.85E-07	<0.01%	
Ethylbenzene	6.44E-07	<0.01%	
Ethylene dibromide	8.14E-09	<0.01%	
Fluoranthene	5.74E-09	<0.01%	
Fluorene	7.03E-09	<0.01%	
Fluorides (F-)	3.84E-06	<0.01%	
Formaldehyde	1.19E-03	<0.01%	
Furans, remaining unspeciated	5.11E-10	<0.01%	
Halogenated hydrocarbons (unspecified)	2.94E-13	<0.01%	
HALON-1301	5.11E-10	<0.01%	
Hexane	4.59E-04	<0.01%	
Hydrocarbons, remaining unspeciated	1.58E-01	0.10%	
Hydrochloric acid	8.14E-03	<0.01%	
Hydrofluoric acid	1.02E-03	<0.01%	
Hydrogen sulfide	3.11E-03	<0.01%	
Indeno(1,2,3-cd)pyrene	9.43E-10	<0.01%	
Iron	3.83E-05	<0.01%	

Table 2-39. CRT manufacturing stage air emissions

Material	Quantity (kg/ (functional unit)	% of process group total	% of grand total
Process group			
Isophorone	3.93E-06	<0.01%	
Lead	1.25E-05	<0.01%	
Magnesium	7.46E-05	<0.01%	
Manganese	2.26E-05	<0.01%	
Mercury	8.81E-07	<0.01%	
Metals, remaining unspeciated	3.16E-07	<0.01%	
Methane	8.98E-01	0.57%	
Methyl chloride	3.59E-06	<0.01%	
Methyl ethyl ketone	2.64E-06	<0.01%	
Methyl hydrazine	1.15E-06	<0.01%	
Methyl methacrylate	1.36E-07	<0.01%	
Methyl tert-butyl ether	2.37E-07	<0.01%	
Molybdenum	1.97E-06	<0.01%	
Naphthalene	3.54E-07	<0.01%	
Nickel	1.24E-04	<0.01%	
Nitrogen oxides	5.88E-01	0.37%	
Nitrous oxide	1.64E-02	0.01%	
Nonmethane hydrocarbons, remaining unspeciated	1.10E-01	0.07%	
n-Propane	1.69E-06	<0.01%	
Other organics	7.83E-02	0.05%	
o-xylene	1.11E-06	<0.01%	
Pentane	6.62E-04	<0.01%	
Phenanthrene	2.30E-08	<0.01%	
Phenol	1.08E-07	<0.01%	
Phosphorus (yellow or white)	1.25E-05	<0.01%	
PM	1.31E-01	0.08%	
PM-10	2.28E-04	<0.01%	
Polycyclic aromatic hydrocarbons	5.87E-11	<0.01%	
Propionaldehyde	2.58E-06	<0.01%	
Pyrene	3.65E-09	<0.01%	
Selenium	9.47E-06	<0.01%	
Silicon	1.72E-05	<0.01%	
Sodium	1.02E-04	<0.01%	
Styrene	1.69E-07	<0.01%	
Sulfur oxides	8.10E-01	0.52%	
Tetrachloroethylene	2.92E-07	<0.01%	
Toluene	3.81E-06	<0.01%	
Vanadium	2.68E-04	<0.01%	
Vinyl acetate	5.15E-08	<0.01%	
Zinc (elemental)	1.02E-05	<0.01%	
Total	**1.57E+02**	100.00%	**85.96%**

Table 2-39. CRT manufacturing stage air emissions

Material	Quantity (kg/ (functional unit)	% of process group total	% of grand total
Process group			
Grand Total	1.83E+02		100.00%

Table 2-40. CRT manufacturing stage water outputs (wastewaters and pollutants)

Material	Disposition	Quantity (kg/ functional unit)	% of process group total	% of grand total
Process group				
WASTEWATER STREAMS				
Tube				
Wastewater stream	treatment	5.26e+01	9.87%	
Wastewater stream	surface water	4.81e+02	90.13%	
Total		**5.33e+02**	100.00%	**35.42%**
Glass/frit				
Wastewater stream	surface water	**3.62e+01**		**2.40%**
PWB				
Wastewater stream	treatment	**4.22e+01**		**2.80%**
Fuels				
Wastewater stream	surface water	**8.94e+02**		**59.38%**
Grand Total		**1.51e+03**		**100.00%**
WASTEWATER POLLUTANTS				
Tube				
BOD	surface water	6.39e-03	5.34%	
Chromium ore	surface water	1.02e-05	<0.01%	
Chromium ore	treatment	1.03e-06	<0.01%	
COD	surface water	7.22e-03	6.04%	
COD	treatment	8.33e-03	6.97%	
Copper	surface water	1.80e-06	<0.01%	
Cyanide (-1)	surface water	6.06e-07	<0.01%	
Dissolved solids	treatment	8.01e-02	67.03%	
Fluoride	surface water	3.45e-03	2.89%	
Fluoride	treatment	3.51e-04	0.29%	
Iron	surface water	1.65e-04	0.14%	
Lead	surface water	3.01e-06	<0.01%	
Lead	treatment	1.03e-06	<0.01%	
Manganese	surface water	3.60e-06	<0.01%	
Molybdenum	surface water	1.20e-07	<0.01%	
Nickel	surface water	7.93e-05	0.07%	
Nitrogen	surface water	7.18e-03	6.01%	
Oil & grease	surface water	2.41e-04	0.20%	
Phosphate as P2O5	surface water	1.21e-06	<0.01%	
Phosphorus (yellow or white)	surface water	5.05e-05	0.04%	
Suspended solids	surface water	4.63e-03	3.87%	
Suspended solids	treatment	1.28e-03	1.07%	
Zinc (elemental)	surface water	1.39e-05	0.01%	
Zinc (elemental)	treatment	1.03e-06	<0.01%	
Total		**1.20e-01**	100.00%	**2.51%**
Glass/frit				
BOD	surface water	8.20e-06	<0.01%	

Table 2-40. CRT manufacturing stage water outputs (wastewaters and pollutants)

Material	Disposition	Quantity (kg/ functional unit)	% of process group total	% of grand total
Process group				
Chloride ions	surface water	1.01e+00	21.73%	
Chromium	surface water	8.20e-08	<0.01%	
COD	surface water	8.20e-06	<0.01%	
Dissolved solids	surface water	3.62e+00	77.84%	
Fluorides (F-)	surface water	2.93e-03	0.06%	
Iron	surface water	2.77e-03	0.06%	
Lead	surface water	4.34e-05	<0.01%	
Nickel	surface water	8.20e-08	<0.01%	
Nitrates/nitrites	surface water	3.95e-06	<0.01%	
Oil & grease	surface water	7.22e-03	0.16%	
Suspended solids	surface water	7.23e-03	0.16%	
Total		**4.65e+00**	100.00%	**97.45%**
PWB				
Copper (+1 & +2)	treatment	9.71e-05	85.71%	
Lead cmpds	treatment	1.62e-05	14.29%	
Total		**1.13e-04**	100.00%	**0.00%**
Japanese grid				
Sulfate ion (-4)	surface water	8.72e-04	97.46%	
Suspended solids	surface water	2.27e-05	2.54%	
Total		**8.94e-04**	100.00%	**0.02%**
U.S. grid				
Sulfate ion (-4)	treatment	1.09e-03	97.46%	
Suspended solids	treatment	2.84e-05	2.54%	
Total		**1.12e-03**	100.00%	**0.02%**
Fuels				
Acids (H+)	surface water	2.50e-09	<0.01%	
Adsorbable organic halides	surface water	2.27e-15	<0.01%	
Aluminum (+3)	surface water	8.62e-10	<0.01%	
Ammonia ions	surface water	1.01e-07	0.10%	
Aromatic hydrocarbons	surface water	5.33e-13	<0.01%	
Barium cmpds	surface water	1.71e-12	<0.01%	
BOD	surface water	1.21e-06	1.22%	
Cadmium cmpds	surface water	1.78e-15	<0.01%	
Chloride ions	surface water	3.56e-05	36.07%	
Chromium (III)	surface water	3.31e-10	<0.01%	
Chromium (VI)	surface water	3.31e-10	<0.01%	
COD	surface water	9.80e-06	9.92%	
Copper (+1 & +2)	surface water	3.55e-14	<0.01%	
Cyanide (-1)	surface water	2.49e-15	<0.01%	
Dissolved organics	surface water	6.62e-09	<0.01%	
Dissolved solids	surface water	2.21e-07	0.22%	

Table 2-40. CRT manufacturing stage water outputs (wastewaters and pollutants)

Material	Disposition	Quantity (kg/ functional unit)	% of process group total	% of grand total
Process group				
Fluorides (F-)	surface water	1.80e-08	0.02%	
Halogenated matter (organic)	surface water	7.11e-16	<0.01%	
Hydrocarbons, remaining unspeciated	surface water	2.61e-09	<0.01%	
Iron (+2 & +3)	surface water	3.79e-11	<0.01%	
Lead cmpds	surface water	7.11e-15	<0.01%	
Mercury compounds	surface water	8.17e-18	<0.01%	
Metals, remaining unspeciated	surface water	6.27e-08	0.06%	
Nickel cmpds	surface water	3.55e-15	<0.01%	
Nitrate	surface water	4.53e-09	<0.01%	
Other nitrogen	surface water	9.59e-14	<0.01%	
Phenol	surface water	2.21e-08	0.02%	
Phosphates	surface water	2.02e-11	<0.01%	
Polycyclic aromatic hydrocarbons	surface water	8.53e-15	<0.01%	
Salts (unspecified)	surface water	9.83e-09	<0.01%	
Sodium (+1)	surface water	4.59e-05	46.44%	
Sulfate ion (-4)	surface water	4.26e-09	<0.01%	
Sulfide	surface water	1.38e-09	<0.01%	
Suspended solids	surface water	5.19e-06	5.26%	
TOCs	surface water	5.33e-12	<0.01%	
Toluene	surface water	7.82e-14	<0.01%	
Waste oil	surface water	6.26e-07	0.63%	
Zinc (+2)	surface water	1.58e-10	<0.01%	
Total		**9.88e-05**	100.00%	**0.00%**
Grand Total		**4.77e+00**		**100.00%**

Table 2-41. CRT manufacturing stage hazardous waste outputs (kg/functional unit)

Material	Disposition	Quantity (kg/ functional unit)	% of process group total	% of grand total
Process group				
Tube				
Frit	landfill	2.99e-03	15.58%	
Lead sulfate cake	landfill	2.67e-05	0.14%	
Silica coat waste	treatment	2.86e-04	1.49%	
Slag and ash	landfill	2.47e-03	12.90%	
Slurry scrap (chromium-based)	landfill	8.62e-04	4.50%	
Spent solvent, unspecified	treatment	2.75e-04	1.43%	
Unspecified sludge	landfill	5.22e-03	27.26%	
Unspecified sludge	recycling/reuse	5.56e-03	29.03%	
Waste oxygenated solvents	treatment	9.48e-05	0.49%	
Waste water treatment (WWT) filters	landfill	3.40e-04	1.78%	
Total		**1.92e-02**	100.00%	**1.70%**
Glass/frit				
Barium debris (D008 waste)	landfill	2.14e-04	0.59%	
Broken CRT glass	landfill	1.88e-03	5.17%	
Chrome debris (D007 waste)	treatment	1.47e-04	0.41%	
Chrome liquid waste (D007 waste)	recycling/reuse	9.80e-03	26.95%	
cinders from CRT glass mfg (70% PbO)	landfill	8.26e-03	22.71%	
CRT glass faceplate EP dust (Pb) (D008 waste)	landfill	1.03e-03	2.83%	
CRT glass funnel EP dust (Pb) (D008 waste)	recycling/reuse	5.01e-03	13.78%	
Hazardous sludge (Pb) (D008)	landfill	1.52e-03	4.17%	
Hydrofluoric acid	landfill	1.78e-03	4.89%	
Lead contaminated grit (D008 waste)	landfill	3.46e-05	0.10%	
Lead debris (D008 waste)	landfill	2.14e-04	0.59%	
sludge from CRT glass mfg (1% PbO)	landfill	8.77e-04	2.41%	
Waste acid (mostly 3% HCl solution)	recycling/reuse	3.93e-03	10.81%	
Waste Batch (Ba, Pb) (D008 waste)	landfill	1.41e-03	3.89%	
Waste finishing sludge (Pb) (D008 waste)	landfill	2.56e-04	0.70%	
Total		**3.64e-02**	100.00%	**3.23%**
PWB				
General Hazardous Waste	treatment	1.24e-01	27.26%	
PWB-Decontaminating debris	treatment	1.55e-02	3.41%	
PWB-Lead contaminated waste oil	treatment	1.16e-02	2.56%	
PWB-Route dust	recycling/reuse	1.20e-02	2.64%	
PWB-Solder dross	recycling/reuse	6.70e-02	14.72%	
PWB-Waste cupric etchant	recycling/reuse	2.25e-01	49.42%	
Total		**4.55e-01**	100.00%	**40.45%**

Table 2-41. CRT manufacturing stage hazardous waste outputs (kg/functional unit)

Material	Disposition	Quantity (kg/ functional unit)	% of process group total	% of grand total
Process group				
Fuels				
Hazardous waste	landfill	**6.15e-01**		**54.62%**
Grand Total		**1.13e+00**		**100.00%**

Table 2-42. CRT manufacturing stage solid waste outputs (kg/functional unit)

Material	Disposition	Quantity(kg/ functional unit)	% of process group total	% of grand total
Process group				
Monitor Assembly				
Broken CRT glass	recycling/reuse	3.82e-01	75.07%	
Cables/wires	recycling/reuse	8.86e-03	1.74%	
Printed wiring board (PWB)	recycling/reuse	3.70e-02	7.28%	
Waste plastics from CRT monitor	recycling/reuse	8.09e-02	15.91%	
Total		**5.09e-01**	100.00%	**0.63%**
Tube				
Broken CRT glass	recycling/reuse	6.94e-01	37.43%	
Ferric chloride	recycling/reuse	3.69e-01	19.93%	
Sludge (aquadag)	landfill	2.22e-03	0.12%	
Sludge (phosphor)	landfill	4.31e-03	0.23%	
Spent solvents (toluene,xylene,dimethyl formamide,isopropyl alcohol)	recycling/reuse	4.17e-02	2.25%	
Unspecified sludge	recycling/reuse	1.26e-01	6.78%	
Waste alkali (cleaning caustic and alkali soda effluent)	recycling/reuse	2.12e-02	1.15%	
Waste metals, unspecified	recycling/reuse	8.79e-02	4.74%	
Waste oil	recycling/reuse	1.43e-03	0.08%	
Waste oil	treatment	2.55e-03	0.14%	
Waste Plastic (packing material)	treatment	3.01e-02	1.63%	
Waste Plastic (styrene foam)	recycling/reuse	3.77e-03	0.20%	
Waste water treatment (WWT) sludge	landfill	8.43e-02	4.55%	
Waste water treatment (WWT) sludge	recycling/reuse	3.72e-01	20.06%	
Wastepaper	recycling/reuse	8.34e-03	0.45%	
Wood, average	landfill	4.94e-03	0.27%	
Total		**1.85e+00**	100.00%	**2.28%**
Glass/frit				
abrasive sludge	recycling/reuse	4.21e-02	11.34%	
acid absorbent	landfill	8.13e-05	0.02%	
blasting media	landfill	3.66e-04	0.10%	
Cobalt nitrate	treatment	6.10e-05	0.02%	
CRT glass, faceplate	landfill	2.43e-02	6.54%	
Diesel fuel	treatment	4.07e-05	0.01%	
Dust	treatment	3.43e-03	0.92%	
Nickel nitrate	treatment	6.10e-05	0.02%	
Oily rags & filter media	landfill	3.25e-04	0.09%	
Oily rags & filter media	recycling/reuse	4.07e-05	0.01%	
parts cleaner solvent	recycling/reuse	8.13e-05	0.02%	
Plating process sludge	landfill	3.28e-04	0.09%	
Potassium Carbonate	landfill	3.30e-03	0.89%	

Table 2-42. CRT manufacturing stage solid waste outputs (kg/functional unit)

Material	Disposition	Quantity(kg/ functional unit)	% of process group total	% of grand total
Process group				
sludge (calcium fluoride, CaF2)	recycling/reuse	1.75e-02	4.72%	
Sodium Carbonate	landfill	3.29e-03	0.89%	
Unspecified sludge	landfill	7.69e-03	2.07%	
Waste alkali, unspecified	treatment	4.21e-05	0.01%	
Waste oil	treatment	6.54e-03	1.76%	
Waste refractory	landfill	2.44e-03	0.66%	
Waste water treatment (WWT) sludge	landfill	2.59e-01	69.68%	
PM	landfill	5.33e-04	0.14%	
Total		**3.72e-01**	100.00%	**0.46%**
PWB				
PWB-Drill dust	landfill	1.49e-02	0.36%	
Unspecified solid waste	recycling/reuse	4.33e-01	10.53%	
Unspecified solid waste	treatment	3.66e+00	89.11%	
Total		**4.11e+00**	100.00%	**5.06%**
Japanese grid				
Coal waste	landfill	6.48e-01	61.12%	
Dust/sludge	landfill	2.50e-01	23.59%	
Fly/bottom ash	landfill	1.62e-01	15.28%	
Total		**1.06e+00**	100.00%	**1.31%**
U.S. grid				
Coal waste	landfill	8.12e-01	61.10%	
Dust/sludge	landfill	3.14e-01	23.63%	
Fly/bottom ash	landfill	2.03e-01	15.27%	
Total		**1.33e+00**	100.00%	**1.64%**
Fuels				
Aluminum scrap	recycling/reuse	1.82e-04	<0.01%	
Aluminum scrap, Wabash 319	recycling/reuse	5.08e-07	<0.01%	
Bauxite residues	landfill	1.21e-02	0.02%	
FGD sludge	landfill	2.14e-01	0.30%	
Mineral waste	landfill	2.61e-03	<0.01%	
Mixed industrial (waste)	landfill	1.00e+00	1.39%	
Non toxic chemical waste (unspecified)	landfill	6.11e-04	<0.01%	
Slag and ash	landfill	6.66e+01	92.62%	
Slag and ash	recycling/reuse	6.85e-01	0.95%	
Unspecified solid waste (incinerated)	treatment	1.33e-02	0.02%	
Unspecified waste	landfill	3.38e+00	4.70%	
Total		**7.19e+01**	100.00%	**88.62%**
Grand Total		**8.12e+01**		**100.00%**

Table 2-43. CRT manufacturing stage radioactive waste outputs

Material	Disposition	Quantity (kg/ functional unit)	% of process group total	% of grand total
Process group				
Japanese grid				
Low-level radioactive waste	landfill	1.10e-04	76.93%	
Uranium, depleted	landfill	3.31e-05	23.07%	
Total		**1.43e-04**	100.00%	**79.72%**
U.S. grid				
Low-level radioactive waste	landfill	2.80e-05	76.93%	
Uranium, depleted	landfill	8.41e-06	23.07%	
Total		**3.65e-05**	100.00%	**20.28%**
Grand Total		**1.80e-04**		**100.00%**

Table 2-44. CRT manufacturing stage radioactivity outputs

Material	Disposition	Quantity (Bq/ functional unit)	% of process group total	% of grand total
Process group				
Japanese grid				
Antimony-124 (isotope)	treatment	4.95e-01	<0.01%	
Antimony-125 (isotope)	treatment	1.97e+00	<0.01%	
Argon-41 (isotope)	air	1.00e+03	0.03%	
Barium-140 (isotope)	treatment	3.67e-02	<0.01%	
Bromine-89 (isotope)	air	1.16e-04	<0.01%	
Bromine-90 (isotope)	air	4.72e-05	<0.01%	
Cesium-134 (isotope)	air	3.18e-03	<0.01%	
Cesium-134 (isotope)	treatment	1.32e+00	<0.01%	
Cesium-137 (isotope)	air	2.40e-02	<0.01%	
Cesium-137 (isotope)	treatment	1.99e+00	<0.01%	
Chromium-51 (isotope)	air	6.29e-02	<0.01%	
Chromium-51 (isotope)	treatment	2.39e+00	<0.01%	
Cobalt-57 (isotope)	air	1.69e-04	<0.01%	
Cobalt-57 (isotope)	treatment	5.78e-02	<0.01%	
Cobalt-58 (isotope)	air	2.16e-03	<0.01%	
Cobalt-58 (isotope)	treatment	2.35e+01	<0.01%	
Cobalt-60 (isotope)	air	1.62e-02	<0.01%	
Cobalt-80 (isotope)	treatment	6.17e+00	<0.01%	
Iodine-131 (isotope)	air	7.58e-02	<0.01%	
Iodine-131 (isotope)	treatment	1.10e+00	<0.01%	
Iodine-132 (isotope)	air	1.54e-02	<0.01%	
Iodine-132 (isotope)	treatment	4.17e-01	<0.01%	
Iodine-133 (isotope)	air	7.03e+01	<0.01%	
Iodine-133 (isotope)	treatment	4.72e-01	<0.01%	
Iodine-134 (isotope)	air	7.98e-02	<0.01%	
Iodine-135 (isotope)	air	4.01e-03	<0.01%	
Iodine-135 (isotope)	treatment	3.38e-01	<0.01%	
Iron-55 (isotope)	treatment	5.62e+00	<0.01%	
Iron-59 (isotope)	treatment	2.88e-01	<0.01%	
Krypton-85 (isotope)	air	1.66e+03	0.06%	
Krypton-85M (isotope)	air	8.06e+01	<0.01%	
Krypton-85M (isotope)	treatment	1.49e+00	<0.01%	
Krypton-87 (isotope)	air	3.00e+01	<0.01%	
Krypton-88 (isotope)	air	1.41e+02	<0.01%	
Lanthanum-140 (isotope)	treatment	3.93e-02	<0.01%	
Manganese-54 (isotope)	air	8.92e-04	<0.01%	
Manganese-54 (isotope)	treatment	1.57e+00	<0.01%	
Molybdenum-99 (isotope)	treatment	2.97e+06	98.42%	
Niobium-95 (isotope)	air	3.54e-05	<0.01%	
Niobium-95 (isotope)	treatment	4.05e-01	<0.01%	

Table 2-44. CRT manufacturing stage radioactivity outputs

Material	Disposition	Quantity (Bq/ functional unit)	% of process group total	% of grand total
Process group				
Rubidium-88 (isotope)	air	3.29e-01	<0.01%	
Ruthenium-103 (isotope)	treatment	4.95e-02	<0.01%	
Silver-110M (isotope)	air	1.06e-06	<0.01%	
Silver-110M (isotope)	treatment	5.78e-01	<0.01%	
Sodium-24 (isotope)	treatment	8.80e-02	<0.01%	
Strontium-89 (isotope)	treatment	9.51e-02	<0.01%	
Strontium-90 (isotope)	treatment	2.24e-02	<0.01%	
Strontium-95 (isotope)	treatment	2.46e-01	<0.01%	
Sulfur-136 (isotope)	treatment	5.30e-02	<0.01%	
Technetium-99M (isotope)	air	4.75e-06	<0.01%	
Technetium-99M (isotope)	treatment	3.45e-02	<0.01%	
Tin-113 (isotope)	treatment	5.46e-02	<0.01%	
Tritium-3 (isotope)	air	2.35e+03	0.08%	
Tritium-3 (isotope)	treatment	1.76e+04	0.58%	
Xenon-131M (isotope)	air	1.36e+02	<0.01%	
Xenon-131M (isotope)	treatment	1.81e+01	<0.01%	
Xenon-133 (isotope)	air	1.30e+03	0.04%	
Xenon-133 (isotope)	treatment	2.78e+03	0.09%	
Xenon-133M (isotope)	air	1.96e+04	0.65%	
Xenon-133M (isotope)	treatment	2.28e+01	<0.01%	
Xenon-135 (isotope)	air	7.39e+02	0.02%	
Xenon-135 (isotope)	treatment	2.07e+01	<0.01%	
Xenon-135M (isotope)	air	1.41e+01	<0.01%	
Xenon-138 (isotope)	air	4.68e+01	<0.01%	
Zinc-85 (isotope)	treatment	2.65e-02	<0.01%	
Zirconium-95 (isotope)	air	9.16e-05	<0.01%	
Total		**3.01e+06**	100.00%	**79.70%**
U.S. grid				
Antimony-124 (isotope)	treatment	1.26e-01	<0.01%	
Antimony-125 (isotope)	treatment	5.02e-01	<0.01%	
Argon-41 (isotope)	air	2.55e+02	0.03%	
Barium-140 (isotope)	treatment	9.33e-03	<0.01%	
Bromine-89 (isotope)	air	2.95e-05	<0.01%	
Bromine-90 (isotope)	air	1.20e-05	<0.01%	
Cesium-134 (isotope)	air	8.09e-04	<0.01%	
Cesium-134 (isotope)	treatment	3.37e-01	<0.01%	
Cesium-136 (isotope)	treatment	1.44e-02	<0.01%	
Cesium-137 (isotope)	air	6.11e-03	<0.01%	
Cesium-137 (isotope)	treatment	5.06e-01	<0.01%	
Chromium-51 (isotope)	air	1.60e-02	<0.01%	
Chromium-51 (isotope)	treatment	6.07e-01	<0.01%	

Table 2-44. CRT manufacturing stage radioactivity outputs

Material	Disposition	Quantity (Bq/ functional unit)	% of process group total	% of grand total
Process group				
Cobalt-57 (isotope)	air	4.30e-05	<0.01%	
Cobalt-57 (isotope)	treatment	1.47e-02	<0.01%	
Cobalt-58 (isotope)	air	5.49e+01	<0.01%	
Cobalt-58 (isotope)	treatment	5.98e+00	<0.01%	
Cobalt-60 (isotope)	air	4.13e-03	<0.01%	
Cobalt-80 (isotope)	treatment	1.57e+00	<0.01%	
Iodine-131 (isotope)	air	1.93e-02	<0.01%	
Iodine-131 (isotope)	treatment	2.80e-01	<0.01%	
Iodine-132 (isotope)	air	3.92e-03	<0.01%	
Iodine-132 (isotope)	treatment	1.06e-01	<0.01%	
Iodine-133 (isotope)	air	1.79e+01	<0.01%	
Iodine-133 (isotope)	treatment	1.20e-01	<0.01%	
Iodine-134 (isotope)	air	2.03e-02	<0.01%	
Iodine-135 (isotope)	air	1.02e-03	<0.01%	
Iodine-135 (isotope)	treatment	8.60e-02	<0.01%	
Iron-55 (isotope)	treatment	1.43e+00	<0.01%	
Iron-59 (isotope)	treatment	7.34e-02	<0.01%	
Krypton-85 (isotope)	air	4.23e+02	0.06%	
Krypton-85M (isotope)	air	2.05e+01	<0.01%	
Krypton-85M (isotope)	treatment	3.78e-01	<0.01%	
Krypton-87 (isotope)	air	7.62e+00	<0.01%	
Krypton-88 (isotope)	air	3.58e+01	<0.01%	
Lanthanum-140 (isotope)	treatment	9.99e-03	<0.01%	
Manganese-54 (isotope)	air	2.27e-04	<0.01%	
Manganese-54 (isotope)	treatment	4.00e-01	<0.01%	
Molybdenum-99 (isotope)	treatment	7.55e+05	98.41%	
Niobium-95 (isotope)	air	9.01e-06	<0.01%	
Niobium-95 (isotope)	treatment	1.03e-01	<0.01%	
Rubidium-88 (isotope)	air	8.37e-02	<0.01%	
Ruthenium-103 (isotope)	treatment	1.26e-02	<0.01%	
Silver-110M (isotope)	air	2.69e-07	<0.01%	
Silver-110M (isotope)	treatment	1.47e-01	<0.01%	
Sodium-24 (isotope)	treatment	2.24e-02	<0.01%	
Strontium-89 (isotope)	treatment	2.42e-02	<0.01%	
Strontium-90 (isotope)	treatment	5.69e-03	<0.01%	
Strontium-95 (isotope)	treatment	6.27e-02	<0.01%	
Sulfur-136 (isotope)	treatment	1.35e-02	<0.01%	
Technetium-99M (isotope)	air	1.21e-06	<0.01%	
Technetium-99M (isotope)	treatment	8.77e-03	<0.01%	
Tin-113 (isotope)	treatment	1.39e-02	<0.01%	
Tritium-3 (isotope)	air	5.98e+02	0.08%	

Table 2-44. CRT manufacturing stage radioactivity outputs

Material	Disposition	Quantity (Bq/ functional unit)	% of process group total	% of grand total
Process group				
Tritium-3 (isotope)	treatment	4.47e+03	0.58%	
Xenon-131M (isotope)	air	3.45e+01	<0.01%	
Xenon-131M (isotope)	treatment	4.60e+00	<0.01%	
Xenon-133 (isotope)	air	4.98e+03	0.65%	
Xenon-133 (isotope)	treatment	7.07e+02	0.09%	
Xenon-133M (isotope)	air	3.31e+02	0.04%	
Xenon-133M (isotope)	treatment	5.79e+00	<0.01%	
Xenon-135 (isotope)	treatment	5.27e+00	<0.01%	
Xenon-135M (isotope)	air	3.59e+00	<0.01%	
Xenon-138 (isotope)	air	1.19e+01	<0.01%	
Zinc-85 (isotope)	treatment	6.75e-03	<0.01%	
Zirconium-95 (isotope)	air	2.33e-05	<0.01%	
Total		**7.67e+05**	100.00%	**20.27%**
Fuels				
Radioactive substance (unspecified)	air	9.19e+02	99.08%	
Radioactive substance (unspecified)	surface water	8.52e+00	0.92%	
Total		**9.27e+02**	100.00%	**0.02%**
Grand Total		**3.78e+06**		**100.00%**

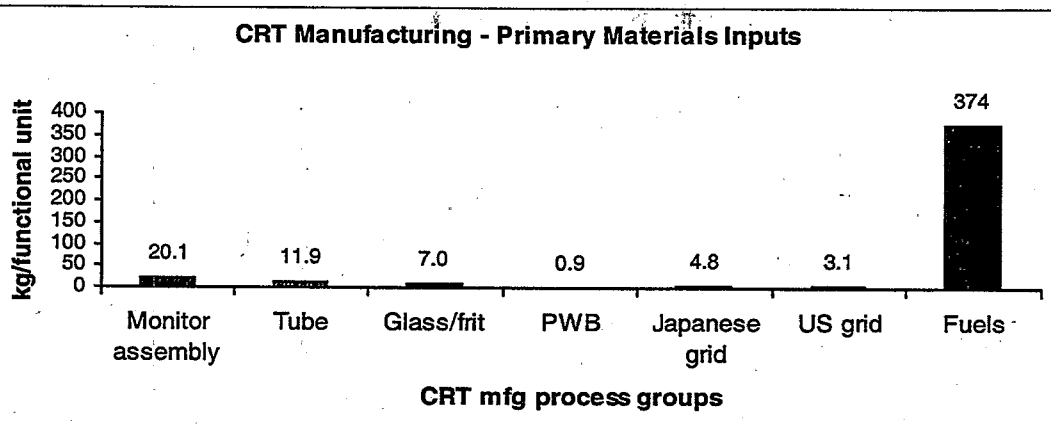

Figure 2-24. CRT manufacturing primary inputs

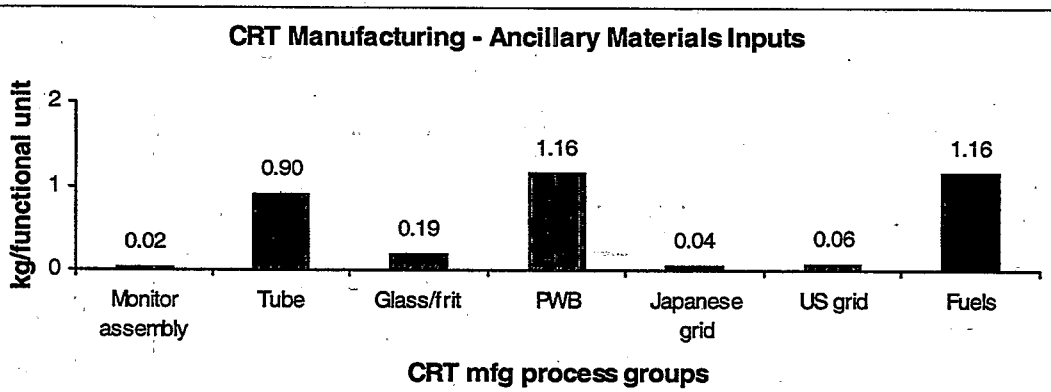

Figure 2-25. CRT manufacturing ancillary inputs

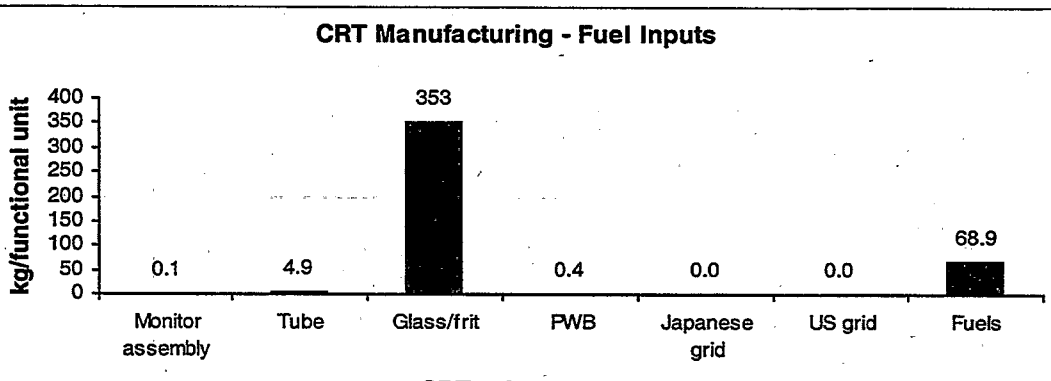

Figure 2-26. CRT manufacturing fuel inputs

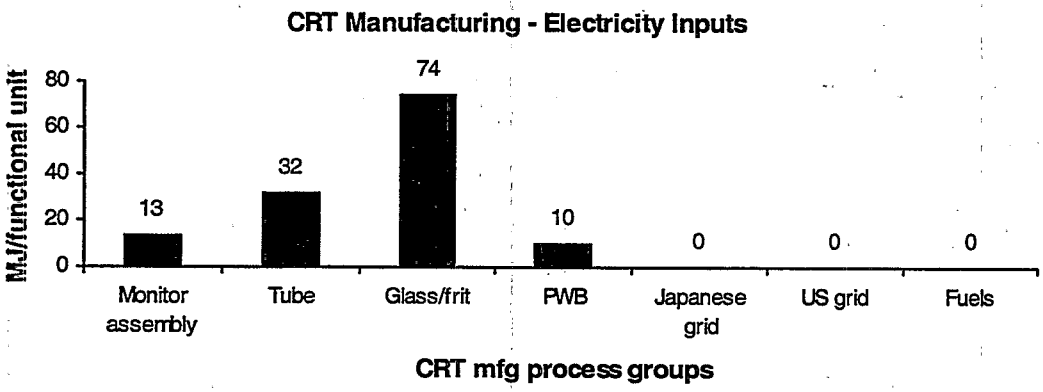

Figure 2-27. CRT manufacturing electricity inputs

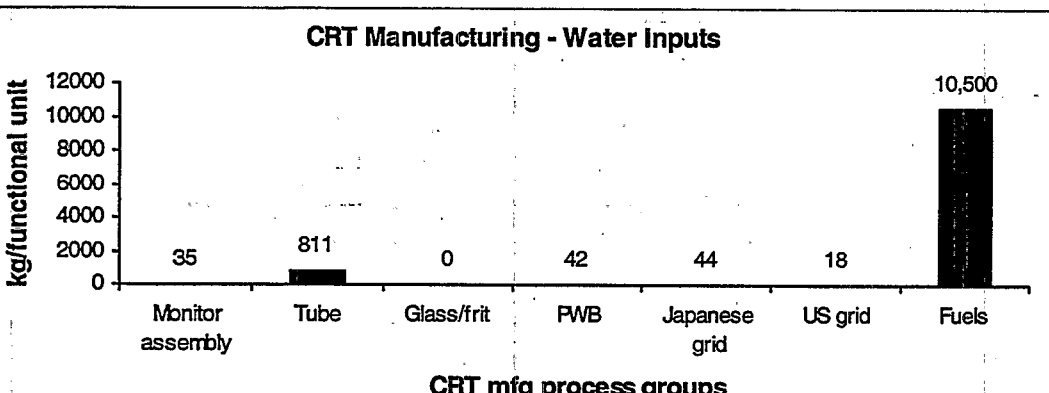

Figure 2-28. CRT manufacturing water inputs

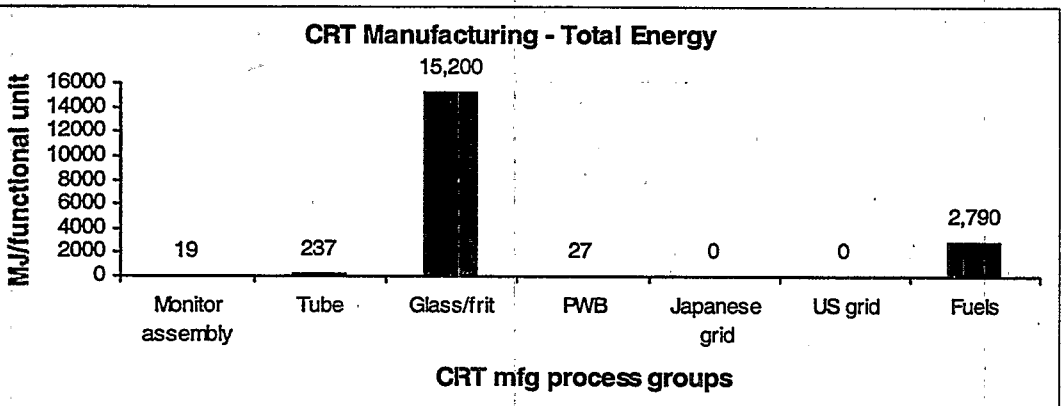

Figure 2-29. CRT manufacturing energy inputs

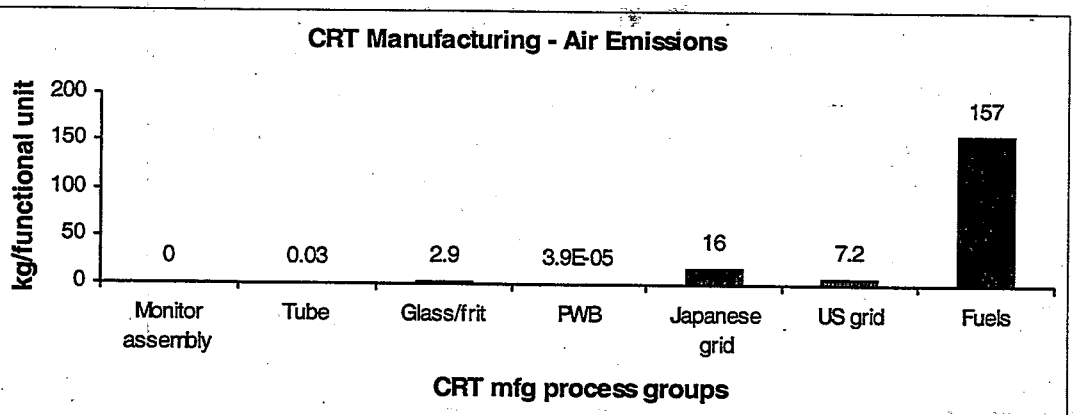

Figure 2-30. CRT manufacturing air emissions

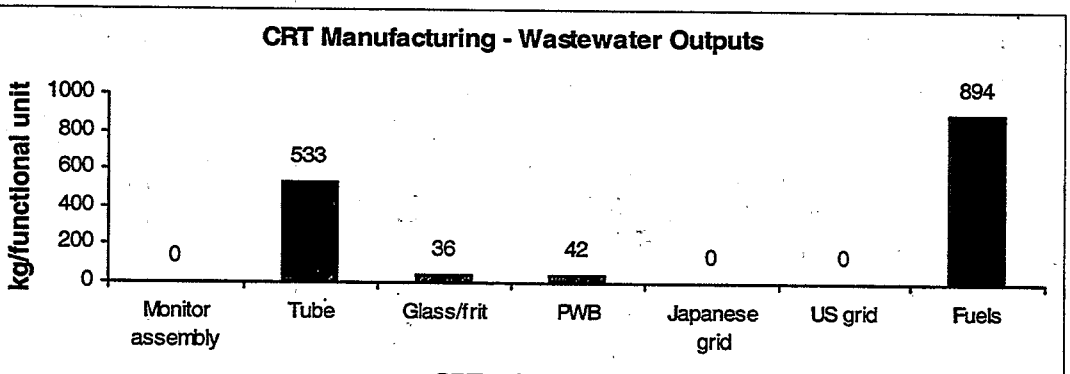

Figure 2-31. CRT manufacturing wastewater outputs

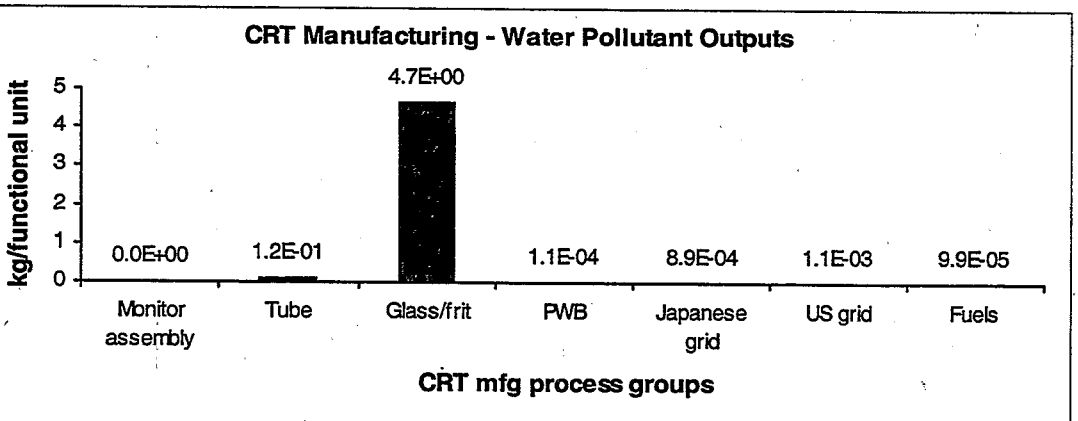

Figure 2-32. CRT manufacturing water pollutant outputs

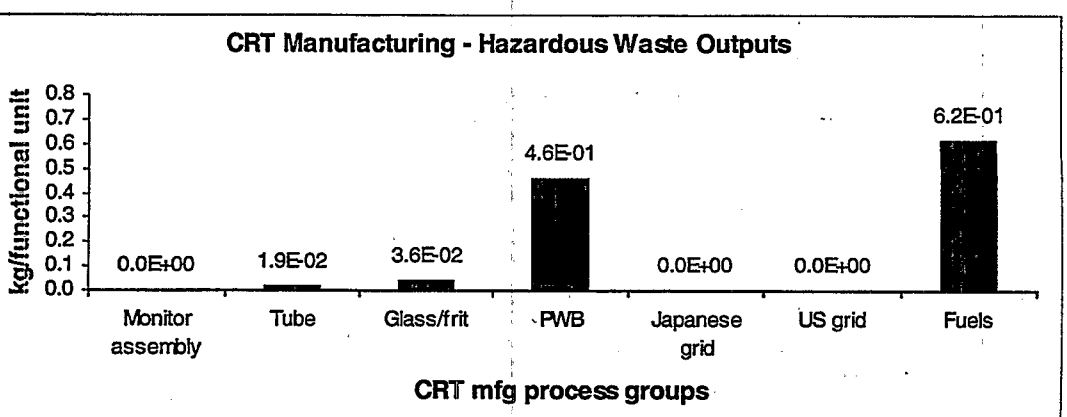

Figure 2-33. CRT manufacturing hazardous waste outputs

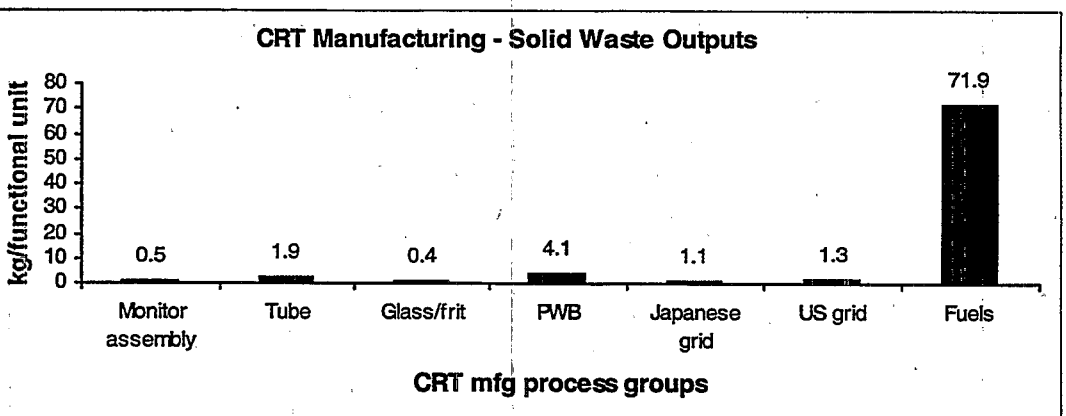

Figure 2-34. CRT manufacturing solid waste outputs

Among the utility inputs, both fuels and electricity were greatest in the glass/frit manufacturing processes (Figures 2-26 and 2-27). The fuels, especially, are dominated by the glass/frit process group, representing 83% of the mass of all the fuels in the manufacturing life-cycle stage. It is LPG in this inventory that clearly dominates the fuel inputs at about 351 kg/functional unit (99% of the glass/frit fuel inputs) (Table 2-38). Water inputs are greatest in the fuel production processes, contributing 1,050 kg (or liter)/functional unit (Figure 2-28). Total energy use from manufacturing is shown in Figure 2-29. The glass/frit manufacturing process group contributes the greatest to the total energy impacts in the manufacturing stage. A sensitivity analysis will be conducted on the glass data and more details are provided in Section 2.7.3.

For outputs from the manufacturing stage, the mass of air emissions are dominated by fuel production (Figure 2-30). Individual material (pollutant) contributions for each process group are presented in Table 2-39. Wastewater outputs (i.e., the volume or mass of wastewater released) are also greatest from the fuel production processes (Figure 2-31; Table 2-40); however, the mass of chemical pollutants in the wastewater is greatest from the glass/frit

manufacturing process group (4.65 kg/functional unit) out of the total manufacturing stage mass of pollutants, which is 4.77 kg/functional unit (Figure 2-32; Table 2-40).

Hazardous wastes from the CRT manufacturing stage were a small portion of the overall hazardous wastes generated by mass. Nonetheless, for purposes of future manufacturing stage improvement assessments, Table 2-41 presents the individual material contributions for each manufacturing process group; and Figure 2-33 shows that fuels production contributes the most (0.62 kg/functional unit) hazardous waste to the manufacturing stage. Manufacturing solid wastes are not as small a portion of the total mass of solid wastes throughout the CRT life-cycle (42%) as hazardous wastes are, as was depicted in Figure 2-21. Fuels production is the greatest contributor to manufacturing-generated solid wastes (71.9 kg/functional unit), followed by PWB manufacturing (4.1 kg/functional unit) (Figure 2-34 and Table 2-43).

Radioactive waste and radioactivity are directly related to the electricity generation process and therefore, only the Japanese and U.S. electric grid processes generate these outputs (some small radioactivity outputs are generated by fuels production processes) in the manufacturing stage. (These outputs also occur in upstream processes that have an electric grid included in the inventory.) Tables 2-44 and 2-45 show that more radioactive wastes and radioactivity are from the Japanese grid. This is a result of more manufacturing processes as modeled in this project being in Japan.

2.7.1.2 LCD inventory results

The LCD inventory is presented similar to the CRT inventory above. The total LCD inventory presented in Table 2-24 and Figures 2-5, 2-6, and 2-7 shows the inventory from all life-cycle stages combined. The totals by life-cycle stage are presented in Table 2-45, Figure 2-35, Figure 2-36, and Figure 2-37.

Table 2-45. LCD inventory by life-cycle stage

Inventory type	Upstream	Mfg	Use	EOL	Total	Units*
Inputs						
Primary materials	2.35e+02	4.92e+01	8.01e+01	-2.19e+00	3.62e+02	kg
Ancillary materials	1.06e+00	2.04e+02	1.29e+00	2.11e+00	2.08e+02	kg
Water	2.63e+02	2.15e+03	4.25e+02	-1.80e+01	2.82e+03	kg
Fuels	1.47e+01	2.58e+01	0	-1.95e+00	3.86e+01	kg (or L)
Electricity	3.46e+01	3.16e+02	8.53e+02	1.62e-01	1.20e+03	MJ
Total energy	6.33e+02	1.44e+03	8.53e+02	-8.44e+01	2.84e+03	MJ
Outputs						
Air pollutants	1.12e+02	6.48e+01	1.68e+02	1.30e+00	3.46e+02	kg
Wastewater	8.57e+00	3.12e+03	0	-2.41e+00	3.13e+03	kg
Water pollutants	4.60e-01	1.23e+00	2.62e-02	-4.09e-02	1.68e+00	kg (or L)
Hazardous waste	6.72e-03	4.64e+00	0	1.64e+00	6.29e+00	kg
Solid waste	1.31e+01	1.26e+01	3.11e+01	-4.42e+00	5.23e+01	kg
Radioactive waste	1.37e-04	4.87e-04	8.52e-04	1.62e-07	1.48e-03	kg
Radioactivity	1.20e+07	1.02e+07	1.79e+07	3.40e+03	4.01e+07	Bq

*Per functional unit (i.e., one LCD monitor over its effective life)

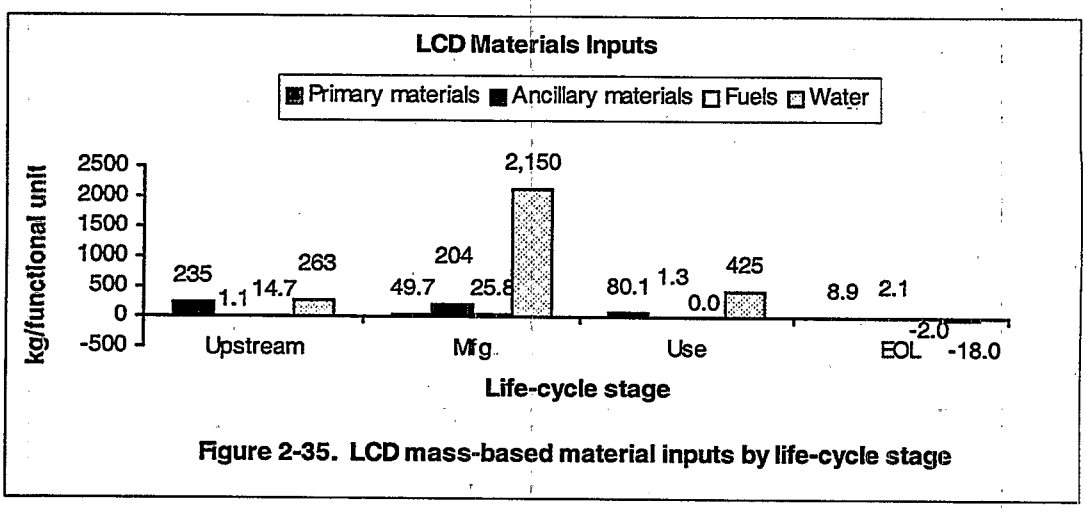

Figure 2-35. LCD mass-based material inputs by life-cycle stage

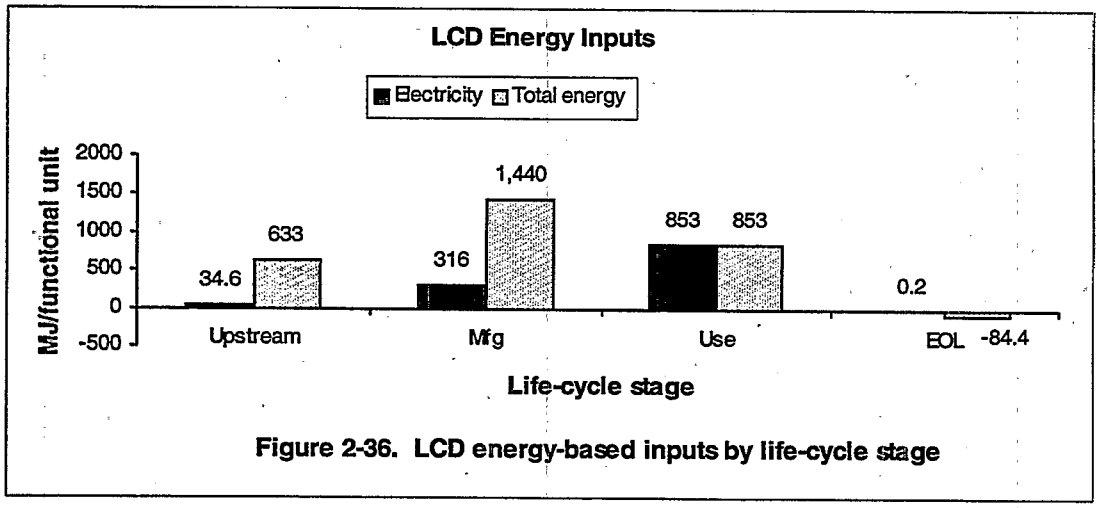

Figure 2-36. LCD energy-based inputs by life-cycle stage

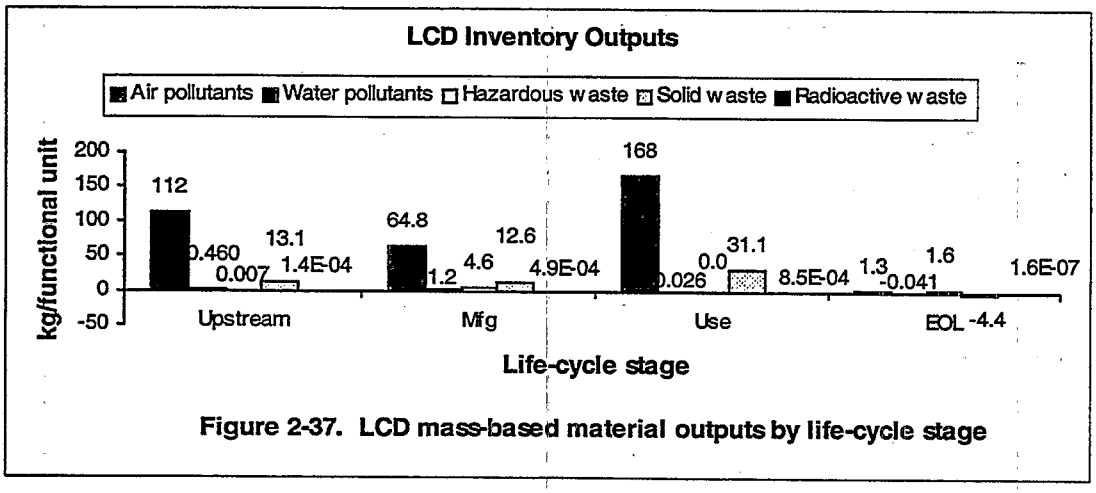

Figure 2-37. LCD mass-based material outputs by life-cycle stage

Considering inputs, Figure 2-35 shows that of the inputs measured in mass, the water inputs constitute the majority of the inputs by mass for the entire life cycle, and most of the water inputs are in the manufacturing life-cycle stage. Details on each inventory type are provided below. When considering which life-cycle stage contributes most to an inventory category, the manufacturing stage has the largest inventory by mass for ancillary materials, fuels, and water inputs. Primary material inputs are dominated by the upstream stages while electricity inputs are dominated by the use stage. The total energy is dominated by the manufacturing life-cycle stage (Figure 2-36). Note that LPG production from glass manufacturing does not dominate much of the LCD inventory as it did for the CRT because of the smaller amount of glass used in the LCD compared to the CRT.

Of the outputs measured in mass (air emissions, wastewater, water pollutants and hazardous, solid, and radioactive waste), wastewater constitutes the greatest output (Table 2-46); however, wastewater alone is not used to calculate impacts. Instead, water pollutants are used to calculate impacts and therefore listed separately in the inventory. Of the remaining outputs measured in mass (i.e., air emissions, water pollutants and hazardous, solid and radioactive waste), which are shown in Figure 2-37, air emissions are the greatest contributor to the outputs. Note again, as mentioned for the CRT, that radioactivity is measured in Bequerels (Bq) and cannot be compared on the same scale.

Considering each output type and their contributions by life-cycle stage, the mass of water pollutants is greatest in the manufacturing life-cycle stage, due to the fuel production processes that support fuel consumption in the manufacturing processes being included in the manufacturing life-cycle stage. Wastewater and hazardous waste outputs are greatest in the manufacturing stage; air emissions, solid waste, radioactive waste, and radioactivity have the greatest contribution from the use stage. As with the CRT, all the output totals represented in Table 2-45 include outputs to all dispositions.

The tables and figures discussed above show the total inventories for particular input or output types by life-cycle stage. Tables in Appendix J list each material that contributes to those totals. Figures 2-38 through 2-50 show the total contribution by life-cycle stage, based on the entire input/output type-specific tables in Appendix J. Summary tables for the LCD (Tables 2-46 through 2-54), developed from the Tables in Appendix J, show the top contributing inventory items to each input or output type. Note that Table 2-48 includes input/output types that are classified together as utilities: water, fuel, electricity and total energy.

LCD Primary Inputs

Figure 2-38 shows that most LCD primary materials by mass are from the upstream life-cycle stages. The top 99.9% of the materials contributing to the total LCD primary input inventory are shown in Table 2-46. The largest material contributors are natural gas, coal and petroleum (a combined 89% of all the primary LCD inputs), which are used to generate electricity consumed throughout the life-cycle of the monitor. Most of the electricity consumed in the LCD life-cycle is in the manufacturing and use stages, as was seen in Figure 2-36. However, most of the natural gas primary material reported in the materials processing stage (229 kg/functional unit) is not used to generate electricity, but is an ancillary material in the LCD monitor/module manufacturing process. More detail on the processes that contribute greatest within the manufacturing stage will be presented after brief discussions of the life-cycle stage breakdowns for each inventory type. For the complete list of primary materials in the LCD

inventory, the total mass, and the mass contribution of each life-cycle stage, see Appendix J, Table J-10.

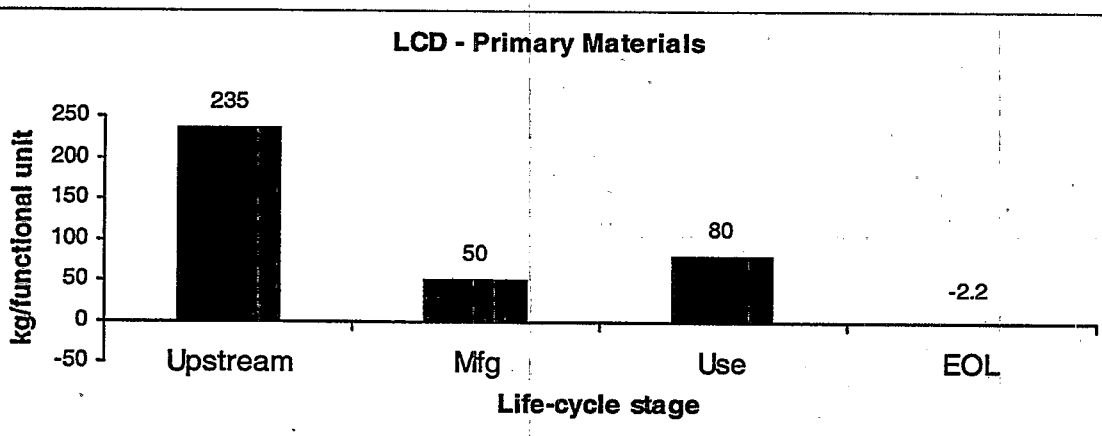

Figure 2-38. LCD primary material inputs by life-cycle stage

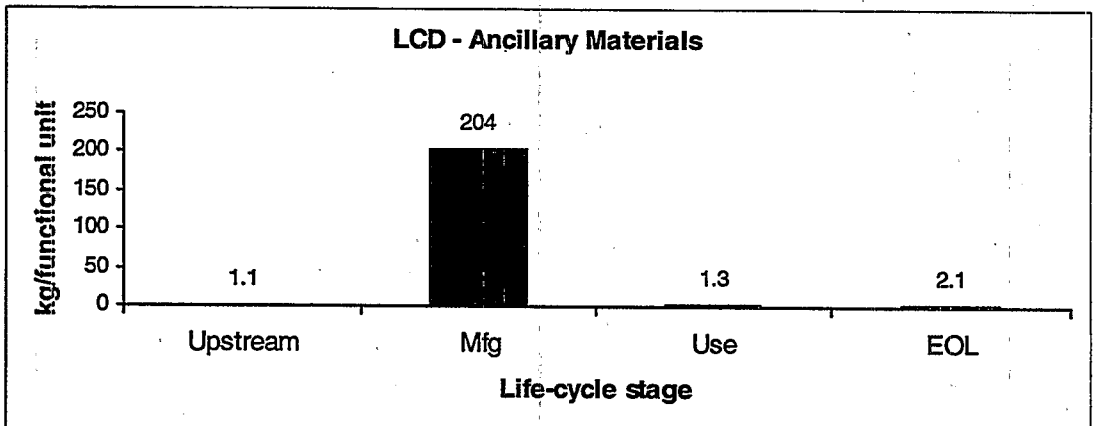

Figure 2-39. LCD ancillary material inputs by life-cycle stage

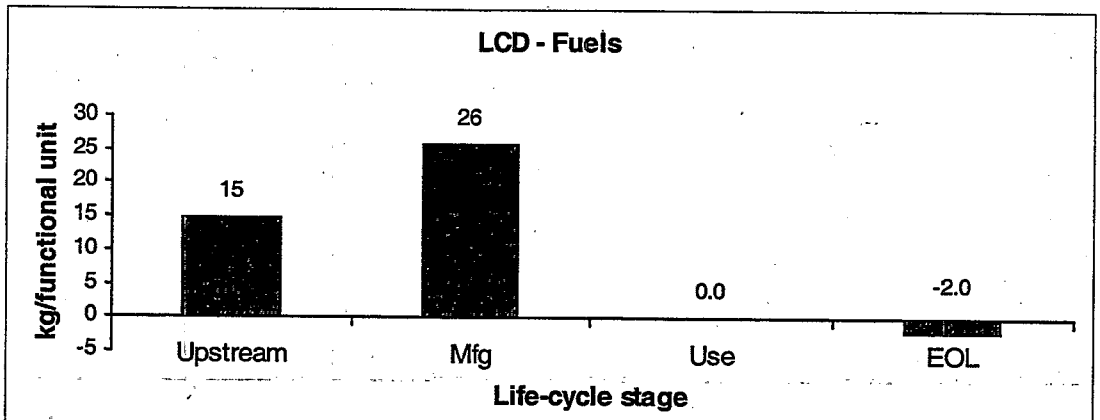

Figure 2-40. LCD fuel inputs by life-cycle stage

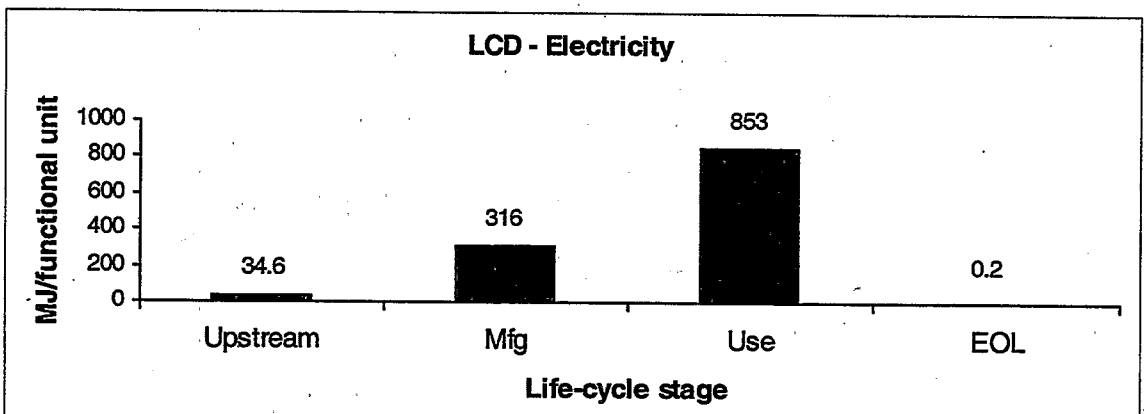

Figure 2-41. LCD electricity inputs by life-cycle stage

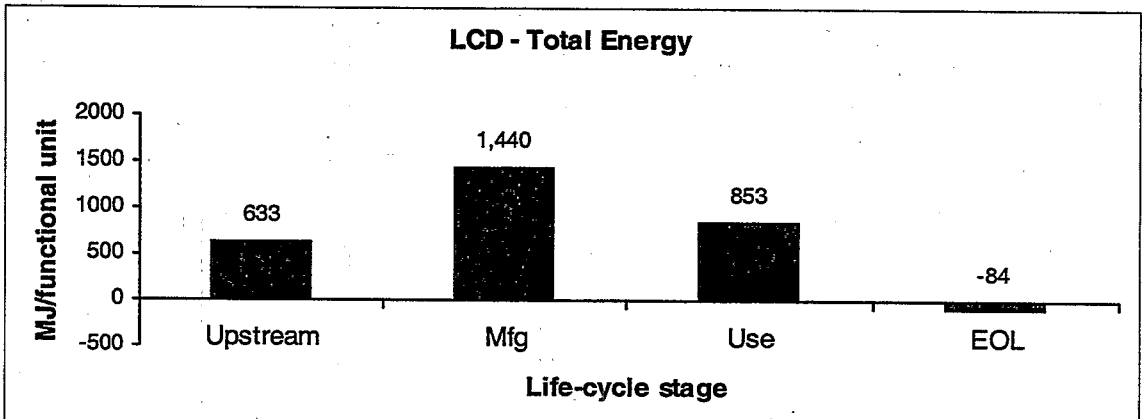

Figure 2-42. LCD energy inputs by life-cycle stage

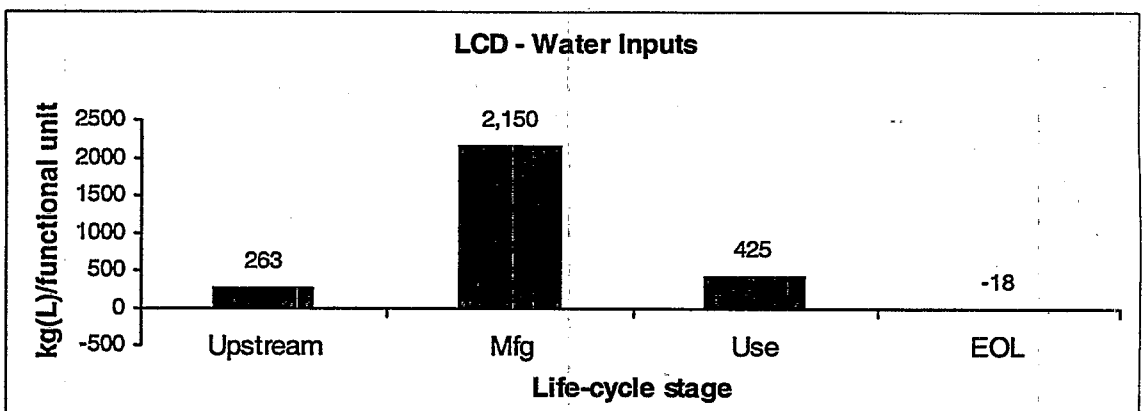

Figure 2-43. LCD water inputs by life-cycle stage

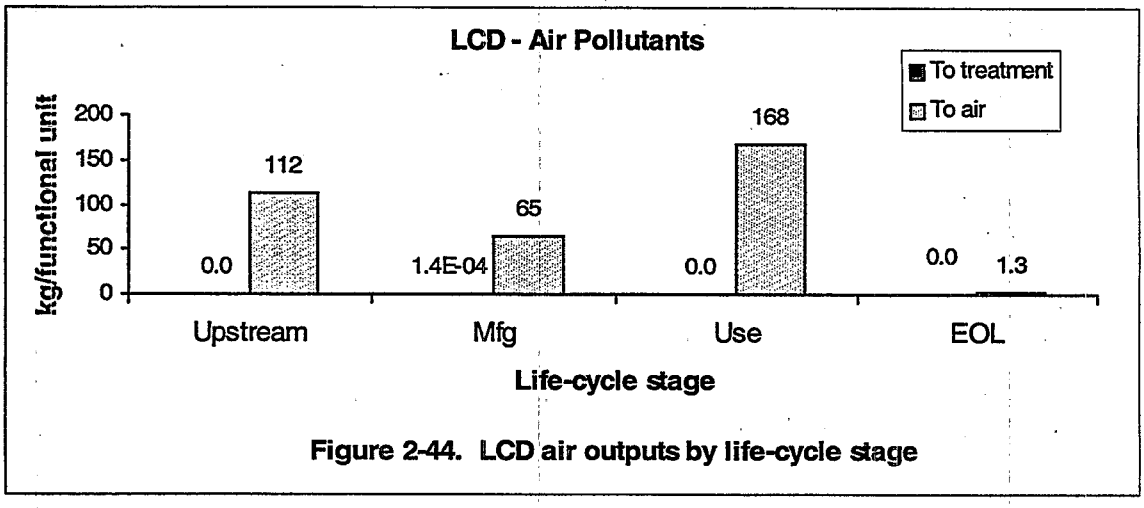

Figure 2-44. LCD air outputs by life-cycle stage

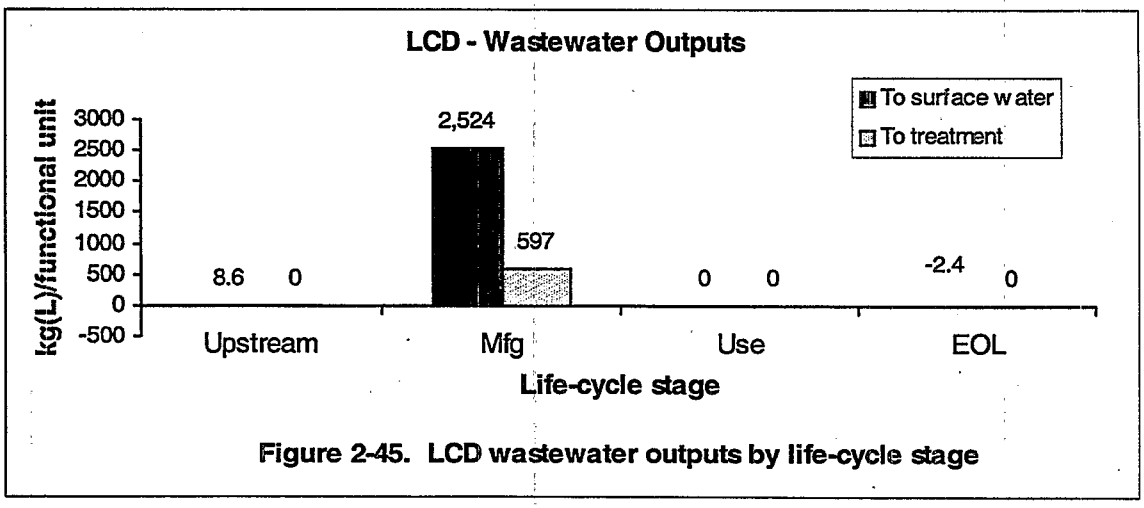

Figure 2-45. LCD wastewater outputs by life-cycle stage

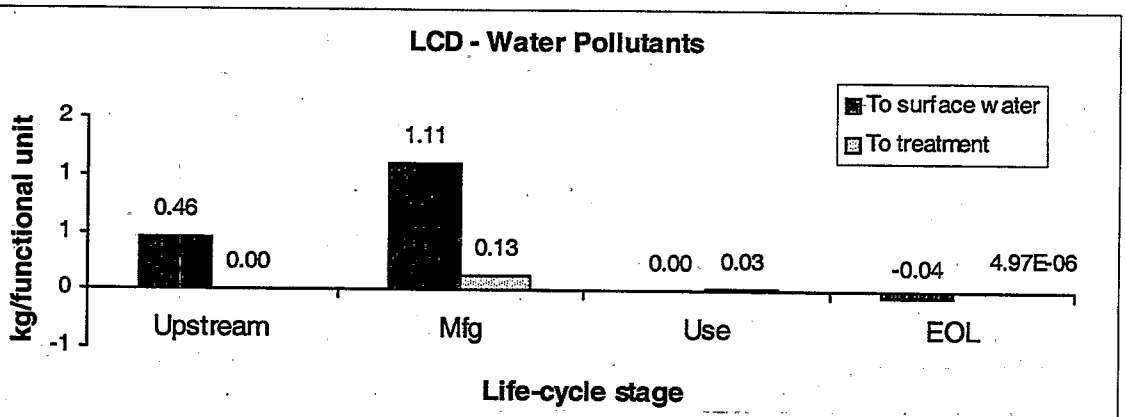

Figure 2-46. LCD water pollutant outputs by life-cycle stage

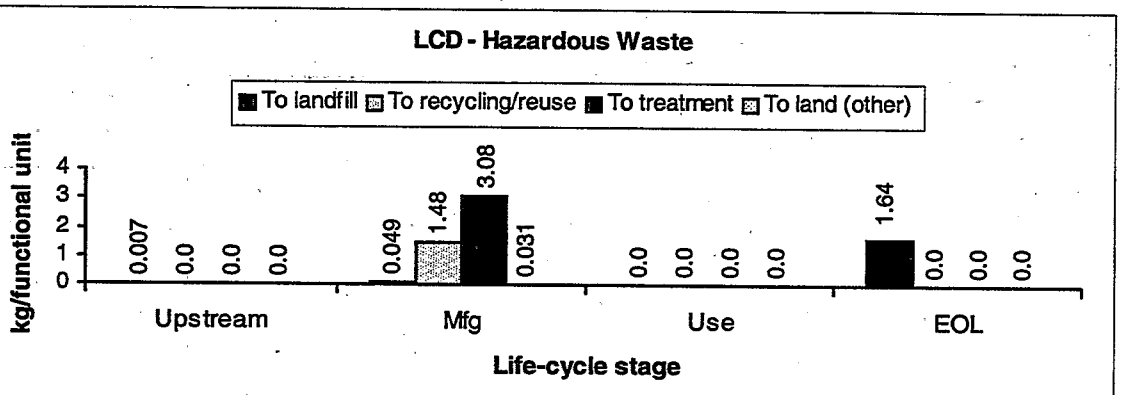

Figure 2-47. LCD hazardous waste outputs by life-cycle stage

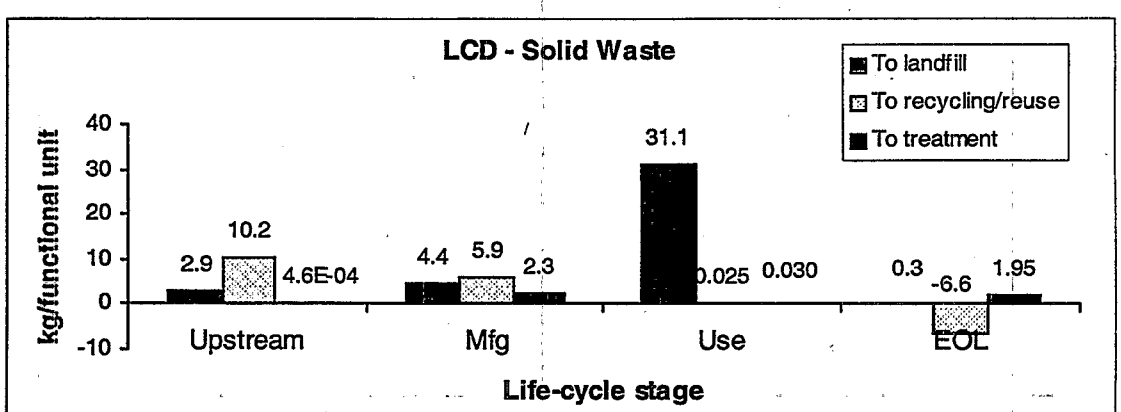

Figure 2-48. LCD solid waste outputs by life-cycle stage

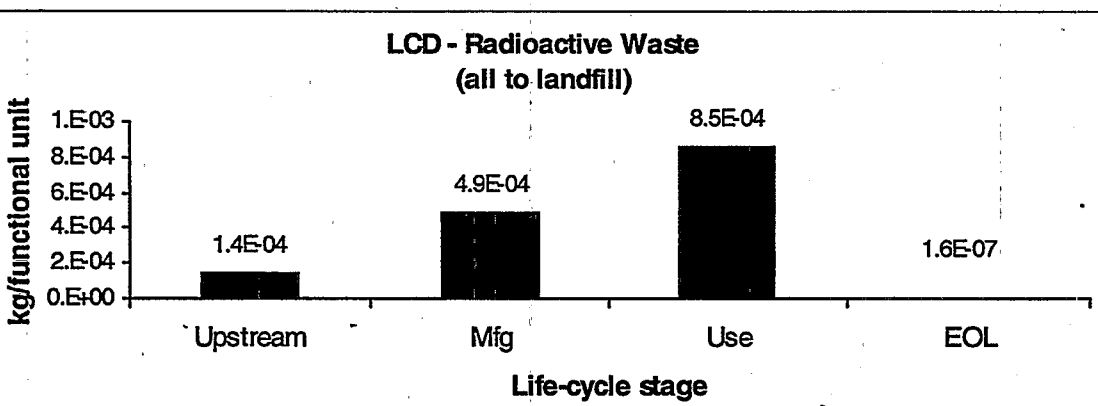

Figure 2-49. LCD radioactive waste outputs by life-cycle stage

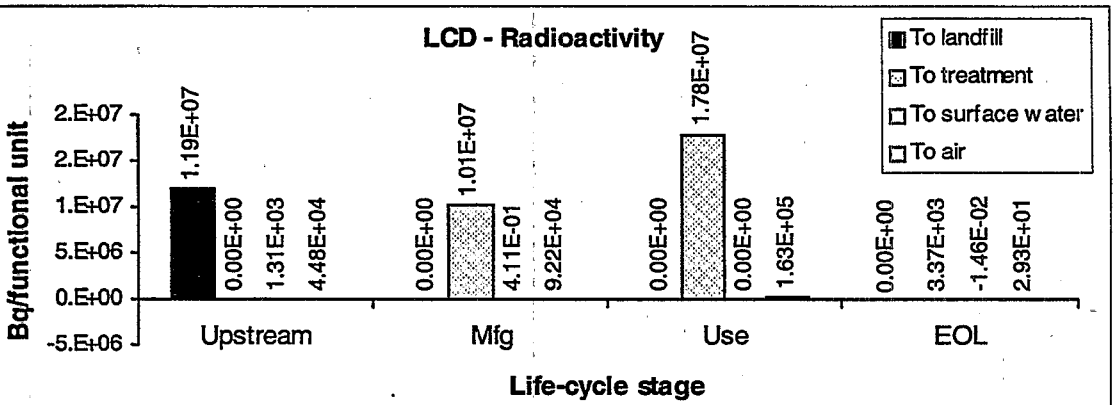

Figure 2-50. LCD radioactivity outputs by life-cycle stage

Table 2-46. Top 99.9% of LCD primary material inputs (kg/functional unit)

Material	Upstream	Mfg	Use	EOL	Total	% of total
Natural gas (in ground)	2.29E+02	5.16E+00	0	-1.08E+00	2.33E+02	64.25%
Coal, average (in ground)	1.72E+00	8.03E+00	6.69E+01	1.27E-02	7.67E+01	21.15%
Petroleum (in ground)	7.09E-01	2.23E+01	1.42E+00	-1.00E+00	2.34E+01	6.45%
Natural gas	0	4.22E+00	5.22E+00	-5.75E-02	9.39E+00	2.59%
Assembled LCD monitor	0	0	6.50E+00	0	6.50E+00	1.79%
Iron (Fe, ore)	3.26E+00	0	0	0	3.26E+00	0.90%
Steel	0	2.53E+00	0	0	2.53E+00	0.70%
Assembled 15" LCD backlight unit	0	1.48E+00	0	0	1.48E+00	0.41%
LCD module	0	1.18E+00	0	0	1.18E+00	0.33%
Polycarbonate resin	0	5.16E-01	0	0	5.16E-01	0.14%
Bauxite (Al2O3, ore)	0	5.09E-01	0	0	5.09E-01	0.14%
Iron scrap	4.63E-01	0	0	0	4.63E-01	0.13%
LCD glass	0	4.52E-01	0	0	4.52E-01	0.12%
Poly(methyl methacrylate)	0	3.83E-01	0	0	3.83E-01	0.11%
15" LCD light guide	0	3.74E-01	0	0	3.74E-01	0.10%
PWB-laminate	0	3.74E-01	0	0	3.74E-01	0.10%
Printed wiring board (PWB)	0	3.74E-01	0	0	3.74E-01	0.10%
Styrene-butadiene copolymers	0	3.62E-01	0	0	3.62E-01	0.10%
PPE	0	3.00E-01	0	0	3.00E-01	0.08%
Cables/wires	0	2.34E-01	0	0	2.34E-01	0.06%
LCD front glass (with color filters)	0	1.78E-01	0	0	1.78E-01	0.05%
Aluminum (elemental)	0	1.34E-01	0	0	1.34E-01	0.04%
Sand	0	1.11E-01	0	0	1.11E-01	0.03%
Recycled LCD glass	0	9.54E-02	0	0	9.54E-02	0.03%

LCD Ancillary Inputs

As presented in Figure 2-39, the greatest mass of ancillary LCD inputs is in the manufacturing life-cycle stage at approximately 204 kg/functional unit. Table 2-47 shows that liquified natural gas (LNG) contributes about 93% to this total. It is in the LCD module/monitor manufacturing process where this large amount of LNG was reported as an ancillary material (to be discussed below). Note that this is separate from LNG reported as a fuel, and LNG as an ancillary material is not used to calculate energy impacts in the LCIA. Following LNG is nitrogen at about 3% and clay at less than 1% of the total ancillary materials by mass. Excluding LNG from the inventory, nitrogen constitutes about 50% and clay 14% of the total ancillary materials in the LCD life-cycle. The contributions from the manufacturing stage will be discussed in further detail below. See Table J-11 in Appendix J for the complete list of ancillary materials in the LCD inventory.

Table 2-47. Top 99% of LCD ancillary material inputs (kg/functional unit)

Material	Upstream	Mfg	Use	EOL	Total	% of total
LNG	0	1.94e+02	0	0	1.94e+02	93.19%
Nitrogen	0	6.02e+00	0	0	6.02e+00	2.89%
Clay (in ground)	1.30e-03	0	0	1.69e+00	1.69e+00	0.81%
Limestone	0	1.08e-01	8.99e-01	1.71e-04	1.01e+00	0.48%
Sand (in ground)	9.55e-03	1.32e-03	0	5.60e-01	5.71e-01	0.27%
Sodium hydroxide	0	4.45e-01	0	0	4.45e-01	0.21%
Hydrogen	0	4.44e-01	0	0	4.44e-01	0.21%
Lime	0	4.74e-02	3.95e-01	7.49e-05	4.42e-01	0.21%
Sodium chloride (NaCl, in ground or sea)	4.37e-01	6.08e-04	0	1.08e-05	4.38e-01	0.21%
Limestone (CaCO3, in ground)	5.07e-01	5.49e-02	0	-1.55e-01	4.06e-01	0.20%
Isopropyl alcohol	0	3.49e-01	0	0	3.49e-01	0.17%
Sulfuric acid	0	3.25e-01	0	0	3.25e-01	0.16%

LCD Utility Inputs

Utility inputs in the LCD life-cycle are presented in Table 2-48 and include fuel (kg/functional unit), electricity (MJ/functional unit), water inputs (kg or L/functional unit), and total energy (MJ/functional unit; a combination of fuel and electricity inputs). Table 2-48 and Figure 2-40 show that most fuels (26 kg/functional unit) are used in the manufacturing stage. This represents 67% of the total fuels. LPG (16.8 kg/functional unit) dominates the total fuel inputs at 44% of all the fuels in the LCD life-cycle. More detail as to the breakdown by process within the manufacturing stage will be presented below after each input/output type is discussed.

Electricity inputs are dominated by the use stage (853 MJ/functional unit), followed by the manufacturing stage (316 MJ/functional unit) (see Figure 2-41). When fuel energy and electrical energy are combined into a total energy input value, the overall energy from manufacturing exceeds that from the use stage (1,440 MJ/functional unit versus 853 MJ/functional unit). This is also depicted in Figure 2-42.

The other utility considered in Table 2-48 is water (Figure 2-43). Approximately 76% (2,150 L/functional unit) of the water inputs in the LCD life-cycle are from the manufacturing processes. The life-cycle stage contributing the next most to water inputs is the use stage at 15% (425 L/functional unit). The upstream contributes about 9% (263 L/functional unit). Table J-12 in Appendix J provides the complete list of inventory items for the LCD.

Table 2-48. LCD utility inputs

Material	Upstream	Mfg	Use	EOL	Total	% of total
Fuels (kg/functional unit):						
LPG	0	1.68E+01	0	1.38E-03	1.68E+01	43.63%
Natural gas (in ground)	1.03E+01	2.41E+00	0	-1.38E-01	1.26E+01	32.66%
LNG	0	3.22E+00	0	0	3.22E+00	8.34%
Coal, average (in ground)	2.49E+00	6.86E-01	0	-7.66e-03	3.17E+00	8.21%
Petroleum (in ground)	1.52E+00	4.84E-01	0	-3.81e-02	1.96e+00	5.08%
Kerosene	0	4.65E-01	0	0	4.65e-01	1.21%
Coal, lignite (in ground)	4.10E-01	0	0	0	4.10e-01	1.06%
Natural gas	0	1.16E+00	0	-8.61E-01	3.01e-01	0.78%
Steam	0	1.45E-01	0	0	1.45e-01	0.37%
Fuel oil #6	0	1.25E-01	0	0	1.25e-01	0.33%
Fuel oil #2	0	5.42E-02	0	0	5.42e-02	0.14%
Uranium (U, ore)	7.86E-05	1.15E-05	0	0	9.01e-05	<0.01%
Fuel oil #4	0	2.11E-01	0	-9.09e-01	-6.99e-01	-1.81%
Total fuels	1.47E+01	2.58e+01	0	-1.95E+00	3.86e+01	100.00%
Electricity (MJ/functional unit):						
Electricity	3.46e+01	3.16e+02	8.53e+02	1.62e-01	1.20e+03	
Water (kg or L/functional unit):						
Water	2.63E+02	2.15E+03	4.25E+02	-1.80E+01	2.82e+03	
Total energy (fuels and electricity, MJ/functional unit):						
Energy	6.33E+02	1.44E+03	8.53E+02	-8.44E+01	2.84E+03	

LCD Air Outputs

Air emissions from the LCD life-cycle are greatest (by mass) in the use stage as seen in Figure 2-44. This indicates that most air emissions by mass are from the generation of electricity used by consumers of the monitors. Forty-nine percent of the total life-cycle air emissions by mass (or about 168 kg/functional unit) are from the use stage. Carbon dioxide (CO_2) emissions from the use stage alone constitute about 166 kg/functional unit, or almost 48% of all air emissions by mass in the life-cycle and nearly 99% of the use stage air emissions. The remaining air emissions that contribute to the top 99.99% of air emissions are presented in Table 2-49 and the complete list of air emissions are presented alphabetically in Table J-13 in Appendix J. The appendix also provides life-cycle stage subtotals. The next largest air emissions, by life-cycle stage, are emitted during the upstream stages, which contribute about 32% to the total life-cycle air emissions. All the air emissions in the inventory except for ethylacetate and methyl ethyl ketone from the manufacturing stage (a combined 1.36×10^{-4} kg/functional unit) were reported as being emitted directly to the air (see Appendix J, Table J-13). Only those materials directly released to the air are used to calculate impacts. This will be discussed further in Chapter 3.

Table 2-49. Top 99.99% of LCD air emissions (kg/functional unit)

Material	Disposition	Upstream	Mfg	Use	EOL	Total	% of total
Carbon dioxide	Air	1.07e+02	6.22e+01	1.66e+02	1.39e+00	3.36e+02	97.18%
Methane	Air	3.54e+00	1.22e-01	2.41e-01	-2.82e-02	3.87e+00	1.12%
Nitrogen oxides	Air	6.56e-01	7.62e-01	4.39e-01	-1.36e-02	1.84e+00	0.53%
Sulfur dioxide	Air	4.63e-02	2.95e-01	9.30e-01	2.96e-04	1.27e+00	0.37%
Tetramethyl ammonium	Air	0	6.43e-01	0	0	6.43e-01	0.19%
Other organics	Air	4.45e-01	1.35e-02	0	-2.41e-03	4.56e-01	0.13%
Carbon monoxide	Air	3.74e-01	3.85e-02	3.02e-02	-3.45e-03	4.39e-01	0.13%
Nitrogen fluoride	Air	0	2.45e-01	0	0	2.45e-01	0.07%
Nonmethane hydrocarbons	Air	2.07e-01	8.87e-03	0	-1.26e-03	2.15e-01	0.06%
Hydrochloric acid	Air	1.50e-03	6.58e-02	4.02e-02	-6.88e-04	1.07e-01	0.03%
Benzene	Air	8.85e-02	2.70e-03	4.36e-05	-4.82e-04	9.07e-02	0.03%
PM	Air	9.16e-02	6.99e-03	0	-1.24e-02	8.62e-02	0.02%
Ammonia	Air	1.12e-02	6.26e-02	0	-6.95e-05	7.37e-02	0.02%
Phosphine	Air	0	6.26e-02	0	0	6.26e-02	0.02%
Hydrofluoric acid	Air	2.27e-04	5.27e-02	5.02e-03	-1.47e-04	5.78e-02	0.02%
Sulfur oxides	Air	2.57e-02	4.07e-02	0	-1.93e-02	4.71e-02	0.01%
Unspecified LCD process	Air	0	4.49e-02	0	0	4.49e-02	0.01%
Cr-etchant, unspecified	Air	0	4.12e-02	0	0	4.12e-02	0.01%
Nitrogen dioxide	Air	3.08e-02	0	0	4.46e-04	3.12e-02	<0.01%
PM-10	Air	3.45e-07	6.85e-03	2.16e-02	3.43e-06	2.84e-02	<0.01%
Isopropyl alcohol	Air	0	1.78e-02	0	0	1.78e-02	<0.01%
Hydrocarbons, remaining	Air	9.30e-03	7.75e-03	0	-6.51e-04	1.64e-02	<0.01%
Al-etchant, unspecified	Air	0	1.37e-02	0	0	1.37e-02	<0.01%

LCD Water Outputs

The volume (or mass) of wastewater released throughout the LCD life-cycle is approximately 3,128 L (kg) per functional unit. Approximately 19% of that is sent to treatment as opposed to direct discharge to surface water (81%; Figure 2-45). The mass of chemical pollutants within the wastewater streams were calculated separately from the total wastewater volume. The total mass of water pollutants released, presented by life-cycle stage are shown in Figure 2-46. Of the small amount of water pollutants released, the manufacturing life-cycle stage contributes the greatest with approximately 1.23 kg per functional unit. This is about 73% of all the water pollutants for the entire life-cycle. The upstream stages have the second greatest mass of water pollutants at nearly 0.46 kg/functional unit (27%). The use and EOL stages are small contributors, with the EOL being negative due to recovery processes within the EOL stage. To see the top 99% contributors to the water pollutant quantities, Table 2-50 reveals that chloride and sodium ions contribute nearly 61% to all the water pollutants in the life-cycle, mostly from the manufacturing and upstream stages. For the complete inventory, listing water pollutants alphabetically and by life-cycle stage, see Appendix J, Table J-14. Further details on the manufacturing stage will be provided later.

Table 2-50. Top 99% of LCD water pollutant outputs (kg/functional unit)

Material	Disposition	Upstream	Mfg	Use	EOL	Total	% of total
Chloride ions	surface water	2.33e-01	3.12e-01	0	-1.58e-02	5.29e-01	31.53%
Sodium (+1)	surface water	1.73e-01	3.41e-01	0	-2.03e-02	4.94e-01	29.42%
Dissolved solids	surface water	3.21e-03	1.75e-01	0	-5.69e-05	1.78e-01	10.63%
COD	surface water	7.67e-03	8.20e-02	0	-2.69e-03	8.70e-02	5.18%
Nitrogen	surface water	1.44e-05	7.98e-02	0	0	7.98e-02	4.76%
Suspended solids	surface water	4.98e-03	5.80e-02	0	-1.44e-03	6.15e-02	3.66%
BOD	treatment	0	5.74e-02	0	0	5.74e-02	3.42%
COD	treatment	0	3.90e-02	0	0	3.90e-02	2.33%
BOD	surface water	7.72e-04	2.79e-02	0	-3.18e-04	2.83e-02	1.69%
Sulfate ion (-4)	surface water	2.40e-02	2.94e-03	0	-1.20e-06	2.69e-02	1.60%
Sulfate ion (-4)	treatment	0	1.32e-04	2.55e-02	4.84e-06	2.57e-02	1.53%
Fluorides (F-)	surface water	5.14e-05	1.29e-02	0	-5.01e-06	1.30e-02	0.77%
Nitrogen	treatment	0	1.26e-02	0	0	1.26e-02	0.75%
Phosphorus (yellow or white)	treatment	0	6.91e-03	0	0	6.91e-03	0.41%
Waste oil	surface water	1.75e-03	4.87e-03	0	-2.06e-04	6.41e-03	0.38%
Suspended solids	treatment	0	5.60e-03	6.65e-04	1.26e-07	6.26e-03	0.37%
Phosphorus (yellow or white)	surface water	1.92e-06	4.33e-03	0	0	4.33e-03	0.26%
Colon bacillus (bacteria in large intestine)	surface water	0	3.89e-03	0	0	3.89e-03	0.23%
Oil & grease	treatment	0	3.61e-03	0	0	3.61e-03	0.21%

LCD Hazardous Waste Outputs

The total mass of hazardous waste generated throughout the life-cycle of the LCD is about 6.29 kg/functional unit. Figure 2-47 shows that this is mostly from the manufacturing stage, which contributes 4.64 kg/functional unit, or almost 74%. The EOL stage hazardous waste outputs equal 1.64 kg/functional unit, or 26%. The disposition of the waste will be used to determine how impacts are calculated in Chapter 3. Only hazardous wastes sent to landfills are directly calculated as impacts, which will be presented and discussed in Chapter 3. Figure 2-47 shows what portion of hazardous wastes are landfilled, recycled/reused, treated or otherwise land-applied. Nearly all of the hazardous waste in the manufacturing stage (~99%) is recycled/reused or treated. Less than 1% of the hazardous waste from the manufacturing stage is landfilled. Nearly all the hazardous waste from the EOL stage is landfilled. Table 2-51 shows the top contributors to the LCD life-cycle. Note that multiple entries of a material are due to different dispositions for that material. See Table J-15 in Appendix J for the complete alphabetical inventory of hazardous waste outputs. Additional detail on the manufacturing stage are presented below.

Table 2-51. Top 99% of LCD hazardous waste outputs (kg/functional unit)

Material	Disposition	Upstream	Mfg	Use	EOL	Total	% of total
Isopropyl alcohol	treatment	0	1.91E+00	0	0	1.91E+00	30.41%
EOL LCD Monitor, landfilled	landfill	0	0	0	1.64E+00	1.64E+00	26.13%
Waste acid (mainly HF)	recycling/reuse	0	5.69E-01	0	0	5.69E-01	9.04%
Thinner, unspecified	treatment	0	5.40E-01	0	0	5.40E-01	8.57%
Remover, unspecified	treatment	0	3.03E-01	0	0	3.03E-01	4.81%
Sodium sulfate	recycling/reuse	0	2.44E-01	0	0	2.44E-01	3.89%
Isopropyl alcohol	recycling/reuse	0	1.69E-01	0	0	1.69E-01	2.69%
Tetramethyl ammonium hydroxide	recycling/reuse	0	1.42E-01	0	0	1.42E-01	2.26%
Waste acid (mainly HF)	treatment	0	1.36E-01	0	0	1.36E-01	2.15%
PWB-Waste cupric etchant	recycling/reuse	0	9.93E-02	0	0	9.93E-02	1.58%
Remover, unspecified	recycling/reuse	0	8.84E-02	0	0	8.84E-02	1.40%
Hazardous waste, unspecified	treatment	0	6.16E-02	0	0	6.16E-02	0.98%
Rinse, unspecified	recycling/reuse	0	4.67E-02	0	0	4.67E-02	0.74%
Spent solvent (non-halogenated)	treatment	0	4.66E-02	0	0	4.66E-02	0.74%
Hazardous waste, unspecified	landfill	6.72E-03	2.97E-02	0	-1.05E-03	3.54E-02	0.56%
Waste acids, unspecified	recycling/reuse	0	3.24E-02	0	0	3.24E-02	0.52%
Unspecified sludge	land (other than landfill)	0	3.09E-02	0	0	3.09E-02	0.49%
PWB-Solder dross	recycling/reuse	0	2.96E-02	0	0	2.96E-02	0.47%
Acetone	treatment	0	2.77E-02	0	0	2.77E-02	0.44%
Waste solvent (photoresist)	treatment	0	2.17E-02	0	0	2.17E-02	0.35%
Waste solvent (photoresist)	recycling/reuse	0	2.05E-02	0	0	2.05E-02	0.33%
Spent solvent (with halogenated materials)	treatment	0	1.55E-02	0	0	1.55E-02	0.25%
Phosphoric acid	landfill	0	1.44E-02	0	0	1.44E-02	0.23%

LCD Solid Waste Outputs

Figure 2-48 shows that the use stage contributes the most amount (31 kg/functional unit) of solid waste by mass to the LCD life-cycle, and 100% of that waste is landfilled. The manufacturing stage contributes 12.6 kg/functional unit. In terms of mass, the greatest material contributors to the solid waste outputs for the LCD life-cycle are coal waste (~41%), followed by dust/sludge (16%). Most of this is from the generation of electricity in the use stage (Table 2-52). Note also that the mass of an LCD monitor that is assumed to be landfilled (0.89 kg/functional unit) is 1.7% of the total mass of solid waste in the LCD life-cycle. See Appendix J, Table J-16 for the complete LCD solid waste inventory. The manufacturing stage breakdown will be discussed at the end of this section.

Table 2-52. Top 99% of LCD solid waste outputs (kg/functional unit)

Material	Disposition	Upstream	Mfg	Use	EOL	Total	% of total
Coal waste	landfill	0	2.28E+00	1.90E+01	3.60E-03	2.13E+01	40.64%
Dust/sludge	landfill	0	8.80E-01	7.34E+00	1.39E-03	8.23E+00	15.72%
Fly/bottom ash	landfill	0	5.70E-01	4.75E+00	9.01E-04	5.32E+00	10.16%
Unspecified solid waste	landfill	2.40E+00	0	0	-5.10E-01	1.89E+00	3.62%
Slag and ash	recycle/reuse	8.02E+00	3.40E+00	0	-9.67E+00	1.75E+00	3.35%
Unspecified solid waste	recycle/reuse	1.50E+00	2.11E-01	0	0	1.71E+00	3.27%
Unspecified solid waste	treatment	0	1.63E+00	0	0	1.63E+00	3.11%
Iron scrap	recycle/reuse	1.67E-01	0	0	1.10E+00	1.27E+00	2.42%
EOL LCD Monitor, incinerated	treatment	0	0	0	9.75E-01	9.75E-01	1.86%
EOL LCD Monitor, recycled	recycle/reuse	0	0	0	9.75E-01	9.75E-01	1.86%
EOL LCD Monitor, remanufactured	recycle/reuse	0	0	0	9.75E-01	9.75E-01	1.86%
EOL LCD Monitor, landfilled	landfill	0	0	0	8.94E-01	8.94E-01	1.71%
Unspecified sludge	recycle/reuse	0	8.46E-01	0	0	8.46E-01	1.62%
Waste LCD glass	recycle/reuse	0	7.20E-01	0	0	7.20E-01	1.38%
Unspecified waste	recycle/reuse	4.05E-01	1.72E-01	0	-9.83E-03	5.67E-01	1.08%
CARBON STEEL SCRAP	recycle/reuse	0	0	0	4.58E-01	4.58E-01	0.88%
Waste plastic from LCD modules	treatment	0	4.03E-01	0	0	4.03E-01	0.77%
Polycarbonate	recycle/reuse	0	0	0	3.90E-01	3.90E-01	0.75%
Waste alkali, unspecified	recycle/reuse	0	3.23E-01	0	0	3.23E-01	0.62%
Waste acid (containing F and detergents)	landfill	0	2.70E-01	0	0	2.70E-01	0.52%
Waste LCD glass	landfill	0	2.63E-01	0	0	2.63E-01	0.50%
Mineral waste	landfill	2.20E-01	1.26E-04	0	-4.46E-06	2.21E-01	0.42%
Mining waste	landfill	1.41E-01	0	0	-1.23E-06	1.41E-01	0.27%
Slag and ash	landfill	8.19E-02	3.49E-02	0	-1.99E-03	1.15E-01	0.22%
Waste acids, unspecified	treatment	0	1.05E-01	0	0	1.05E-01	0.20%
Mixed industrial (waste)	landfill	4.34E-02	4.83E-02	0	-1.35E-03	9.04E-02	0.17%
Waste alkali (color filter developer, unspecified)	recycle/reuse	0	8.91E-02	0	0	8.91E-02	0.17%

LCD Radioactive Waste Outputs

Radioactive waste outputs in the LCD inventory are limited to the electricity generation and steel production processes, with steel production processes accounting for only about 9% of the total. Therefore, radioactive wastes will be found wherever electricity is used in a process in the LCD life-cycle. Only very small amounts (approximately 0.0015 kg/functional unit) of radioactive waste are generated over the entire life-cycle of the LCD (Figure 2-49 and Table 2-53). As expected, the majority of this is linked to the use stage, where most electricity is used in the LCD life-cycle, followed by the manufacturing stage. Low-level radioactive waste (78%) and depleted uranium (21%) are most of the waste, with negligible amounts of highly radioactive waste and unspecified radioactive waste. The inventory of radioactive waste outputs is small,

and therefore, Table 2-53 lists all material outputs associated with radioactive waste, in descending order of quantity. Table J-17 in Appendix J lists these in alphabetical order.

Table 2-53. LCD radioactive waste outputs (kg/functional unit)

Material	Disposition	Upstream	Mfg	Use	EOL	Total	% of total
Low-level radioactive waste	landfill	1.28E-04	3.74E-04	6.56E-04	1.24E-07	1.16E-03	78.49%
Uranium, depleted	landfill	0	1.12E-04	1.97E-04	3.73E-08	3.09E-04	20.93%
Radioactive waste (unspecified)	landfill	5.77E-06	0	0	0	5.77E-06	0.39%
Highly radioactive waste (Class C)	landfill	2.72E-06	0	0	0	2.72E-06	0.18%
Total radioactive wastes		1.37E-04	4.87E-04	8.52E-04	1.62E-07	1.48E-03	100.00%

LCD Radioactivity Outputs

Radioactivity is also inventoried in this project as isotopes that are released to the environment. Radioactivity is measured in Bequerels and may be released to air, water, or land, or may also be treated. The quantity of radioactivity for each life-cycle stage and different dispositions are presented in Figure 2-50. Table 2-54 shows the top contributors to the total radioactivity outputs. Radioactivity outputs are associated with the generation of electricity and, therefore, the greatest quantity of radioactivity is from the use stage. Appendix J, Table J-18 lists the complete inventory.

Table 2-54. Top 99.9% of LCD radioactivity outputs (Bq/functional unit)

Material	Disposition	Upstream	Mfg.	Use	EOL	Total	% of total
Molybdenum-99 (isotope)	treatment	0	1.01e+07	1.76e+07	3.35e+03	2.77e+07	69.09%
Plutonium-241 (isotope)	landfill	1.18e+07	0	0	0	1.18e+07	29.33%
Tritium-3 (isotope)	treatment	0	5.96e+04	1.04e+05	1.98e+01	1.64e+05	0.41%
Xenon-133 (isotope)	air	7.63e+02	4.98e+03	1.16e+05	2.21e+01	1.22e+05	0.30%
Xenon-133M (isotope)	air	0	6.59e+04	7.73e+03	1.47e+00	7.36e+04	0.18%
Plutonium-240 (isotope)	landfill	5.08e+04	0	0	0	5.08e+04	0.13%
Cesium-135 (isotope)	landfill	4.59e+04	0	0	0	4.59e+04	0.11%
Radon-222 (isotope)	air	4.30e+04	0	0	0	4.30e+04	0.11%
Plutonium-239 (isotope)	landfill	3.57e+04	0	0	0	3.57e+04	0.09%
Xenon-133 (isotope)	treatment	0	9.43e+03	1.65e+04	3.13e+00	2.60e+04	0.06%
Tritium-3 (isotope)	air	1.09e+02	7.98e+03	1.40e+04	2.65e+00	2.21e+04	0.05%
Krypton-85 (isotope)	air	5.45e+01	5.64e+03	9.88e+03	1.88e+00	1.56e+04	0.04%

LCD Manufacturing Stage

The inventory tables that show the specific materials in each inventory (i.e., those in Appendix J and Tables 2-46 through 2-54) are the sums of the materials from one or more processes within a life-cycle stage. To burrow down deeper into the data, the manufacturing stage inventory data are broken down by process or group of processes. Similar to the CRT analysis, groups of processes were combined where fewer than three companies provided data for a process or where confidentiality agreements precluded presenting individual process data (Table 2-55). Burrowing further into the contributing processes or process groups is necessary for future manufacturing improvement assessments.

Table 2-55. LCD process groups

Process group	Process(es) included
Monitor/module	panel/module manufacturing, monitor assembly
Panel components	polarizer manufacturing, patterning color filters on glass, liquid crystal manufacturing
LCD glass	LCD glass manufacturing
Backlight	backlight unit assembly, backlight light guide, cold cathode fluorescent lamp manufacturing
PWB	PWB manufacturing
Japanese grid	electricity generation - Japanese electric grid
U.S. grid	electricity generation - U.S. electric grid
Fuels	production of fuel oils #2, #4 and #6, LPG, and natural gas

Tables 2-56 through 2-64 list the specific inventories for each process group in the manufacturing stage for each input and output type. Figures 2-51 through 2-61 graph the total inventories for each process group for each input and output type. As revealed in Table 2-45, ancillary material inputs, fuels, water and total energy inputs all were greatest in the manufacturing stage. Similarly, wastewater, water pollutant and hazardous waste outputs were also greatest in the manufacturing stage. Similar to the discussion for CRTs, the manufacturing stage inventories by process group, for all input and output types, are presented here to reveal more specifics about the inventory and to allow manufacturers to conduct improvement assessments.

Table 2-56. LCD manufacturing stage primary material inputs

Material	Quantity (kg/ functional unit)	% of process group total	% of grand total
Process Group			
Module/Monitor			
1,4-butanolide	4.06e-04	0.01%	
1-methyl-2-pyrrolidinone	4.06e-04	0.04%	
2-(2-butoxyethoxy)-ethanol acetate	8.08e-06	<0.01%	
AlNd	2.97e-05	<0.01%	
Aluminum (elemental)	1.01e-01	1.34%	
Assembled 15" LCD backlight unit	1.48e+00	19.67%	
Cables/wires	2.30e-01	3.07%	
Glycol ethers	4.06e-04	0.01%	
Indium tin oxide	5.26e-04	0.01%	
LCD front glass (with color filters)	1.78e-01	2.38%	
LCD glass	2.16e-01	2.88%	
LCD material (confidential)	3.11e-04	<0.01%	
LCD module	1.18e+00	15.78%	
LCD spacers, unspecified	1.69e-05	<0.01%	
Liquid crystals, for 15" LCD	1.24e-03	0.02%	
Mild fiber	7.34e-07	<0.01%	
Molybdenum	1.78e-04	<0.01%	
MoW	9.09e-04	0.01%	
Polarizer	4.07e-02	0.54%	
Polycarbonate resin	4.01e-01	5.35%	
Polyimide alignment layer, unspecified	4.86e-04	0.01%	
PPE	3.00e-01	4.00%	
Printed wiring board (PWB)	3.74e-01	4.98%	
Solder (60% tin, 40% lead)	3.81e-02	0.51%	
Steel	2.50e+00	33.38%	
Styrene-butadiene copolymers	3.62e-01	4.82%	
Titanium	1.33e-04	<0.01%	
Triallyl isocyanurate	1.54e-05	<0.01%	
Triphenyl phosphate	9.25e-02	1.23%	
Unspecified LCD material	1.19e-04	<0.01%	
Total	**7.50e+00**	100.00%	**15.26%**
Panel Components			
3,4,5-trifluorobromobenzene	2.64e-04	0.08%	
3,4-difluorobromobenzene	3.65e-04	0.04%	
4-4(-propylcyclohexyl)cyclohexanone	2.18e-04	0.07%	
4-bromophenol	3.27e-04	0.10%	
4-ethylphenol	7.00e-05	0.02%	
4-pentylphenol	3.42e-04	0.11%	
4-propionylphenol	1.94e-04	0.06%	
LCD glass	2.36e-01	74.75%	

Table 2-56. LCD manufacturing stage primary material inputs

Material	Quantity (kg/ functional unit)	% of process group total	% of grand total
Process Group			
Pigment color resist, unspecified	3.72e-02	11.80%	
Polyester adhesive	6.25e-04	0.20%	
Polyethylene terephthalate	3.14e-02	9.96%	
Polyvinyl alcohol	8.61e-03	2.73%	
Total	**3.16e-01**	100.00%	**0.64%**
Glass mfg			
Barium Carbonate	1.37e-02	4.90%	
Glass, unspecified	2.28e-03	0.23%	
Potassium Carbonate	1.75e-02	6.24%	
Recycled LCD glass	9.54e-02	34.00%	
Sand	1.11e-01	39.64%	
Sodium Carbonate	2.26e-02	8.05%	
Strontium Carbonate	1.53e-02	5.47%	
Zircon Sand	2.51e-03	0.90%	
Total	**2.81e-01**	99.42%	**0.57%**
Backlight			
15" LCD light guide	3.74e-01	37.18%	
Aluminum (elemental)	3.35e-02	3.35%	
Argon	3.53e-05	<0.01%	
Backlight lamp (CCFL)	1.94e-03	0.19%	
Cables/wires	3.43e-03	0.34%	
Glass, unspecified	4.14e-02	4.11%	
Mercury	3.99e-06	<0.01%	
Metals, remaining unspeciated	6.81e-04	0.07%	
Neon	6.31e-05	0.01%	
Poly(methyl methacrylate)	3.83e-01	38.12%	
Polycarbonate resin	1.14e-01	11.38%	
Polyethylene terephthalate	2.74e-02	2.72%	
Rubber, unspecified	6.01e-04	0.06%	
Steel	2.52e-02	2.50%	
Total	**1.01e+00**	100.02%	**2.04%**
PWB			
PWB-laminate	3.74e-01	94.35%	
Solder (63% tin; 37% lead)	2.24e-02	5.66%	
Total	**3.96e-01**	100.00%	**0.81%**
Japanese Grid			
Coal, average (in ground)	7.69e+00	47.41%	
Natural gas	4.20e+00	25.89%	
Petroleum (in ground)	4.33e+00	26.69%	
Uranium, yellowcake	1.02e-03	0.01%	
Total	**1.62e+01**	100.00%	**32.96%**

Table 2-56. LCD manufacturing stage primary material inputs

Material	Quantity (kg/ functional unit)	% of process group total	% of grand total
Process Group			
U.S. Grid			
Coal, average (in ground)	3.47e-01	90.97%	
Natural gas	2.71e-02	7.10%	
Petroleum (in ground)	7.36e-03	1.93%	
Uranium, yellowcake	9.39e-06	<0.01%	
Total	**3.82e-01**	100.00%	**0.78%**
Fuel Production			
Natural gas (in ground)	5.16e+00	22.33%	
Petroleum (in ground)	1.79e+01	77.67%	
Total	**2.31e+01**	100.00%	**46.94%**
Grand Total	**4.92e+01**		**100.00%**

Table 2-57. LCD manufacturing stage ancillary material inputs

Material	Quantity(kg/ functional unit)	% of process group total	% of grand total
Process Group			
Module/Monitor			
1,4-butanolide	4.04e-05	6.91%	
1-Methoxy-2-propanol	1.10e-02	100.00%	
2-(2-butoxyethoxy)-ethanol	3.04e-02	0.02%	
2,2,4-trimethylpentane	1.52e-05	<0.01%	
2-ethoxyl ethylacetate	1.78e-03	<0.01%	
Acetic acid	6.40e-03	<0.01%	
Acetone	1.03e-02	0.01%	
Al-etchant, unspecified	5.88e-03	<0.01%	
Aluminum sulfate	1.05e-01	0.05%	
Ammonia	1.55e-02	0.01%	
Ammonium bifluoride	2.36e-03	<0.01%	
Ammonium fluoride	1.14e-02	0.01%	
Ammonium hydroxide	5.15e-06	<0.01%	
Argon	7.87e-03	<0.01%	
Calcium hydroxide	1.39e-01	0.07%	
Carbon dioxide	3.74e-05	<0.01%	
Chlorine	1.55e-02	0.01%	
Cleaner, unspecified	1.47e-04	<0.01%	
Cresol-formaldehyde resin	8.29e-04	<0.01%	
Cr-etchant, unspecified	1.77e-02	0.01%	
Cyclohexane	2.03e-05	<0.01%	
Dimethylsulfoxide	6.63e-02	0.03%	
Ethanol	1.35e-02	0.01%	
Ethanol amine	7.85e-02	0.04%	
Ferric chloride	8.92e-03	<0.01%	
Fluorocarbon resin	3.38e-06	<0.01%	
Flux, unspecified	7.35e-05	<0.01%	
Glycol ethers	2.12e-02	0.01%	
Helium	6.18e-04	<0.01%	
Hexamethyldisilizane	2.58e-04	<0.01%	
Hydrochloric acid	4.31e-02	0.02%	
Hydrofluoric acid	4.21e-02	0.02%	
Hydrogen	4.44e-01	0.22%	
Hydrogen peroxide	1.47e-04	<0.01%	
Isopropyl alcohol	3.49e-01	0.17%	
ITO etchant, unspecified	2.94e-03	<0.01%	
Krypton	2.58e-05	<0.01%	
LNG	1.94e+02	95.80%	
Methyl ethyl ketone	7.35e-06	<0.01%	
Monosilane	1.12e-03	<0.01%	

Table 2-57. LCD manufacturing stage ancillary material inputs

Material	Quantity(kg/ functional unit)	% of process group total	% of grand total
Process Group			
N-Butylacetate	3.83e-02	0.02%	
Nitric acid	1.24e-02	0.01%	
Nitrogen	5.90e+00	2.91%	
Nitrogen fluoride	1.08e-01	0.05%	
Nitrous oxide	1.36e-03	<0.01%	
Oxygen	7.75e-03	<0.01%	
Perfluoromethane	1.29e-03	<0.01%	
Phosphine	2.69e-02	0.01%	
Phosphoric acid	3.95e-02	0.02%	
Photoresist, unspecified	1.38e-02	0.01%	
Polyaluminum chloride	6.40e-03	<0.01%	
Polyethylene mono(nonylphenyl) ether glycol	3.40e-04	<0.01%	
Polyimide, unspecified	2.94e-05	<0.01%	
Propylene glycol	4.46e-03	<0.01%	
Propylene glycol monomethyl ether acetate	1.56e-02	0.01%	
Rinse, unspecified	5.27e-02	0.03%	
Sodium dihydrogen phosphate dihydrate	4.06e-06	<0.01%	
Sodium hydroxide	3.59e-01	0.18%	
Solder, unspecified	7.35e-05	<0.01%	
Sulfur hexafluoride	1.62e-02	0.01%	
Sulfuric acid	2.29e-01	0.11%	
Surfactant, unspecified	1.09e-04	<0.01%	
Synthetic resin, unspecified	6.57e-04	<0.01%	
Tetramethyl ammonium hydroxide	1.29e-01	0.06%	
Unspecified LCD process material	2.58e-02	0.01%	
Water	6.88e-02	0.03%	
Xylene (mixed isomers)	1.57e-03	<0.01%	
Total	**2.03e+02**	**206.91%**	**99.48%**
Panel Components			
Acetone	1.03e-02	3.19%	
Borax	9.13e-05	0.01%	
Carbon dioxide	4.82e-03	1.50%	
Cyclohexane	3.89e-03	1.21%	
Developing solution, unspecified	4.00e-02	12.45%	
Diluent, unspecified	8.27e-03	2.57%	
Ethanol	1.17e-02	3.65%	
Ethylacetate	9.68e-04	0.30%	
Exfoliation liquid, unspecified	1.43e-02	4.44%	
HCFC-225ca	1.37e-04	0.04%	
HCFC-225cb	1.37e-04	0.04%	
Heptane	1.03e-02	3.19%	

Table 2-57. LCD manufacturing stage ancillary material inputs

Material	Quantity(kg/ functional unit)	% of process group total	% of grand total
Process Group			
Hydrochloric acid	1.74e-03	0.54%	
Hydrogen	3.14e-06	<0.01%	
Methyl ethyl ketone	4.84e-04	0.15%	
Nitric acid second cerium ammonium	1.13e-02	3.51%	
Nitrogen	1.17e-01	36.27%	
Orthoboric acid	7.30e-04	0.23%	
Perchloric acid	3.82e-03	1.19%	
Photoresist, unspecified	2.94e-03	0.91%	
Polyethylene terephthalate	3.20e-02	9.93%	
Sulfuric acid	1.58e-02	4.91%	
Tetrahydrofuran	3.82e-03	1.19%	
Toluene	2.75e-02	8.56%	
Total	**3.22e-01**	99.98%	**0.16%**
LCD Glass			
Aluminum Oxide	1.56e-03	17.30%	
Cerium Oxide	1.52e-04	1.68%	
Chromium Oxide	2.60e-06	0.03%	
Hydrofluoric acid	3.66e-03	40.61%	
Pumice	3.64e-03	40.37%	
Total	**9.02e-03**	100.00%	**0.00%**
Backlight			
Diethyl ether	9.28e-05	14.78%	
Ethanol	4.63e-05	7.36%	
Process material for backlight assembly	7.03e-05	11.19%	
Unspecified ancillary material	4.19e-04	66.67%	
Total	**6.28e-04**	100.00%	**0.00%**
PWB			
Ammonium chloride	3.42e-02	6.68%	
Ammonium hydroxide	3.42e-02	3.42%	
Formaldehyde	2.91e-03	0.57%	
Glycol ethers	1.04e-02	2.03%	
Hydrochloric acid	8.46e-02	16.51%	
Hydrogen peroxide	1.37e-02	2.67%	
Nitric acid	5.99e-02	11.70%	
Polyethylene glycol	2.23e-02	4.34%	
Potassium hydroxide	1.88e-02	3.68%	
Potassium permanganate	5.14e-04	0.10%	
Potassium peroxymonosulfate	3.12e-02	6.08%	
PWB-solder mask solids	1.93e-02	3.76%	
Sodium Carbonate	1.42e-02	2.77%	
Sodium hydroxide	8.56e-02	16.71%	

Table 2-57. LCD manufacturing stage ancillary material inputs

Material	Quantity(kg/ functional unit)	% of process group total	% of grand total
Process Group			
Sulfuric acid	8.05e-02	15.72%	
Total	**5.12e-01**	96.74%	**0.25%**
Japanese Grid			
Lime	4.53e-02	30.57%	
Limestone	1.03e-01	69.43%	
Total	**1.48e-01**	100.00%	**0.07%**
U.S. Grid			
Lime	2.05e-03	30.52%	
Limestone	4.66e-03	69.48%	
Total	**6.71e-03**	100.00%	**0.00%**
Fuel Production			
Bauxite (Al2O3, ore)	2.16e-03	3.66%	
Limestone (CaCO3, in ground)	5.49e-02	93.07%	
Sand (in ground)	1.32e-03	2.24%	
Sodium chloride (NaCl, in ground or in sea)	6.08e-04	1.03%	
Total	**5.90e-02**	100.00%	**0.03%**
Grand Total	**2.04e+02**		**100.00%**

Table 2-58. LCD manufacturing stage utility inputs

Material	Quantity	% of process group total	% of grand total
Process group			
Fuels (kg/functional unit):			
Monitor/Module			
Fuel oil #4	2.11e-01	4.09%	
Kerosene	2.98e-01	5.77%	
LNG	3.22e+00	62.40%	
Liquified petroleum gas (LPG)	5.83e-01	11.30%	
Natural gas	8.48e-01	16.44%	
Total	**5.16e+00**	100.00%	**19.99%**
Panel Components			
Kerosene	1.68e-01	31.97%	
Natural gas	1.18e-07	<0.01%	
Steam (100 psig)	1.45e-01	27.56%	
Fuel oil #2	4.07e-04	0.08%	
Fuel oil #6	1.25e-01	23.91%	
Natural gas	8.64e-02	16.47%	
Total	**5.25e-01**	100.00%	**2.03%**
LCD glass			
Fuel oil #2	5.38e-02	0.33%	
Liquified petroleum gas (LPG)	1.62e+01	99.33%	
Natural gas	5.63e-02	0.34%	
Total	**1.64e+01**	100.00%	**63.44%**
Backlight			
LNG	4.17e-06	50.00%	
Natural gas	4.17e-06	50.00%	
Total	**8.33e-06**	100.00%	**0.00%**
PWB			
Natural gas	**1.72e-01**		**0.67%**
Fuels			
Coal, average (in ground)	6.86e-01	19.19%	
Natural gas (in ground)	2.41e+00	67.27%	
Petroleum (in ground)	4.84e-01	13.54%	
Uranium (U, ore)	1.15e-05	<0.01%	
Total	**3.58e+00**	100.00%	**13.87%**
Grand Total	**2.58e+01**		**100.00%**
Electricity (MJ/functional unit):			
Monitor/Module	2.59e+02		**81.80%**
Panel Components	4.64e+01		**14.70%**
LCD glass	2.20e+00		**0.70%**
Backlight	4.46e+00		**1.41%**
PWB	4.43e+00		**1.40%**

Table 2-58. LCD manufacturing stage utility inputs

Material	Quantity	% of process group total	% of grand total
Process group			
Total	**3.16e+02**		**100.00%**
Water (kg or L/functional unit):			
Monitor/Module	1.08e+03		**49.96%**
Panel Components	2.08e+02		**9.66%**
LCD glass	1.62e+00		**0.08%**
Backlight	1.92e+02		**8.91%**
PWB	1.86e+01		**0.86%**
Japanese electric grid	1.49e+02		**6.91%**
U.S. electric grid	2.20e+00		**0.10%**
Fuels	5.07e+02		**23.53%**
Total	**2.15e+03**		**100.00%**
Total energy (fuels and electricity, MJ/functional unit):			
Monitor/Module	5.08e+02		**35.36%**
Panel Components	6.29e+01		**4.38%**
LCD glass	7.05e+02		**49.03%**
Backlight	4.46e+00		**0.31%**
PWB	1.21e+01		**0.84%**
Fuels	1.45e+02		**10.09%**
Total	**1.44e+03**		**100.00%**

Table 2-59. LCD manufacturing stage air outputs

Material	Quantity (kg/ functional unit)	% of process group total	% of grand total
Process Group			
Module/Monitor			
Acetic acid	1.36e-03	0.07%	
Acetone	1.86e-04	0.02%	
Al-etchant, unspecified	1.37e-02	0.75%	
Ammonia	6.23e-02	3.41%	
Argon	5.80e-03	0.32%	
Carbon dioxide	2.16e-03	0.12%	
Cr-etchant, unspecified	4.12e-02	2.25%	
Cyclohexane	4.85e-05	<0.01%	
Diethylene glycol	9.69e-05	0.01%	
Hexamethyldisilizane	1.37e-06	<0.01%	
Hydrochloric acid	6.06e-02	3.31%	
Hydrofluoric acid	5.21e-02	2.85%	
Hydrogen	1.33e-04	0.01%	
Isopropyl alcohol	1.78e-02	0.97%	
ITO etchant, unspecified	6.86e-03	0.38%	
Monosilane	1.54e-03	0.08%	
N-bromoacetamide	9.18e-03	0.50%	
Nitric acid	2.69e-04	0.01%	
Nitrogen fluoride	2.45e-01	13.43%	
Nitrogen oxides	5.48e-01	30.00%	
Phosphine	6.26e-02	3.43%	
Phosphoric acid	4.85e-05	<0.01%	
PM	1.10e-05	<0.01%	
Polyimide, unspecified	1.40e-04	0.01%	
Sulfur hexafluoride	7.30e-03	0.40%	
Sulfur oxides	1.12e-03	0.06%	
Tetramethyl ammonium hydroxide	6.43e-01	35.16%	
Unspecified LCD process material	4.49e-02	2.46%	
Total	**1.83e+00**	100.00%	**2.82%**
Panel Components			
Carbon dioxide	4.82e-03	81.79%	
Ethylacetate	2.44e-06	<0.01%	
HCFC-225ca	1.40e-04	2.37%	
HCFC-225cb	1.40e-04	2.37%	
Heptane	7.77e-05	1.32%	
Hydrochloric acid	7.32e-06	0.12%	
Methyl ethyl ketone	1.35e-04	2.29%	
Nitrogen oxides	4.11e-04	6.98%	
Nonmethane hydrocarbons, remaining unspeciated	7.77e-05	1.32%	
PM	2.74e-05	0.47%	

Table 2-59. LCD manufacturing stage air outputs

Material	Quantity (kg/ functional unit)	% of process group total	% of grand total
Process Group			
Toluene	5.44e-05	0.92%	
Total	**5.89e-03**	100.00%	**0.01%**
LCD Glass			
Carbon dioxide	1.30e-01	98.45%	
Carbon monoxide	2.07e-07	<0.01%	
Chromium	6.40e-09	<0.01%	
Nitrogen oxides	2.04e-03	1.55%	
PM	5.06e-06	<0.01%	
Sulfur oxides	2.36e-06	<0.01%	
Total	**1.32e-01**	100.00%	**0.20%**
Backlight			
Diethyl ether	9.26e-05	0.31%	
Ethanol	4.63e-05	0.16%	
Nitrogen oxides	2.95e-02	99.29%	
Process material for backlight assembly	7.03e-05	0.24%	
Total	**2.97e-02**	100.00%	**0.05%**
PWB			
Formaldehyde	**1.71e-05**		**0.00%**
Japanese Grid			
1,1,1-Trichloroethane	2.17e-07	<0.01%	
1,2-Dichloroethane	1.54e-07	<0.01%	
2,3,7,8-TCDD	5.65e-14	<0.01%	
2,3,7,8-TCDF	1.96e-13	<0.01%	
2,4-Dinitrotoluene	1.07e-09	<0.01%	
2-Chloroacetophenone	2.69e-08	<0.01%	
2-Methylnaphthalene	8.00e-10	<0.01%	
5-Methyl chrysene	8.46e-11	<0.01%	
Acenaphthene	1.45e-08	<0.01%	
Acenaphthylene	1.11e-09	<0.01%	
Acetaldehyde	2.19e-06	<0.01%	
Acetophenone	5.77e-08	<0.01%	
Acrolein	1.11e-06	<0.01%	
Anthracene	1.53e-09	<0.01%	
Antimony	3.20e-06	<0.01%	
Arsenic	2.36e-06	<0.01%	
Barium	1.74e-06	<0.01%	
Benzene	5.13e-06	<0.01%	
Benzo[a]anthracene	2.69e-09	<0.01%	
Benzo[a]pyrene	1.46e-10	<0.01%	
Benzo[b,j,k]fluoranthene	1.31e-09	<0.01%	
Benzo[g,h,i]perylene	1.45e-09	<0.01%	

Table 2-59. LCD manufacturing stage air outputs

Material	Quantity (kg/ functional unit)	% of process group total	% of grand total
Process Group			
Benzyl chloride	2.69e-06	<0.01%	
Beryllium	1.09e-07	<0.01%	
Biphenyl	6.53e-09	<0.01%	
Bromoform	1.50e-07	<0.01%	
Bromomethane	6.15e-07	<0.01%	
Cadmium	4.74e-07	<0.01%	
Carbon dioxide	5.18e+01	99.14%	
Carbon disulfide	5.00e-07	<0.01%	
Carbon monoxide	9.43e-03	0.02%	
Chloride ions	2.07e-04	<0.01%	
Chlorobenzene	8.46e-08	<0.01%	
Chloroform	2.27e-07	<0.01%	
Chromium (III)	1.86e-06	<0.01%	
Chromium (VI)	4.51e-07	<0.01%	
Chrysene	1.80e-09	<0.01%	
Cobalt	3.98e-06	<0.01%	
Copper	1.07e-06	<0.01%	
Cumene hydroperoxide	2.04e-08	<0.01%	
Cyanide (-1)	9.61e-06	<0.01%	
Di(2-ethylhexyl)phthalate	2.81e-07	<0.01%	
Dibenzo[a,h]anthracene	9.95e-10	<0.01%	
Dichloromethane	1.11e-06	<0.01%	
Dimethyl sulfate	1.85e-07	<0.01%	
Dioxins, remaining unspeciated	2.51e-12	<0.01%	
Ethyl Chloride	1.61e-07	<0.01%	
Ethylbenzene	3.99e-07	<0.01%	
Ethylene dibromide	4.61e-09	<0.01%	
Fluoranthene	5.88e-09	<0.01%	
Fluorene	6.15e-09	<0.01%	
Fluorides (F-)	2.22e-05	<0.01%	
Formaldehyde	3.43e-05	<0.01%	
Furans, remaining unspeciated	4.00e-12	<0.01%	
Hexane	2.58e-07	<0.01%	
Hydrochloric acid	4.61e-03	0.01%	
Hydrofluoric acid	5.77e-04	<0.01%	
Indeno(1,2,3-cd)pyrene	1.51e-09	<0.01%	
Isophorone	2.23e-06	<0.01%	
Lead (Pb, ore)	1.48e-06	<0.01%	
Magnesium	4.23e-05	<0.01%	
Manganese (Mn, ore)	3.67e-06	<0.01%	

Table 2-59. LCD manufacturing stage air outputs

Material	Quantity (kg/ functional unit)	% of process group total	% of grand total
Process Group			
Mercury	3.97e-07	<0.01%	
Methane	2.73e-04	<0.01%	
Methyl chloride	2.04e-06	<0.01%	
Methyl ethyl ketone	1.50e-06	<0.01%	
Methyl hydrazine	6.54e-07	<0.01%	
Methyl methacrylate	7.69e-08	<0.01%	
Methyl tert-butyl ether	1.34e-07	<0.01%	
Molybdenum	5.20e-07	<0.01%	
Naphthalene	7.44e-07	<0.01%	
Nickel	4.95e-05	<0.01%	
Nitrogen oxides	1.37e-01	0.26%	
Nitrous oxide	3.76e-04	<0.01%	
o-xylene	6.49e-08	<0.01%	
Phenanthrene	1.75e-08	<0.01%	
Phenol	6.15e-08	<0.01%	
PM-10	6.72e-03	0.01%	
Propionaldehyde	1.46e-06	<0.01%	
Pyrene	4.24e-09	<0.01%	
Selenium	5.40e-06	<0.01%	
Styrene	9.61e-08	<0.01%	
Sulfur dioxide	2.90e-01	0.56%	
Tetrachloroethylene	1.65e-07	<0.01%	
TOCs, remaining unspeciated	6.63e-04	<0.01%	
Toluene	4.81e-06	<0.01%	
Vanadium	1.92e-05	<0.01%	
Vinyl acetate	2.92e-08	<0.01%	
Xylene (mixed isomers)	1.42e-07	<0.01%	
Zinc (elemental)	1.73e-05	<0.01%	
Total	**5.22e+01**	100.00%	**80.58%**
U.S. Grid			
1,1,1-Trichloroethane	3.71e-09	<0.01%	
1,2-Dichloroethane	6.95e-09	<0.01%	
2,3,7,8-TCDD	2.48e-15	<0.01%	
2,3,7,8-TCDF	8.86e-15	<0.01%	
2,4-Dinitrotoluene	4.86e-11	<0.01%	
2-Chloroacetophenone	1.22e-09	<0.01%	
2-Methylnaphthalene	5.16e-12	<0.01%	
5-Methyl chrysene	3.82e-12	<0.01%	

Table 2-59. LCD manufacturing stage air outputs

Material	Quantity (kg/ functional unit)	% of process group total	% of grand total
Process Group			
Acenaphthene	1.10e-10	<0.01%	
Acenaphthylene	4.37e-11	<0.01%	
Acetaldehyde	9.90e-08	<0.01%	
Acetophenone	2.60e-09	<0.01%	
Acrolein	5.04e-08	<0.01%	
Anthracene	3.77e-11	<0.01%	
Antimony	8.45e-09	<0.01%	
Arsenic	7.26e-08	<0.01%	
Barium	3.98e-09	<0.01%	
Benzene	2.26e-07	<0.01%	
Benzo[a]anthracene	1.80e-11	<0.01%	
Benzo[a]pyrene	6.60e-12	<0.01%	
Benzo[b,j,k]fluoranthene	2.06e-11	<0.01%	
Benzo[g,h,i]perylene	6.98e-12	<0.01%	
Benzyl chloride	1.22e-07	<0.01%	
Beryllium	3.69e-09	<0.01%	
Biphenyl	2.95e-10	<0.01%	
Bromoform	6.77e-09	<0.01%	
Bromomethane	2.78e-08	<0.01%	
Cadmium	9.33e-09	<0.01%	
Carbon dioxide	8.61e-01	98.98%	
Carbon disulfide	2.26e-08	<0.01%	
Carbon monoxide	1.57e-04	0.02%	
Chloride ions	3.52e-07	<0.01%	
Chlorobenzene	3.82e-09	<0.01%	
Chloroform	1.02e-08	<0.01%	
Chromium (III)	4.71e-08	<0.01%	
Chromium (VI)	1.40e-08	<0.01%	
Chrysene	1.98e-11	<0.01%	
Cobalt	2.35e-08	<0.01%	
Copper	1.93e-09	<0.01%	
Cumene	9.20e-10	<0.01%	
Cyanide (-1)	4.34e-07	<0.01%	
Di(2-ethylhexyl)phthalate	1.27e-08	<0.01%	
Dibenzo[a,h]anthracene	1.69e-12	<0.01%	
Dichloromethane	5.04e-08	<0.01%	
Dimethyl sulfate	8.33e-09	<0.01%	
Dioxins, remaining unspeciated	1.13e-13	<0.01%	

Table 2-59. LCD manufacturing stage air outputs

Material	Quantity (kg/ functional unit)	% of process group total	% of grand total
Process Group			
Ethyl Chloride	7.29e-09	<0.01%	
Ethylbenzene	1.64e-08	<0.01%	
Ethylene dibromide	2.08e-10	<0.01%	
Fluoranthene	1.30e-10	<0.01%	
Fluorene	1.63e-10	<0.01%	
Fluoride	3.78e-08	<0.01%	
Formaldehyde	1.64e-07	<0.01%	
Furans, remaining unspeciated	1.80e-13	<0.01%	
Hexane	1.16e-08	<0.01%	
Hydrochloric acid	2.08e-04	0.02%	
Hydrofluoric acid	2.60e-05	<0.01%	
Indeno(1,2,3-cd)pyrene	1.28e-11	<0.01%	
Isophorone	1.01e-07	<0.01%	
Lead	2.47e-08	<0.01%	
Magnesium	1.91e-06	<0.01%	
Manganese	8.83e-08	<0.01%	
Mercury	1.45e-08	<0.01%	
Methane	1.25e-03	0.14%	
Methyl chloride	9.20e-08	<0.01%	
Methyl ethyl ketone	6.77e-08	<0.01%	
Methyl hydrazine	2.95e-08	<0.01%	
Methyl methacrylate	3.47e-09	<0.01%	
Methyl tert-butyl ether	6.08e-09	<0.01%	
Molybdenum	1.13e-09	<0.01%	
Naphthalene	3.54e-09	<0.01%	
Nickel	1.33e-07	<0.01%	
Nitrogen oxides	2.28e-03	0.26%	
Nitrous oxide	6.58e-06	<0.01%	
o-xylene	1.10e-10	<0.01%	
Phenanthrene	4.85e-10	<0.01%	
Phenol	2.78e-09	<0.01%	
Phosphorus (yellow or white)	9.59e-09	<0.01%	
PM-10	1.12e-04	0.01%	
Propionaldehyde	6.60e-08	<0.01%	
Pyrene	6.45e-11	<0.01%	
Selenium	2.26e-07	<0.01%	
Styrene	4.34e-09	<0.01%	
Sulfur dioxide	4.83e-03	0.56%	

Table 2-59. LCD manufacturing stage air outputs

Material	Quantity (kg/ functional unit)	% of process group total	% of grand total
Process Group			
Tetrachloroethylene	7.47e-09	<0.01%	
TOCs, remaining unspeciated	1.12e-05	<0.01%	
Toluene	4.92e-08	<0.01%	
Vanadium	3.41e-08	<0.01%	
Vinyl acetate	1.32e-09	<0.01%	
Xylene (mixed isomers)	6.42e-09	<0.01%	
Zinc (elemental)	2.95e-08	<0.01%	
Total	**8.70e-01**	100.00%	**1.34%**
Fuel Production			
1,1,1-Trichloroethane	6.91e-09	<0.01%	
1,2-Dichloroethane	1.38e-08	<0.01%	
1,4-Dichlorobenzene	1.89e-08	<0.01%	
2,4-Dinitrotoluene	9.68e-11	<0.01%	
2-Chloroacetophenone	2.42e-09	<0.01%	
3-Methylcholanthrene	2.84e-11	<0.01%	
5-Methyl chrysene	7.60e-12	<0.01%	
Acenaphthene	2.77e-10	<0.01%	
Acenaphthylene	1.16e-10	<0.01%	
Acetaldehyde	1.97e-07	<0.01%	
Acetophenone	5.18e-09	<0.01%	
Acrolein	1.00e-07	<0.01%	
Aldehydes	8.98e-05	<0.01%	
Aluminum (elemental)	9.59e-07	<0.01%	
Ammonia	3.53e-04	<0.01%	
Anthracene	1.15e-10	<0.01%	
Antimony	1.15e-10	<0.01%	
Aromatic hydrocarbons	2.55e-09	<0.01%	
Arsenic	7.13e-07	<0.01%	
Barium	1.77e-08	<0.01%	
Benzene	2.70e-03	0.03%	
Benzo[a]anthracene	6.97e-11	<0.01%	
Benzo[a]pyrene	3.84e-11	<0.01%	
Benzo[b,j,k]fluoranthene	3.80e-11	<0.01%	
Benzo[b]fluoranthene	3.09e-11	<0.01%	
Benzo[g,h,i]perylene	3.21e-11	<0.01%	
Benzo[k]fluoranthene	3.09e-11	<0.01%	
Benzyl chloride	2.42e-07	<0.01%	
Beryllium	7.31e-08	<0.01%	

Table 2-59. LCD manufacturing stage air outputs

Material	Quantity (kg/ functional unit)	% of process group total	% of grand total
Process Group			
Biphenyl	5.88e-10	<0.01%	
Bromoform	1.35e-08	<0.01%	
Bromomethane	5.53e-08	<0.01%	
Butane	3.31e-05	<0.01%	
Cadmium	4.18e-08	<0.01%	
Calcium	8.31e-07	<0.01%	
Carbon dioxide	9.44e+00	97.19%	
Carbon disulfide	4.49e-08	<0.01%	
Carbon monoxide	2.89e-02	0.30%	
Chloride ions	1.75e-06	<0.01%	
Chlorine	1.01e-09	<0.01%	
Chlorobenzene	7.60e-09	<0.01%	
Chloroform	2.04e-08	<0.01%	
Chromium (III)	1.05e-06	<0.01%	
Chromium (VI)	1.05e-06	<0.01%	
Chrysene	6.70e-11	<0.01%	
Cobalt	1.27e-07	<0.01%	
Copper	7.98e-08	<0.01%	
Cumene	1.83e-09	<0.01%	
Cyanide (-1)	8.64e-07	<0.01%	
Di(2-ethylhexyl)phthalate	2.52e-08	<0.01%	
Dibenzo[a,h]anthracene	2.18e-11	<0.01%	
Dichloromethane	1.00e-07	<0.01%	
Dimethyl sulfate	1.66e-08	<0.01%	
Dimethylbenzanthracene	2.36e-10	<0.01%	
Dioxins, remaining unspeciated	5.60e-12	<0.01%	
Ethane	4.88e-05	<0.01%	
Ethyl Chloride	1.45e-08	<0.01%	
Ethylbenzene	3.28e-08	<0.01%	
Ethylene dibromide	4.15e-10	<0.01%	
Fluoranthene	3.01e-10	<0.01%	
Fluorene	3.66e-10	<0.01%	
Fluorides (F-)	1.98e-07	<0.01%	
Formaldehyde	5.78e-05	<0.01%	
Furans, remaining unspeciated	2.60e-11	<0.01%	
Halogenated hydrocarbons (unspecified)	1.42e-14	<0.01%	
HALON-1301	2.47e-11	<0.01%	
Hexane	2.84e-05	<0.01%	

Table 2-59. LCD manufacturing stage air outputs

Material	Quantity (kg/ functional unit)	% of process group total	% of grand total
Process Group			
Hydrocarbons, remaining unspeciated	7.75e-03	0.08%	
Hydrochloric acid	4.15e-04	<0.01%	
Hydrofluoric acid	5.18e-05	<0.01%	
Hydrogen sulfide	1.51e-04	<0.01%	
Indeno(1,2,3-cd)pyrene	5.31e-11	<0.01%	
Iron	1.85e-06	<0.01%	
Isophorone	2.00e-07	<0.01%	
Lead	6.39e-07	<0.01%	
Magnesium	3.80e-06	<0.01%	
Manganese	1.15e-06	<0.01%	
Mercury	4.55e-08	<0.01%	
Metals, remaining unspeciated	1.60e-08	<0.01%	
Methane	1.20e-01	1.24%	
Methyl chloride	1.83e-07	<0.01%	
Methyl ethyl ketone	1.35e-07	<0.01%	
Methyl hydrazine	5.88e-08	<0.01%	
Methyl methacrylate	6.91e-09	<0.01%	
Methyl tert-butyl ether	1.21e-08	<0.01%	
Molybdenum	9.92e-08	<0.01%	
Naphthalene	1.98e-08	<0.01%	
Nickel	6.06e-06	<0.01%	
Nitrogen oxides	4.27e-02	0.44%	
Nitrous oxide	8.13e-04	0.01%	
Nonmethane hydrocarbons, remaining unspeciated	8.79e-03	0.09%	
n-Propane	8.67e-08	<0.01%	
Other organics	1.35e-02	0.14%	
o-xylene	1.59e-07	<0.01%	
Pentane	4.10e-05	<0.01%	
Phenanthrene	1.22e-09	<0.01%	
Phenol	5.53e-09	<0.01%	
Phosphorus (yellow or white)	6.10e-07	<0.01%	
PM	6.95e-03	0.07%	
PM-10	1.11e-05	<0.01%	
Polycyclic aromatic hydrocarbons	2.84e-12	<0.01%	
Propionaldehyde	1.31e-07	<0.01%	
Pyrene	2.00e-10	<0.01%	
Selenium	4.81e-07	<0.01%	
Silicon	8.31e-07	<0.01%	

Table 2-59. LCD manufacturing stage air outputs

Material	Quantity (kg/ functional unit)	% of process group total	% of grand total
Process Group			
Sodium	4.92e-06	<0.01%	
Styrene	8.64e-09	<0.01%	
Sulfur oxides	3.96e-02	0.41%	
Tetrachloroethylene	1.49e-08	<0.01%	
Toluene	2.63e-07	<0.01%	
Vanadium	1.30e-05	<0.01%	
Vinyl acetate	2.63e-09	<0.01%	
Zinc (elemental)	6.04e-07	<0.01%	
Total	**9.72e+00**	100.00%	**15.00%**
Grand Total	**6.48e+01**		**100.00%**

Table 2-60. LCD manufacturing stage water outputs

Material	Disposition	Quantity (kg/ functional unit)	% of process group total	% of grand total
Process Group				
WASTEWATER STREAMS				
Module/monitor	both	2.87e+03		**91.80%**
Panel components	both	3.53e-01		**0.01%**
LCD glass	surface water	1.67e+00		**0.05%**
Backlight	both	1.92e+02		**6.15%**
PWB	treatment	1.86e+01		**0.60%**
Fuels	surface water	4.33e+01		**1.39%**
Total		**3.12e+03**		**100.00%**
WATER POLLUTANTS				
Module/monitor				
1,1,1-Trichloroethane	surface water	2.29e-08	<0.01%	
Antimony	surface water	1.14e-07	<0.01%	
Arsenic	surface water	1.14e-07	<0.01%	
BOD	surface water	1.74e-02	6.69%	
BOD	treatment	5.05e-02	19.41%	
Boron	surface water	4.58e-06	<0.01%	
Cadmium	surface water	1.14e-07	<0.01%	
Chromium	surface water	8.84e-06	<0.01%	
Chromium (VI)	surface water	2.29e-07	<0.01%	
COD	surface water	2.68e-03	1.03%	
COD	treatment	3.90e-02	14.99%	
Colon bacillus (bacteria in large intestine)	surface water	3.89e-03	1.50%	
Copper	surface water	9.18e-07	<0.01%	
Cyanide (-1)	surface water	3.66e-06	<0.01%	
Cyanide (-1)	treatment	6.67e-07	<0.01%	
Dissolved solids	surface water	7.55e-03	2.90%	
Fluorides (F-)	surface water	1.28e-02	4.91%	
Fluorides (F-)	treatment	2.40e-04	0.09%	
Hexane	surface water	5.88e-04	0.23%	
Iron	surface water	2.63e-06	<0.01%	
Lead	surface water	6.17e-06	<0.01%	
Manganese	surface water	2.29e-07	<0.01%	
Mercury	surface water	9.69e-08	<0.01%	
Nickel	surface water	2.29e-07	<0.01%	
Nitrogen	surface water	7.93e-02	30.45%	
Nitrogen	treatment	1.16e-02	4.45%	
Oil & grease	surface water	2.02e-04	0.08%	
Oil & grease	treatment	3.53e-03	1.35%	
Organic phosphorus, unspecified	surface water	2.29e-07	<0.01%	
Phenol	surface water	2.29e-07	<0.01%	
Phosphorus (yellow or white)	surface water	4.31e-03	1.65%	

Table 2-60. LCD manufacturing stage water outputs

Material	Disposition	Quantity (kg/ functional unit)	% of process group total	% of grand total
Process Group				
Phosphorus (yellow or white)	treatment	6.91e-03	2.65%	
Polychlorinated biphenyls	surface water	1.14e-08	<0.01%	
Suspended solids	surface water	1.55e-02	5.96%	
Suspended solids	treatment	4.26e-03	1.64%	
Tetrachloroethylene	surface water	2.29e-08	<0.01%	
Tin	surface water	4.58e-07	<0.01%	
Trichloroethylene	surface water	2.29e-08	<0.01%	
Zinc (elemental)	surface water	2.63e-06	<0.01%	
Total		**2.60e-01**	100.00%	**21.11%**
Panel components				
BOD	surface water	1.34e-03	15.44%	
BOD	treatment	3.89e-03	44.73%	
Borax	treatment	1.31e-06	0.02%	
COD	surface water	2.21e-03	25.45%	
Hydrochloric acid	treatment	3.29e-06	0.04%	
Nitrogen	surface water	5.71e-04	6.58%	
Orthoboric acid	treatment	1.31e-06	0.02%	
Phosphorus (yellow or white)	surface water	2.48e-05	0.29%	
Suspended solids	surface water	6.46e-04	7.43%	
Total		**8.69e-03**	100.00%	**0.70%**
LCD glass				
BOD	surface water	3.80e-07	<0.01%	
Chloride ions	surface water	4.68e-02	21.73%	
Chromium	surface water	3.80e-09	<0.01%	
COD	surface water	3.80e-07	<0.01%	
Dissolved solids	surface water	1.68e-01	77.84%	
Fluorides (F-)	surface water	1.36e-04	0.06%	
Iron	surface water	1.28e-04	0.06%	
Lead	surface water	2.01e-06	<0.01%	
Nickel	surface water	3.80e-09	<0.01%	
Nitrate	surface water	1.83e-07	<0.01%	
Oil & grease	surface water	3.34e-04	0.16%	
Suspended solids	surface water	3.35e-04	0.16%	
Total		**2.15e-01**	100.00%	**17.46%**
Backlight				
BOD	treatment	3.00e-03	54.50%	
Iron	treatment	8.33e-05	1.51%	
Lead	treatment	8.33e-07	0.02%	
Mercury	treatment	8.33e-08	<0.01%	
Nickel	treatment	3.33e-06	0.06%	
Nitrogen	treatment	1.00e-03	18.17%	

Table 2-60. LCD manufacturing stage water outputs

Material	Disposition	Quantity (kg/ functional unit)	% of process group total	% of grand total
Process Group				
Oil & grease	treatment	8.33e-05	1.51%	
Suspended solids	treatment	1.33e-03	24.22%	
Total		**5.50e-03**	100.00%	**0.45%**
PWB				
Copper (+1 & +2)	treatment	4.28e-05	85.71%	
Lead cmpds	treatment	7.14e-06	14.29%	
Total		**5.00e-05**	100.00%	**0.00%**
Japanese grid				
Sulfate ion (-4)	surface water	2.93e-03	97.46%	
Suspended solids	surface water	7.63e-05	2.54%	
Total		**3.01e-03**	100.00%	**0.24%**
U.S. grid				
Sulfate ion (-4)	treatment	1.32e-04	97.46%	
Suspended solids	treatment	3.45e-06	2.54%	
Total		**1.36e-04**	100.00%	**0.01%**
Fuels				
Acids (H+)	surface water	1.76e-08	<0.01%	
Adsorbable organic halides	surface water	1.82e-11	<0.01%	
Aluminum (+3)	surface water	6.88e-06	<0.01%	
Ammonia ions	surface water	1.33e-03	0.18%	
Aromatic hydrocarbons	surface water	4.25e-09	<0.01%	
Barium cmpds	surface water	1.36e-08	<0.01%	
BOD	surface water	9.12e-03	1.23%	
Cadmium cmpds	surface water	1.42e-11	<0.01%	
Chloride ions	surface water	2.65e-01	35.77%	
Chromium (III)	surface water	3.49e-09	<0.01%	
Chromium (VI)	surface water	3.49e-09	<0.01%	
COD	surface water	7.71e-02	10.42%	
Copper (+1 & +2)	surface water	2.84e-10	<0.01%	
Cyanide (-1)	surface water	1.99e-11	<0.01%	
Dissolved organics	surface water	4.67e-08	<0.01%	
Dissolved solids	surface water	2.01e-05	<0.01%	
Fluorides (F-)	surface water	1.76e-06	<0.01%	
Halogenated matter (organic)	surface water	5.67e-12	<0.01%	
Hydrocarbons, remaining unspeciated	surface water	1.70e-05	<0.01%	
Iron (+2 & +3)	surface water	1.73e-08	<0.01%	
Lead cmpds	surface water	5.67e-11	<0.01%	
Mercury compounds	surface water	6.52e-14	<0.01%	
Metals, remaining unspeciated	surface water	4.72e-04	0.06%	
Nickel cmpds	surface water	2.84e-11	<0.01%	
Nitrate	surface water	2.97e-06	<0.01%	

Table 2-60. LCD manufacturing stage water outputs

Material	Disposition	Quantity (kg/ functional unit)	% of process group total	% of grand total
Process Group				
Other nitrogen	surface water	7.66e-10	<0.01%	
Phenol	surface water	1.75e-04	0.02%	
Phosphates	surface water	2.83e-08	<0.01%	
Polycyclic aromatic hydrocarbons	surface water	6.81e-11	<0.01%	
Salts (unspecified)	surface water	7.84e-05	0.01%	
Sodium (+1)	surface water	3.41e-01	46.05%	
Sulfate ion (-4)	surface water	4.36e-06	<0.01%	
Sulfide	surface water	9.86e-09	<0.01%	
Suspended solids	surface water	4.14e-02	5.59%	
TOCs	surface water	4.25e-08	<0.01%	
Toluene	surface water	6.24e-10	<0.01%	
Waste oil	surface water	4.87e-03	0.66%	
Zinc (+2)	surface water	1.40e-09	<0.01%	
Total		**7.40e-01**	100.00%	**60.02%**
Grand Total		**1.23e+00**		**100.00%**

Table 2-61. LCD manufacturing stage hazardous waste outputs

Material	Disposition	Quantity (kg/ functional unit)	% of process group total	% of grand total
Process Group				
Monitor/module				
Mercury	recycling/reuse	2.00e-06	<0.01%	
Waste metals, unspecified	recycling/reuse	1.17e-03	0.03%	
Waste acids, unspecified	recycling/reuse	3.24e-02	0.76%	
Waste acid (mainly HF)	recycling/reuse	5.69e-01	13.30%	
Waste acid (mainly HF)	treatment	1.36e-01	3.17%	
Unspecified sludge	land (other than landfill)	3.09e-02	0.72%	
Thinner, unspecified	treatment	5.40e-01	12.62%	
Tetramethyl ammonium hydroxide	recycling/reuse	1.42e-01	3.33%	
Sodium sulfate	recycling/reuse	2.44e-01	5.72%	
Rinse, unspecified	recycling/reuse	4.67e-02	1.09%	
Remover, unspecified	recycling/reuse	8.84e-02	2.07%	
Remover, unspecified	treatment	3.03e-01	7.08%	
Phosphoric acid	landfill	1.44e-02	0.34%	
Nitric acid	landfill	3.43e-04	0.01%	
Isopropyl alcohol	recycling/reuse	1.69e-01	3.95%	
Isopropyl alcohol	treatment	1.91e+00	44.75%	
Ferric chloride	recycling/reuse	1.37e-02	0.32%	
Acetone	treatment	2.77e-02	0.65%	
Acetic acid	landfill	4.46e-03	0.10%	
Total		**4.28e+00**	100.00%	**92.11%**
Panel components				
Spent solvents (F003 waste)	treatment	2.74e-04	0.24%	
Flammable liquids (F003 waste)	treatment	9.13e-04	0.80%	
Acid waste (D002 waste)	treatment	1.19e-03	1.04%	
Spent solvent (with halogenated materials)	treatment	1.55e-02	13.63%	
Spent solvent (non-halogenated)	treatment	4.66e-02	40.89%	
HCFC-225cb	recycling/reuse	3.11e-05	0.03%	
HCFC-225ca	recycling/reuse	3.11e-05	0.03%	
Waste solvent (photoresist)	recycling/reuse	2.05e-02	18.00%	
Waste solvent (photoresist)	treatment	2.17e-02	19.05%	
Waste acid (chrome mixed acid)	recycling/reuse	7.18e-03	6.29%	
Total		**1.14e-01**	100.00%	**2.46%**
LCD glass				
Waste Batch (Ba, Pb) (D008 waste)	landfill	6.55e-05	8.18%	
Waste acid (mostly 3% HCl solution)	recycling/reuse	1.82e-04	22.74%	
Hydrofluoric acid	landfill	8.24e-05	10.29%	
Chrome liquid waste (D007 waste)	recycling/reuse	4.54e-04	56.70%	
Chrome debris (D007 waste)	treatment	6.83e-06	0.85%	
Barium debris (D008 waste)	landfill	9.91e-06	1.24%	

Table 2-61. LCD manufacturing stage hazardous waste outputs

Material	Disposition	Quantity (kg/ functional unit)	% of process group total	% of grand total
Process Group				
Total		**8.01e-04**	100.00%	**0.02%**
Backlight				
Hazardous waste, unspecified	recycling/reuse	1.42e-02	67.68%	
Hazardous waste, unspecified	treatment	6.80e-03	32.31%	
Waste glass, with mercury	landfill	1.05e-10	<0.01%	
Waste CCFL, with mercury	treatment	8.17e-10	<0.01%	
Waste CCFL, with lead	treatment	8.17e-08	<0.01%	
Silver	landfill	2.72e-09	<0.01%	
Chromium	landfill	1.52e-06	0.01%	
Total		**2.11e-02**	100.00%	**0.45%**
PWB				
PWB-Waste cupric etchant	recycling/reuse	9.93e-02	49.42%	
PWB-Solder dross	recycling/reuse	2.96e-02	14.72%	
PWB-Route dust	recycling/reuse	5.31e-03	2.64%	
PWB-Lead contaminated waste oil	treatment	5.14e-03	2.56%	
PWB-Decontaminating debris	treatment	6.85e-03	3.41%	
Hazardous waste, unspecified	treatment	5.48e-02	27.26%	
Total		**2.01e-01**	100.00%	**4.33%**
Fuels				
Hazardous waste, unspecified	landfill	**2.97e-02**		**0.64%**
Grand Total		**4.64e+00**		**100.00%**

Table 2-62. LCD manufacturing stage solid waste outputs

Material	Disposition	Quantity (kg/ functional unit)	% of process group total	% of grand total
Process Group				
Monitor/module				
Isopropyl alcohol	treatment	1.03e-02	0.33%	
LCD panel waste	landfill	2.43e-02	0.77%	
Printed wiring board (PWB)	landfill	7.50e-03	0.24%	
Remover, unspecified	treatment	3.09e-02	0.98%	
Unspecified sludge	recycling/reuse	8.46e-01	26.79%	
Unspecified sludge	treatment	5.73e-02	1.82%	
Unspecified solid waste	recycling/reuse	2.02e-02	0.64%	
Waste acid (containing F and detergents)	landfill	2.70e-01	8.56%	
Waste acids, unspecified	treatment	1.05e-01	3.32%	
Waste alkali, unspecified	recycling/reuse	3.23e-01	10.24%	
Waste LCD glass	landfill	2.06e-01	6.52%	
Waste LCD glass	recycling/reuse	7.20e-01	22.80%	
Waste metals, unspecified	recycling/reuse	2.93e-03	0.09%	
Waste oil	treatment	1.61e-02	0.51%	
Waste plastic from LCD modules	recycling/reuse	7.40e-02	2.35%	
Waste plastic from LCD modules	treatment	4.03e-01	12.77%	
Waste plastics from LCD monitor	landfill	4.05e-02	1.28%	
Total		**3.16e+00**	100.00%	**25.07%**
Panel components				
Isopropyl alcohol	recycling/reuse	2.53e-02	11.75%	
Polyester resin	recycling/reuse	3.20e-02	14.84%	
Unspecified solid waste	treatment	1.10e-02	5.09%	
Used silica gel	landfill	6.22e-04	0.29%	
Waste alkali (color filter developer, unspecified)	recycling/reuse	8.91e-02	41.37%	
Waste LCD glass	landfill	5.74e-02	26.66%	
Total		**2.15e-01**	100.00%	**1.71%**
LCD glass				
abrasive sludge	recycling/reuse	1.95e-03	32.61%	
acid absorbent	landfill	3.77e-06	0.06%	
blasting media	landfill	1.70e-05	0.28%	
Cinders from LCD glass mfg	landfill	3.83e-04	6.40%	
Cobalt nitrate	treatment	2.83e-06	0.05%	
Diesel fuel	treatment	1.88e-06	0.03%	
Dust	treatment	1.59e-04	2.65%	
LCD glass EP dust	landfill	4.77e-05	0.80%	
LCD glass EP dust	recycling/reuse	2.32e-04	3.88%	
LCD glass, unspecified	landfill	1.13e-03	18.83%	
Nickel nitrate	treatment	2.83e-06	0.05%	
Oily rags & filter media	landfill	1.51e-05	0.25%	

Table 2-62. LCD manufacturing stage solid waste outputs

Material	Disposition	Quantity (kg/ functional unit)	% of process group total	% of grand total
Process Group				
Oily rags & filter media	recycling/reuse	1.88e-06	0.03%	
parts cleaner solvent	recycling/reuse	3.77e-06	0.06%	
Plating process sludge	landfill	1.52e-05	0.25%	
Potassium Carbonate	landfill	1.53e-04	2.55%	
sludge (calcium fluoride, CaF2)	recycling/reuse	8.13e-04	13.59%	
Sludge from LCD glass mfg	landfill	4.06e-05	0.68%	
Sodium Carbonate	landfill	1.53e-04	2.55%	
Unspecified sludge	landfill	3.56e-04	5.95%	
Waste alkali, unspecified	treatment	1.95e-06	0.03%	
Waste LCD glass	landfill	8.70e-05	1.45%	
Waste oil	treatment	3.03e-04	5.07%	
Waste refractory	landfill	1.13e-04	1.89%	
Total		**5.98e-03**	100.00%	**0.05%**
Backlight				
Broken CCFL	landfill	2.69e-07	<0.01%	
Cardboard	treatment	1.82e-05	0.34%	
Polyethylene, foamed	treatment	9.99e-04	18.50%	
Polyethylene/polypropylene waste	treatment	2.72e-03	50.45%	
Unspecified nonhazardous waste	recycling/reuse	1.26e-04	2.32%	
Waste backlight casing (PC)	landfill	1.46e-05	0.27%	
Waste backlight light guide (PMMA)	landfill	1.52e-03	28.12%	
Total		**5.40e-03**	100.00%	**0.04%**
PWB				
PWB-Drill dust	landfill	6.59e-03	0.36%	
Unspecified solid waste	recycling/reuse	1.91e-01	10.53%	
Unspecified solid waste	treatment	1.62e+00	89.11%	
Total		**1.81e+00**	100.00%	**14.40%**
Japanese grid				
Coal waste	landfill	2.18e+00	61.12%	
Dust/sludge	landfill	8.42e-01	23.59%	
Fly/bottom ash	landfill	5.45e-01	15.28%	
Total		**3.57e+00**	100.00%	**28.34%**
U.S. grid				
Coal waste	landfill	9.85e-02	61.10%	
Dust/sludge	landfill	3.81e-02	23.63%	
Fly/bottom ash	landfill	2.46e-02	15.27%	
Total		**1.61e-01**	100.00%	**1.28%**
Fuels				
Aluminum scrap	recycling/reuse	8.77e-06	<0.01%	
Aluminum scrap, Wabash 319	recycling/reuse	2.37e-08	<0.01%	
Bauxite residues	landfill	5.87e-04	0.02%	

Table 2-62. LCD manufacturing stage solid waste outputs

Material	Disposition	Quantity (kg/ functional unit)	% of process group total	% of grand total
Process Group				
FGD sludge	landfill	1.09e-02	0.30%	
Mineral waste	landfill	1.26e-04	<0.01%	
Mixed industrial (waste)	landfill	4.83e-02	1.32%	
Non toxic chemical waste (unspecified)	landfill	2.95e-05	<0.01%	
Slag and ash	landfill	3.40e+00	92.69%	
Slag and ash	recycling/reuse	3.49e-02	0.95%	
Unspecified solid waste (incinerated)	treatment	6.44e-04	0.02%	
Unspecified waste	landfill	1.72e-01	4.70%	
Total		**3.66e+00**	100.00%	**29.10%**
Grand Total		**1.26e+01**		**100.00%**

Table 2-63. LCD manufacturing stage radioactive waste outputs

Material	Disposition	Quantity (kg/ functional unit)	% of process group total	% of grand total
Process Group				
Japanese grid				
Low-level radioactive waste	landfill	3.71e-04	76.93%	
Uranium, depleted	landfill	1.11e-04	23.07%	
Total		**4.82e-04**	100.00%	**99.09%**
U.S. grid				
Low-level radioactive waste	landfill	3.40e-06	76.93%	
Uranium, depleted	landfill	1.02e-06	23.07%	
Total		**4.42e-06**	100.00%	**0.91%**
Grand Total		**4.87e-04**		**100.00%**

Table 2-64. LCD manufacturing stage radioactivity outputs

Material	Disposition	Quantity (Bq/ functional unit)	% of process group total	% of grand total
Process Group				
Japanese grid				
Antimony-124 (isotope)	treatment	1.67e+00	<0.01%	
Antimony-125 (isotope)	treatment	6.63e+00	<0.01%	
Argon-41 (isotope)	air	3.37e+03	0.03%	
Barium-140 (isotope)	treatment	1.23e-01	<0.01%	
Bromine-89 (isotope)	air	3.90e-04	<0.01%	
Bromine-90 (isotope)	air	1.59e-04	<0.01%	
Cesium-134 (isotope)	air	1.07e-02	<0.01%	
Cesium-134 (isotope)	treatment	4.45e+00	<0.01%	
Cesium-137 (isotope)	air	8.08e-02	<0.01%	
Cesium-137 (isotope)	treatment	6.69e+00	<0.01%	
Chromium-51 (isotope)	air	2.11e-01	<0.01%	
Chromium-51 (isotope)	treatment	8.02e+00	<0.01%	
Cobalt-57 (isotope)	air	5.68e-04	<0.01%	
Cobalt-57 (isotope)	treatment	1.94e-01	<0.01%	
Cobalt-58 (isotope)	air	7.26e-03	<0.01%	
Cobalt-58 (isotope)	treatment	7.90e+01	<0.01%	
Cobalt-60 (isotope)	air	5.46e-02	<0.01%	
Cobalt-80 (isotope)	treatment	2.07e+01	<0.01%	
Iodine-131 (isotope)	air	2.55e-01	<0.01%	
Iodine-131 (isotope)	treatment	3.70e+00	<0.01%	
Iodine-132 (isotope)	air	5.18e-02	<0.01%	
Iodine-132 (isotope)	treatment	1.40e+00	<0.01%	
Iodine-133 (isotope)	air	2.37e+02	<0.01%	
Iodine-133 (isotope)	treatment	1.59e+00	<0.01%	
Iodine-134 (isotope)	air	2.68e-01	<0.01%	
Iodine-135 (isotope)	air	1.35e-02	<0.01%	
Iodine-135 (isotope)	treatment	1.14e+00	<0.01%	
Iron-55 (isotope)	treatment	1.89e+01	<0.01%	
Iron-59 (isotope)	treatment	9.70e-01	<0.01%	
Krypton-85 (isotope)	air	5.59e+03	0.06%	
Krypton-85M (isotope)	air	2.71e+02	<0.01%	
Krypton-85M (isotope)	treatment	5.00e+00	<0.01%	
Krypton-87 (isotope)	air	1.01e+02	<0.01%	
Krypton-88 (isotope)	air	4.73e+02	<0.01%	
Lanthanum-140 (isotope)	treatment	1.32e-01	<0.01%	
Manganese-54 (isotope)	air	3.00e-03	<0.01%	
Manganese-54 (isotope)	treatment	5.29e+00	<0.01%	
Molybdenum-99 (isotope)	treatment	9.98e+06	98.42%	
Niobium-95 (isotope)	air	1.19e-04	<0.01%	
Niobium-95 (isotope)	treatment	1.36e+00	<0.01%	

Table 2-64. LCD manufacturing stage radioactivity outputs

Material	Disposition	Quantity (Bq/ functional unit)	% of process group total	% of grand total
Process Group				
Rubidium-88 (isotope)	air	1.11e+00	<0.01%	
Ruthenium-103 (isotope)	treatment	1.67e-01	<0.01%	
Silver-110M (isotope)	air	3.56e-06	<0.01%	
Silver-110M (isotope)	treatment	1.94e+00	<0.01%	
Sodium-24 (isotope)	treatment	2.96e-01	<0.01%	
Strontium-89 (isotope)	treatment	3.20e-01	<0.01%	
Strontium-90 (isotope)	treatment	7.52e-02	<0.01%	
Strontium-95 (isotope)	treatment	8.29e-01	<0.01%	
Sulfur-136 (isotope)	treatment	1.78e-01	<0.01%	
Technetium-99M (isotope)	air	1.60e-05	<0.01%	
Technetium-99M (isotope)	treatment	1.16e-01	<0.01%	
Tin-113 (isotope)	treatment	1.84e-01	<0.01%	
Tritium-3 (isotope)	air	7.90e+03	0.08%	
Tritium-3 (isotope)	treatment	5.91e+04	0.58%	
Xenon-131M (isotope)	air	4.56e+02	<0.01%	
Xenon-131M (isotope)	treatment	6.08e+01	<0.01%	
Xenon-133 (isotope)	air	4.37e+03	0.04%	
Xenon-133 (isotope)	treatment	9.34e+03	0.09%	
Xenon-133M (isotope)	air	6.58e+04	0.65%	
Xenon-133M (isotope)	treatment	7.65e+01	<0.01%	
Xenon-135 (isotope)	air	2.48e+03	0.02%	
Xenon-135 (isotope)	treatment	6.97e+01	<0.01%	
Xenon-135M (isotope)	air	4.74e+01	<0.01%	
Xenon-138 (isotope)	air	1.57e+02	<0.01%	
Zinc-85 (isotope)	treatment	8.92e-02	<0.01%	
Zirconium-95 (isotope)	air	3.08e-04	<0.01%	
Total		**1.01e+07**	100.00%	**99.09%**
U.S. grid				
Antimony-124 (isotope)	treatment	1.53e-02	<0.01%	
Antimony-125 (isotope)	treatment	6.09e-02	<0.01%	
Argon-41 (isotope)	air	3.09e+01	0.03%	
Barium-140 (isotope)	treatment	1.13e-03	<0.01%	
Bromine-89 (isotope)	air	3.58e-06	<0.01%	
Bromine-90 (isotope)	air	1.45e-06	<0.01%	
Cesium-134 (isotope)	air	9.82e-05	<0.01%	
Cesium-134 (isotope)	treatment	4.09e-02	<0.01%	
Cesium-136 (isotope)	treatment	1.75e-03	<0.01%	
Cesium-137 (isotope)	air	7.41e-04	<0.01%	
Cesium-137 (isotope)	treatment	6.13e-02	<0.01%	
Chromium-51 (isotope)	air	1.94e-03	<0.01%	
Chromium-51 (isotope)	treatment	7.36e-02	<0.01%	

Table 2-64. LCD manufacturing stage radioactivity outputs

Material	Disposition	Quantity (Bq/ functional unit)	% of process group total	% of grand total
Process Group				
Cobalt-57 (isotope)	air	5.21e-06	<0.01%	
Cobalt-57 (isotope)	treatment	1.78e-03	<0.01%	
Cobalt-58 (isotope)	air	6.65e+00	<0.01%	
Cobalt-58 (isotope)	treatment	7.25e-01	<0.01%	
Cobalt-60 (isotope)	air	5.01e-04	<0.01%	
Cobalt-80 (isotope)	treatment	1.90e-01	<0.01%	
Iodine-131 (isotope)	air	2.34e-03	<0.01%	
Iodine-131 (isotope)	treatment	3.39e-02	<0.01%	
Iodine-132 (isotope)	air	4.75e-04	<0.01%	
Iodine-132 (isotope)	treatment	1.28e-02	<0.01%	
Iodine-133 (isotope)	air	2.17e+00	<0.01%	
Iodine-133 (isotope)	treatment	1.45e-02	<0.01%	
Iodine-134 (isotope)	air	2.46e-03	<0.01%	
Iodine-135 (isotope)	air	1.24e-04	<0.01%	
Iodine-135 (isotope)	treatment	1.04e-02	<0.01%	
Iron-55 (isotope)	treatment	1.73e-01	<0.01%	
Iron-59 (isotope)	treatment	8.90e-03	<0.01%	
Krypton-85 (isotope)	air	5.13e+01	0.06%	
Krypton-85M (isotope)	air	2.48e+00	<0.01%	
Krypton-85M (isotope)	treatment	4.58e-02	<0.01%	
Krypton-87 (isotope)	air	9.25e-01	<0.01%	
Krypton-88 (isotope)	air	4.34e+00	<0.01%	
Lanthanum-140 (isotope)	treatment	1.21e-03	<0.01%	
Manganese-54 (isotope)	air	2.75e-05	<0.01%	
Manganese-54 (isotope)	treatment	4.85e-02	<0.01%	
Molybdenum-99 (isotope)	treatment	9.15e+04	98.41%	
Niobium-95 (isotope)	air	1.09e-06	<0.01%	
Niobium-95 (isotope)	treatment	1.25e-02	<0.01%	
Rubidium-88 (isotope)	air	1.02e-02	<0.01%	
Ruthenium-103 (isotope)	treatment	1.53e-03	<0.01%	
Silver-110M (isotope)	air	3.26e-08	<0.01%	
Silver-110M (isotope)	treatment	1.78e-02	<0.01%	
Sodium-24 (isotope)	treatment	2.72e-03	<0.01%	
Strontium-89 (isotope)	treatment	2.93e-03	<0.01%	
Strontium-90 (isotope)	treatment	6.90e-04	<0.01%	
Strontium-95 (isotope)	treatment	7.60e-03	<0.01%	
Sulfur-136 (isotope)	treatment	1.64e-03	<0.01%	
Technetium-99M (isotope)	air	1.47e-07	<0.01%	
Technetium-99M (isotope)	treatment	1.06e-03	<0.01%	
Tin-113 (isotope)	treatment	1.68e-03	<0.01%	
Tritium-3 (isotope)	air	7.25e+01	0.08%	

Table 2-64. LCD manufacturing stage radioactivity outputs

Material	Disposition	Quantity (Bq/ functional unit)	% of process group total	% of grand total
Process Group				
Tritium-3 (isotope)	treatment	5.42e+02	0.58%	
Xenon-131M (isotope)	air	4.18e+00	<0.01%	
Xenon-131M (isotope)	treatment	5.58e-01	<0.01%	
Xenon-133 (isotope)	air	6.04e+02	0.65%	
Xenon-133 (isotope)	treatment	8.57e+01	0.09%	
Xenon-133M (isotope)	air	4.01e+01	0.04%	
Xenon-133M (isotope)	treatment	7.02e-01	<0.01%	
Xenon-135 (isotope)	air	2.28e+01	0.02%	
Xenon-135 (isotope)	treatment	6.39e-01	<0.01%	
Xenon-135M (isotope)	air	4.35e-01	<0.01%	
Xenon-138 (isotope)	air	1.44e+00	<0.01%	
Zinc-85 (isotope)	treatment	8.18e-04	<0.01%	
Zirconium-95 (isotope)	air	2.82e-06	<0.01%	
Total		**9.30e+04**	100.00%	**0.91%**
Fuels				
Radioactive substance (unspecified)	air	4.44e+01	99.08%	
Radioactive substance (unspecified)	surface water	4.11e-01	0.92%	
Total		**4.48e+01**	100.00%	**0.00%**
Grand Total		**1.02e+07**		**100.00%**

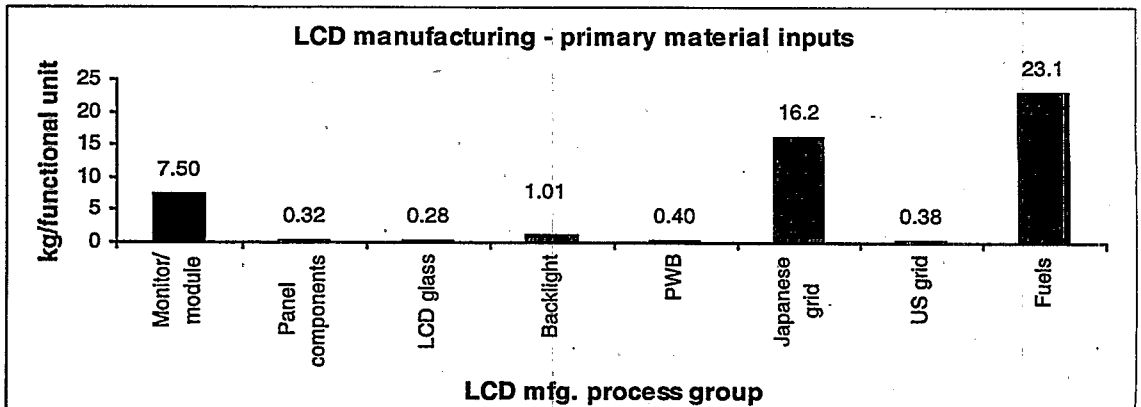

Figure 2-51. LCD manufacturing primary material inputs

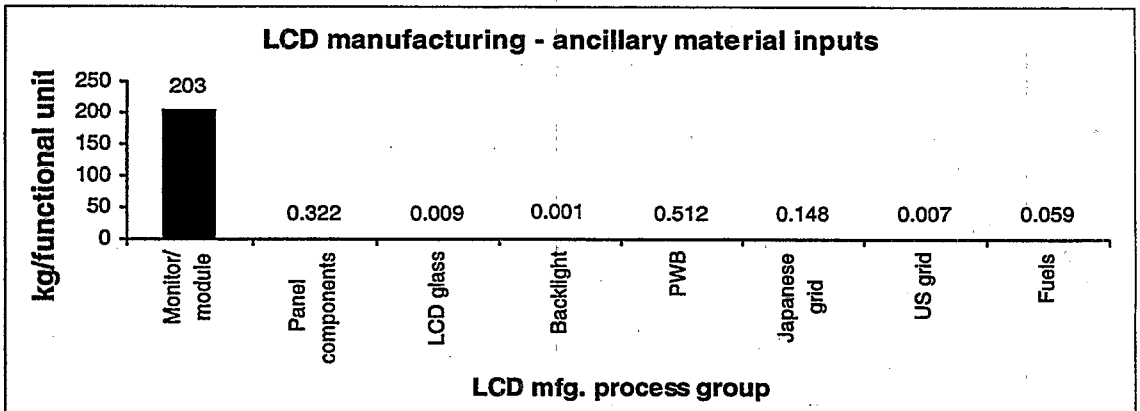

Figure 2-52. LCD manufacturing ancillary material inputs

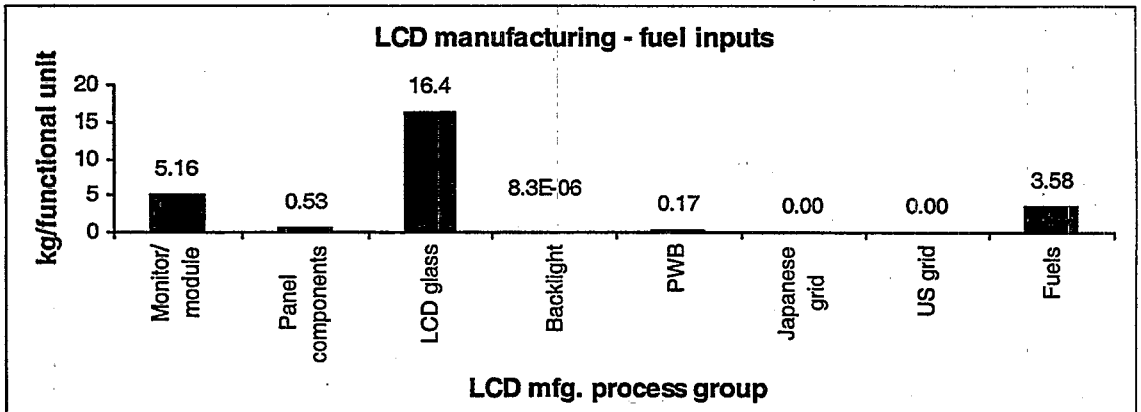

Figure 2-53. LCD manufacturing fuel inputs

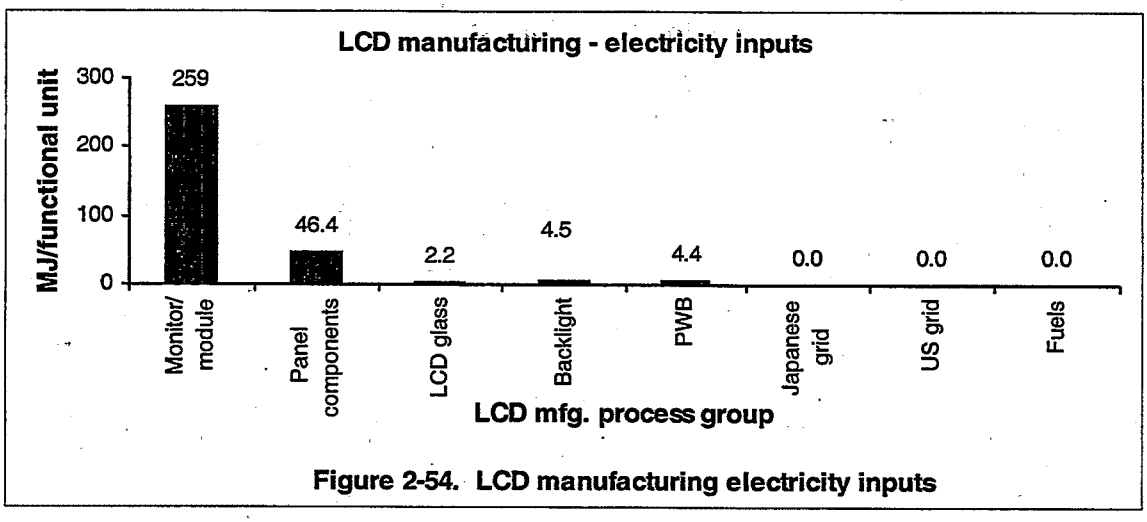

Figure 2-54. LCD manufacturing electricity inputs

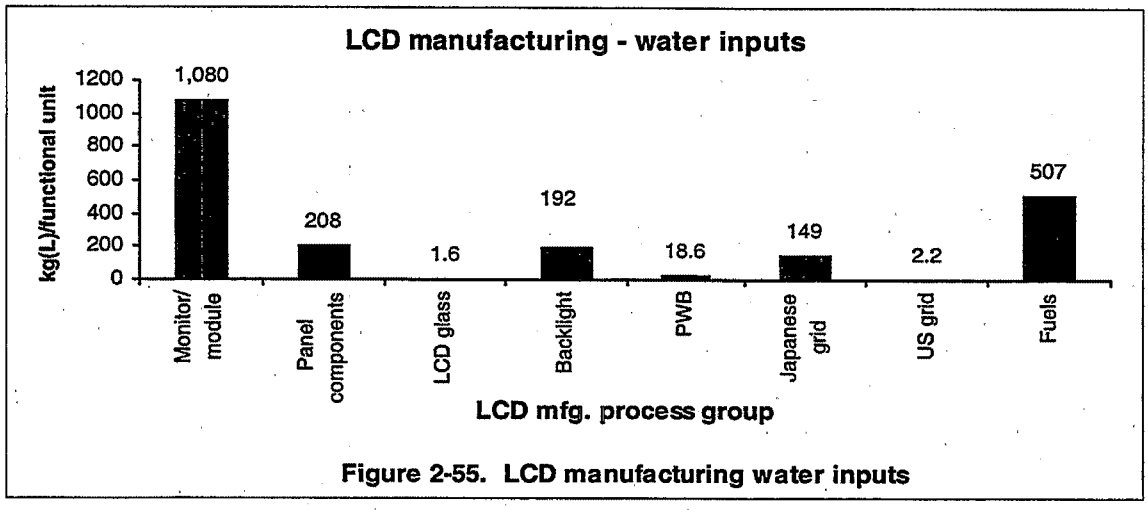

Figure 2-55. LCD manufacturing water inputs

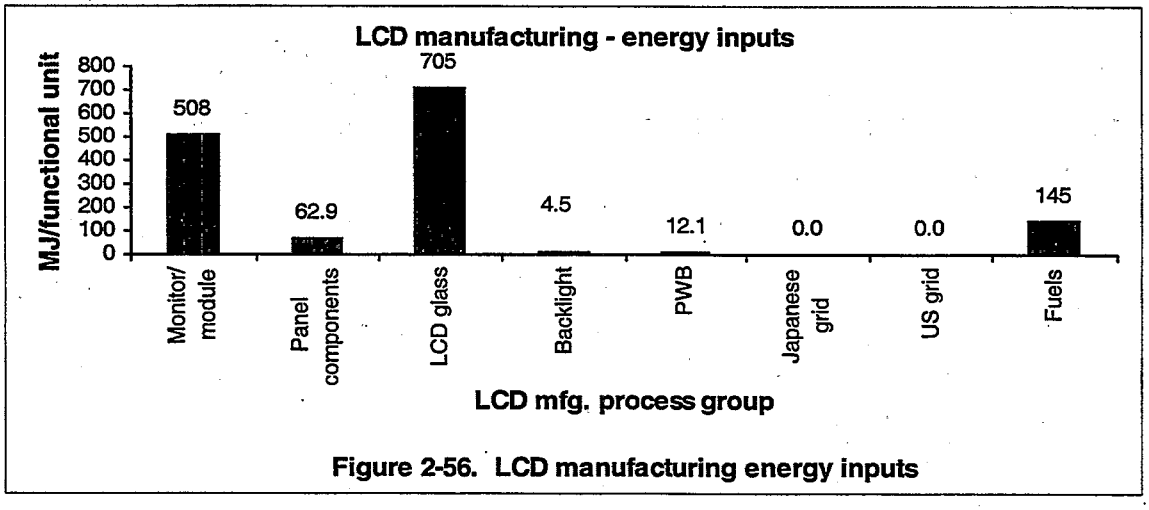

Figure 2-56. LCD manufacturing energy inputs

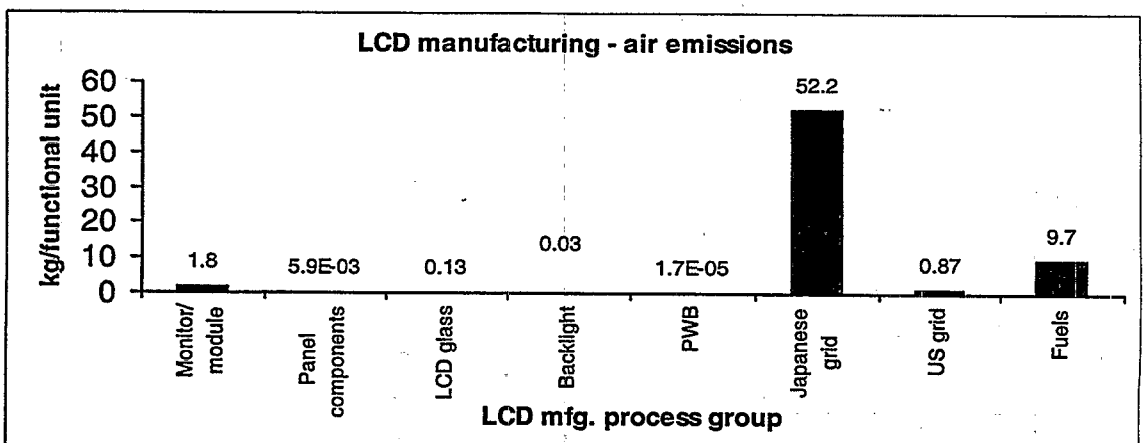

Figure 2-57. LCD manufacturing air pollutant outputs

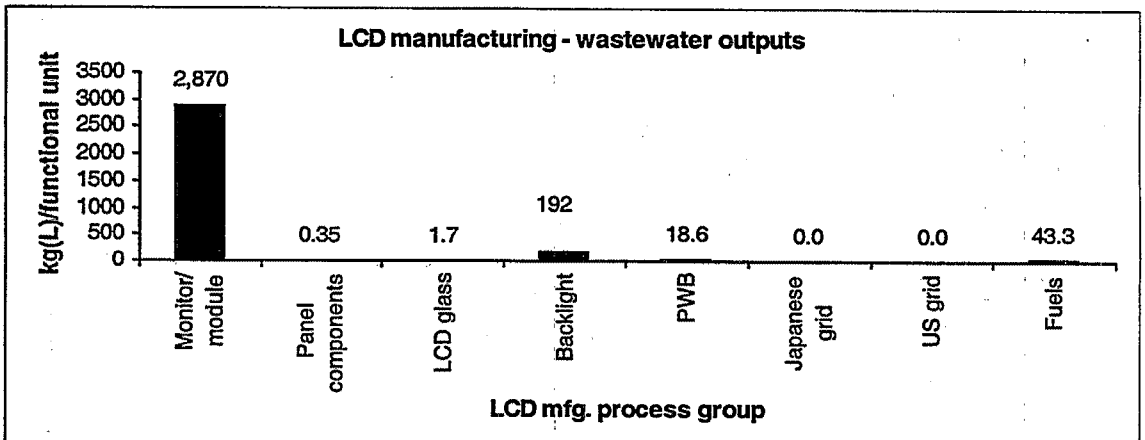

Figure 2-58. LCD manufacturing wastewater outputs

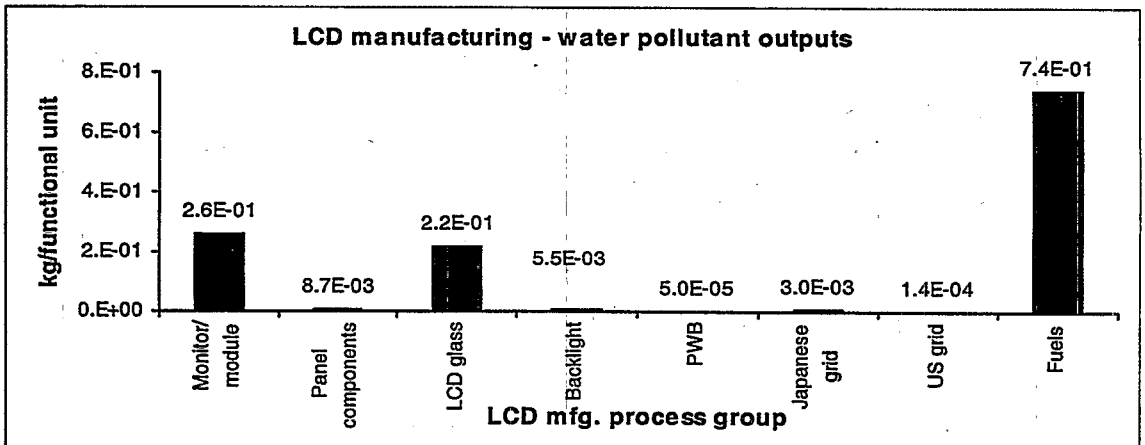

Figure 2-59. LCD manufacturing water pollutant outputs

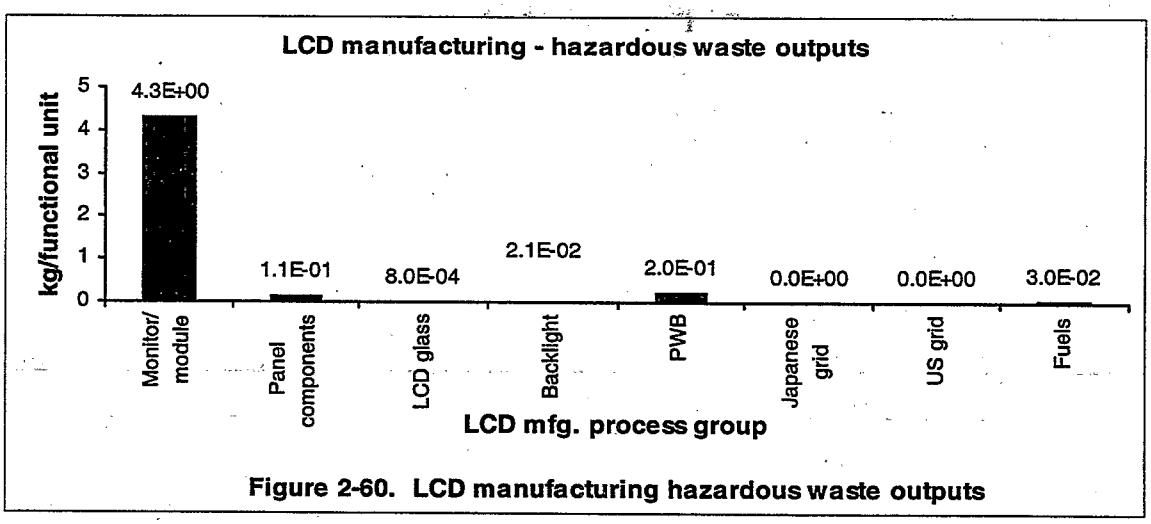

Figure 2-60. LCD manufacturing hazardous waste outputs

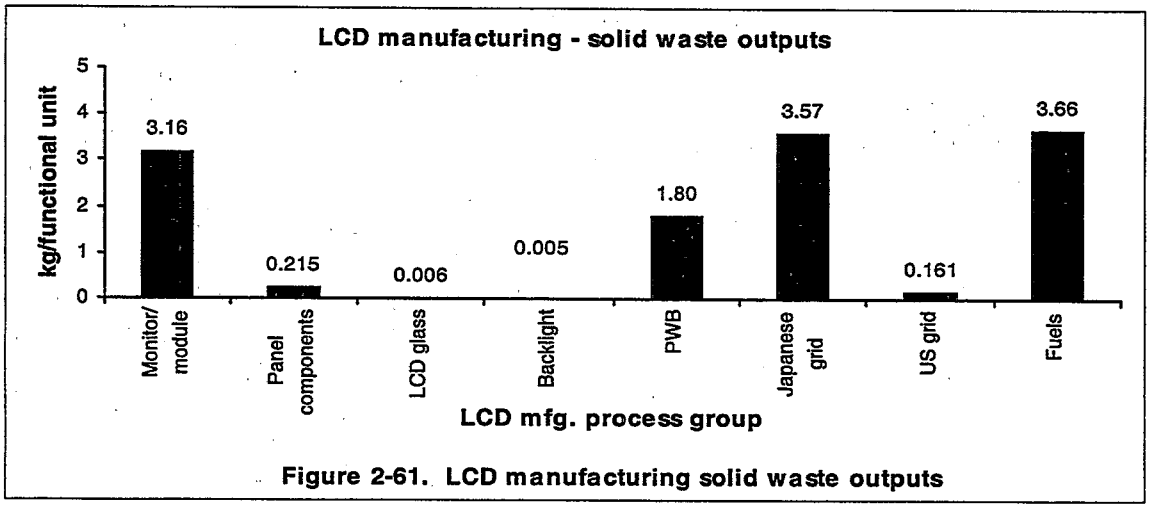

Figure 2-61. LCD manufacturing solid waste outputs

Of the total 49 kg of primary materials per functional unit in the manufacturing stage, the fuels production contributes the greatest (23.1 kg/functional unit), followed by the Japanese electric grid (16.2 kg/functional unit) (Figure 2-51 and Table 2-56). Nearly all (203 out of 204 kg/functional unit) of the ancillary materials used during manufacturing are from the monitor/module process group (Figure 2-52 and Table 2-57). Liquified natural gas (LNG) constitutes about 96% (194 kg/functional unit) of the total ancillary materials in the monitor/module process group. As stated earlier, this is not used to calculate energy impacts.

Of the utility inputs, electricity and water inputs were greatest in the monitor/module manufacturing processes; fuels were greatest in the LCD glass manufacturing process group (Figures 2-53, 2-54, and 2-55). Sixty-three percent of the fuel inputs are from the LCD glass manufacturing process group. Within that group, the use of LPG clearly dominates at about 16.2 kg/functional unit (over 99% of the LCD glass fuel inputs) (Table 2-58).[6] The monitor/module manufacturing fuel inputs are about 20% of the total manufacturing fuel inputs (5.2 kg/functional unit). About 259 MJ/functional unit of electricity in the LCD manufacturing stage are from the monitor/module processes[7], or 82% of all manufacturing electricity (Figure 2-54). The total energy, which converts fuel mass into energy and adds that to the electrical energy, is greatest in the LCD glass manufacturing processes and contributes 705 MJ/functional unit to the 1,440 MJ/functional unit in the manufacturing stage (Figure 2-56). Water inputs are most significant in the monitor/module manufacturing process, contributing 1,080 kg (or liter)/functional unit (Figure 2-55), which is 50% of all the manufacturing water inputs. The fuels production and panel components process groups contribute about 24% and 10% to the water manufacturing inputs, respectively.

For outputs from the manufacturing stage, the mass of air emissions are dominated by the generation of electricity (Figure 2-57). Individual material (pollutant) contributions for each process group are presented in Table 2-59. Wastewater outputs (i.e., the volume or mass of wastewater released) are greatest for the monitor/module manufacturing processes (92%) (Figure 2-58), but only 21% of the chemical pollutants in the wastewater streams come from those processes (Figure 2-59). Table 2-60 shows the individual contributions from each material.

Hazardous wastes from the LCD manufacturing stage dominated over other life-cycle stages, and within the manufacturing stage, the monitor/module processes had the greatest hazardous waste outputs by mass (4.3 kg/functional unit) (Figure 2-60). The greatest contributors by mass are isopropyl alcohol (a total of 2.1 kg/functional unit, or 49% of all wastes from the monitor/module manufacturing processes) (Table 2-61). These wastes, however, are recycled and although they are a large portion of the inventory, they will not affect the impact assessment (to be presented in Chapter 3) as they are not directly released to the environment.

Solid wastes generated during the manufacturing stage were only about 21% of the overall solid wastes generated throughout the LCD life-cycle, as was shown earlier in

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[6] Note: An industry participant questioned the large fuel contribution reported here; however, further discussions with industry supported that no valid reason could justify removing these data. Glass energy inputs are evaluated in a sensitivity analysis (see Section 2.7.3 and 3.4).

[7] This amount of electricity is consistent with the industry participant that expressed doubt in the large fuel energy contribution and subsequent overall energy use amount in module manufacturing.

Figure 2-48. Within the manufacturing stage, the fuels production, Japanese grid and monitor/module manufacturing process groups are all major contributors to the solid waste outputs (Figure 2-61). The individual material contributions are provided in Table 2-62.

Radioactive waste and radioactivity are directly related to the electricity generation process and therefore, only the Japanese and U.S. electric grid processes generate these outputs in the manufacturing stage. Tables 2-63 and 2-64 show that more radioactive wastes and radioactivity are from the Japanese electric grid. This is a result of more manufacturing processes being in Japan, as modeled in this project, as well as the greater fraction of nuclear power in the Japanese electric grid.

2.7.2 Relative Data Quality

Sections 2.2 through 2.6 (and associated appendices) discuss the data quality and data limitations for each life-cycle stage. Several factors contribute to the overall quality for an entire life-cycle stage. For example, the manufacturing stage includes several different processes that were collected from several different companies. The quality of one data set from one company may be very different from that of another company. Relative data quality estimates have been made for each life-cycle stage, including electricity generation, which is included in more than one life-cycle stage (Table 2-65). In addition, transportation data quality is listed in Table 2-65, although it has been excluded from the analysis due to the very low data quality.

Table 2-65. Relative data quality

Life-cycle stage	Relative data quality
Upstream	Moderate
Manufacturing	Moderate to high
Use	Moderate to high
EOL	Low to moderate
Electricity generation	High
Transportation	Very low

2.7.3 Sensitivity Analyses

The inventory results presented above in Section 2.7.1 are the "baseline" results in this study. The baseline scenario includes the parameters/assumptions presented in the methodologies for the effective life scenario. However, due to assumptions and uncertainties in this LCA, as in any LCA, sensitivity analyses on the baseline results have been conducted. Four areas have been identified where sensitivity analyses were most warranted:

- use stage lifespan assumptions;
- glass manufacturing energy inputs;
- LCD monitor/module manufacturing energy inputs, and
- LCD EOL disposition assumptions.

Selected sensitivity analyses were chosen based on the data with either the greatest uncertainties or with a large uncertainty and a major contributor to the inventory results. The matrix in Table 2-66 shows the different sensitivity analyses or scenarios that are considered in the impact assessment results. Discussions of the sensitivity analyses for manufactured life (use stage), glass manufacturing energy inputs, LCD monitor manufacturing energy inputs, and LCD EOL inventories follow in this section. Complete inventories of each sensitivity analysis scenario are not presented; however, the effects determined in the LCIA results of the sensitivity analyses are shown in Chapter 3 (see Section 3.4).

Table 2-66. List of sensitivity analysis scenarios

Monitor type	Sensitivity analysis scenario
Baseline analyses (for reference)	
CRT	Effective life scenario with average glass energy inputs (all glass manufacturing energy data used)
LCD	Effective life scenario with average glass energy inputs (all glass manufacturing energy data used) and outliers in the LCD module manufacturing energy data removed
Sensitivity analyses	
CRT	Manufactured life scenario same as baseline except lifespan is based on manufactured life instead of effective life, which results in some revised functional equivalency calculations (see Section 2.7.3.1 below)
LCD	Manufactured life scenario same as baseline except lifespan is based on manufactured life, which results in some revised functional equivalency calculations (see Section 2.7.3.1 below)
CRT	Modified glass energy scenario same as baseline except comparatively high glass manufacturing energy inputs are removed
LCD	Modified glass energy scenario same as baseline except comparatively high glass manufacturing energy inputs are removed
LCD	Modified LCD module energy scenario same as baseline except LCD monitor/ module manufacturing energy outliers are included in the average
LCD	Modifed LCD EOL scenario same as baseline except LCD EOL dispositions are modified

2.7.3.1 Manufactured life scenario

To address uncertainties in the use stage lifespan assumptions, we applied the manufacturing life scenario to the CRT and LCD life-cycle profiles. (See Section 2.4 for a discussion of the product use stage and the differences in the "effective life" versus "manufactured life" life span assumptions.) Recall that the LCD manufactured life (45,000 hours) is 3.6 times greater than the CRT manufactured life (12,500 hours). In an LCA, comparisons are made based on functional equivalency. Therefore, if one monitor will operate for a longer period of time than another, impacts should be based on an equivalent use. Thus,

based on equivalent use periods, under the manufactured life scenario 3.6 CRTs would need to be manufactured for every LCD. This was incorporated into the profile analysis for the comparative manufactured life LCA. Similarly, on average, 1.4 LCD backlights (which can be cost-effectively replaced) will be needed during the manufactured lifetime of an LCD monitor. This was also incorporated into the profile. Thus, the following modifications were made:

- change the CRT electricity input in the use stage from 635 kWh (2,286 MJ) to 788 kWh (2,837 MJ); [8]
- change the LCD electricity input in the use stage from 237 kWh (853 MJ) to 1,035 kWh (3,726 MJ);
- increase the manufacturing of CRTs by a factor of 3.6 to account for the functional equivalency of CRTs and LCDs. This was done by increasing the functional unit (22 kg CRT monitor) by a factor of 3.6, which equates to manufacturing 3.6 times more CRTs than in the baseline case; and
- increase the manufacturing of the LCD backlight lamp by a factor of 1.4 to account for the functional equivalency of LCDs and CRTs. This was done by increasing the backlight lamp mass (0.0023 kg), which is an input to the backlight unit assembly process, by a factor of 1.4.

Note that functional equivalency modification requires that the manufactured life scenario results be used only when comparing the CRT and LCD. These results cannot be accurately used to compare EL to ML for CRT or LCD. LCIA results of the sensitivity analysis are presented in Chapter 3.

2.7.3.2 Modified glass energy scenario

In the second case, the energy input values for CRT glass manufacturing (and consequently LCD glass manufacturing) were considered uncertain due to the large discrepancy in fuel and electricity values among the individual data sets. The baseline case uses the average of the data supplied and confirmed by the companies who supplied the data. However, because one set of data was significantly higher, that one set of data was removed from the profile for the sensitivity analysis. (A statistical evaluation of the glass manufacturing data for outliers could not be conducted because there were not enough data sets.)

In the baseline scenario, the averaged primary data from manufacturers of total energy to produce a kilogram of CRT or LCD glass was 1,560 MJ (433 kWh) of energy, with only 0.3% of that as electrical energy. The sensitivity analysis scenario assumes 16.3 MJ (4.5 kWh) per kilogram of glass produced, with approximately 30% as electrical energy. The majority of the fuel energy in the baseline scenario was from LPG. The energy consumption values can be compared to estimates for the entire glass industry, which includes the more prevalent general flat glass, as well as speciality glasses, such as CRT and LCD glass. In a report of the Glass Technology Roadmap Workshop (Energetics Inc. 1997), it was estimated that in practice, about 1.1 MJ of energy are required to melt a kilogram of glass; and electrical energy contributes

[8] This represents the electricity use for a 12,500 hour life span. This figure is then multiplied by a factor of 3.6 in the functional equivalency calculations (see third bullet, below).

approximately 13% of the total process energy requirements from glass production, as reported in 1994. Although this does not translate into energy requirements for CRT or LCD glass, it suggests the baseline data collected for this analysis may be inflated. Therefore, the sensitivity analysis uses revised energy input values for glass production, but it is also not known whether these values represent the true energy requirements for CRT and LCD glass production. The sensitivity analysis is considered a lower bound of energy requirements for monitor glass production.

2.7.3.3 Modified LCD module energy scenario

LCD monitor/module manufacturing energy was another area of relatively large uncertainty and variability in the inventory data. The CDP received seven sets of LCD monitor/module manufacturing data from five companies in Japan and two in Korea. Of these, the manufacturing energy data from one company in Korea was incomplete and could not be used. For the remaining six data sets, total energy inputs ranged from 330 MJ to 7,310 MJ, with a mean and standard deviation of 2,269 MJ and 2,906 MJ, respectively. Given the wide variability in the data and large standard deviation, CDP researchers evaluated the data for outliers by breaking the total energy data points into quartile ranges. Minor outliers are then those within a certain range of multipliers beyond the middle 50 percent of the distribution. That is, the interquartile range (IQR) (i.e., the range of values representing the middle 50 percent) multiplied by 1.5 is the lower bound of the minor outlier and the IQR times three is the upper bound of the minor outlier. Anything beyond IQR times three is a major outlier. Using this approach, one data set was found to be a minor outlier and another was found to be a major outlier. These outliers were excluded from the averages used in the baseline analysis, but included in the averages used in the LCD monitor/module manufacturing energy sensitivity analysis.

Table 2-67 summarizes the energy inputs for the LCD monitor/module manufacturing process group under the baseline and modified LCD module energy scenarios. Note that total energy inputs are approximately 4.5 times lower under the baseline scenario. However, because of the different types of energy (fuel and electricity) employed by different manufacturers, the mean electric energy is higher for the baseline than the modified energy scenario.

2.7.3.4 LCD End-of-life dispositions

Finally, because very few desktop LCDs have reached their end of life, and usually only if they have been damaged in some way, very little is known about the percentage of LCDs that are remanufactured, recycled, landfilled or incinerated. In the baseline scenario, it was assumed that a certain proportion of monitors go to each EOL disposition. As the functional unit in this study is one monitor, we used those proportions to represent the probability that one monitor would go to the respective disposition. To address uncertainties in the allocation of disposition percentages, a sensitivity analysis was conducted with a different set of final disposition numbers. Details and assumptions for the sensitivity analysis are provided in Appendix I. Table 2-68 presents the distribution of LCD EOL dispositions assumed under the baseline and modifed EOL dispositions scenarios. LCIA results for the sensitivity analysis are presented in Section 3.4.

Table 2-67. Energy inputs to the LCD monitor/module manufacturing process group under the baseline and modified energy scenarios

	Total energy (MJ per monitor)	Electric energy (MJ per monitor)	Fuel energy (MJ per monitor)	% electric energy	% fuel energy
Baseline (excludes two outlier data sets from the means used in the inventory)					
Range	333 to 934	199 to 359	48 to 695	25 to 88	12 to 75
Mean	508	259	249	60	40
Standard deviation	284	68	300	27	27
Modified Energy (includes two outlier data sets in the means used in the inventory)					
Range	333 to 7,317	125 to 359	48 to 7,146	2 to 88	12 to 98
Mean	2,274	222	2052	10	90
Standard deviation	2,906	79	2,956	36	36

Table 2-68. Distribution of LCD EOL dispositions in the baseline and modified EOL scenarios

Disposition	Baseline	Modified
Incineration	15%	15%
Recycling	15%	0%
Remanufacturing	15%	40%
Hazardous waste landfill	5%	5%
Solid waste landfill	50%	40%

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Chapter 3

LIFE-CYCLE IMPACT ASSESSMENT

Within LCA, the LCI is a well established methodology; however, LCIA methods are less well defined and continue to evolve (Barnthouse *et al.*, 1997; Fava *et al.*, 1993). For toxicity impacts in particular, there are some methods being applied in practice (e.g., toxicity potentials, critical volume, and direct valuation) (Guinee *et al.*, 1996; ILSI, 1996; Curran, 1996), while others are in development. However, there is currently no general consensus among the LCA community as to one method over another. LCIA sophistication has also been discussed in efforts to determine the appropriate level of analytical sophistication for various types of decision making requirements (Bare *et al.*, 1999) or one that adequately addresses toxicity impacts.

Section 3.1 of this chapter presents the University of Tennessee (UT) LCIA methodology, which takes a more detailed approach to chemical toxicity impacts than some methods currently being used. Section 3.1 also discusses data sources, data quality, and the limitations and uncertainties in the LCIA methodology. The UT methodology calculates life-cycle impact category indicators for a number of impact categories, including several traditional LCA impact categories (e.g., global warming, stratospheric ozone depletion, photochemical smog, and energy consumption). Furthermore, the method calculates relative category indicators for potential chronic human health, aquatic ecotoxicity, and terrestrial ecotoxicity impacts in order to address interest in human and ecological toxicity and to fill a common gap in LCIAs. Work conducted for Saturn Corporation and the EPA Office of Research and Development by the UT Center for Clean Products and Clean Technologies has provided the basis for much of this methodology (Swanson, 2001).

Section 3.2 of this chapter describes the data management and analysis software used to calculate LCIA results. Section 3.3 presents the baseline LCIA results for both the CRT and the LCD. Baseline results are presented by impact category and include a discussion of the specific limitations and uncertainties in each category. Section 3.4 presents sensitivity analyses of the baseline results.

3.1 METHODOLOGY

In its simplest form, LCIA is the evaluation of potential impacts to any system as a result of some action. LCIAs generally classify the consumption and loading data from the inventory stage to various impact categories. Characterization methods are then used to quantify the magnitude of the contribution that loading or consumption could have in producing the associated impact. LCIA does not seek to determine actual impacts, but rather to link the data gathered from the LCI to impact categories and to quantify the relative magnitude of contribution to the impact category (Fava *et al.*, 1993; Barnthouse *et al.*, 1997). Further, impacts in different impact categories are generally calculated based on differing scales and therefore cannot be directly compared.

Conceptually, there are three major phases of LCIA, as defined by the Society of Environmental Toxicology and Chemistry (SETAC) (Fava *et al.*, 1993):

- **Classification** - The process of assignment and initial aggregation of data from inventory studies to impact categories (e.g., greenhouse gases or ozone depletion compounds).
- **Characterization** - The analysis and estimation of the magnitudes of potential impacts for each impact category, derived through application of specific impact assessment tools. In the CDP, "impact scores" are calculated for inventory items that have been classified into various impact categories and then aggregated into life-cycle impact category indicators.
- **Valuation** - The assignment of relative values or weights to different impacts and their integration across impact categories to allow decision makers to assimilate and consider the full range of relevant impact scores across impact categories.

The international standard for life cycle impact assessment, ISO 14042, considers classification and characterization to be mandatory elements of LCIA. Valuation or weighting is an optional element to be included depending on the goals and scope of the study. The CDP addresses the first two LCIA steps and leaves the valuation step to industry or others. In addition, further qualitative risk screening of selected materials is conducted beyond the traditional LCIA "characterization" phase in Chapter 4. The methodologies for life-cycle impact classification and characterization are described in Sections 3.1.1 and 3.1.2, respectively. Sections 3.1.3 and 3.1.4 address data sources and data quality, and limitations and uncertainties associated with the LCIA methodology.

3.1.1 Classification

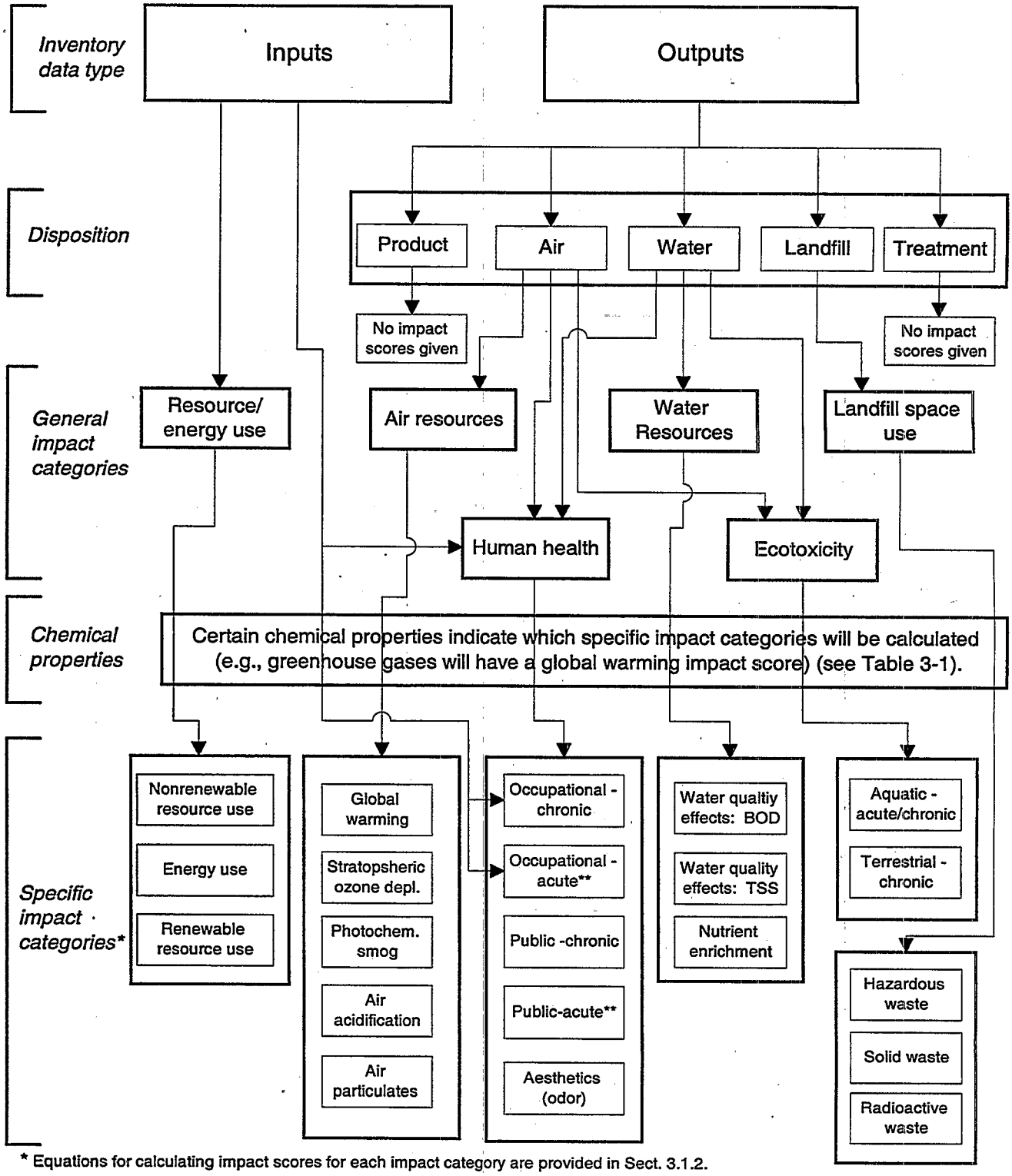
In the first step of classification, impact categories of interest are identified in the scoping phase of the LCA. The categories to be included in the CDP LCIA are listed below:

- Natural Resource Impacts
  - renewable resource use
  - nonrenewable materials use/depletion
  - energy use
  - solid waste landfill use
  - hazardous waste landfill use
  - radioactive waste landfill use
- Abiotic Ecosystem Impacts
  - global warming
  - stratospheric ozone depletion
  - photochemical smog
  - acidification
  - air quality (particulate matter loading)
  - water eutrophication (nutrient enrichment)
  - water quality (biological oxygen demand [BOD] and total suspended solids [TSS])
  - radioactivity

- Potential Human Health and Ecotoxicity Impacts
  - chronic human health effects (occupational and public)
  - aesthetic impacts (odor)
  - aquatic ecotoxicity
  - terrestrial ecotoxicity

The second step of classification is assigning inventory inputs or outputs to applicable impact categories. Classification depends on whether the inventory item is an input or output, what the disposition of the output is, and in some cases the material properties for a particular inventory item. Figure 3-1 shows a conceptual model of classification for the CDP. Table 3-1 presents the inventory types and material properties used to define which impact category will be applicable to an inventory item. One inventory item may have multiple properties and therefore would have multiple impacts. For example, methane is both a global warming gas and has the potential to create photochemical oxidants (smog formation).

Output inventory items from a process may have varying dispositions, such as direct release (to air, water or land), treatment, or recycle/reuse. Outputs with direct release dispositions are classified into impact categories for which impacts will be calculated in the characterization phase of the LCIA. Outputs sent to treatment are considered inputs to a treatment process and impacts are not calculated until direct releases from that process occur. Similarly, outputs to recycle/reuse are considered inputs to previous processes and impacts are not directly calculated for outputs that go to recycle/reuse. Figure 3-1 graphically depicts the relationships between inventory type, dispositions, and impact categories. Note that a product is also an output of a process; however, product outputs are not used to calculate any impacts. Once impact categories for each inventory item are classified, life-cycle impact category indicators are quantitatively estimated through the characterization step.



* Equations for calculating impact scores for each impact category are provided in Sect. 3.1.2.
** Excluded from the scope of the CDP; however, included in the UT Life-Cycle Design Toolkit.
Note, radioactivity (not depicted in this figure) is classified for radioactive isotope outputs to air, water or landfill.

Figure 3-1. Impact classification conceptual model

Table 3-1. Inventory types and properties for classifying inventory items into impact categories

Inventory Type		Chemical/Material Properties	Impact Category
Input	**Output**		
		Natural Resource Impacts	
material, water	----	renewable	renewable resource use
material, fuel	----	nonrenewable	nonrenewable resource use/depletion
electricity, fuel	----	energy	energy use
----	solid waste to landfill	RCRA [a] - defined nonhazardous waste (or other country-specific definitions)	solid waste landfill use
----	hazardous waste to landfill	RCRA [a] - defined hazardous waste (or other country-specific definitions)	hazardous waste landfill use
----	radioactive waste to landfill	radioactive waste	radioactive waste landfill use
		Abiotic Ecosystem Impacts	
----	air	global warming gases	global warming
----	air	ozone depleting substances	stratospheric ozone depletion
----	air	substances that can be photochemically oxidized	photochemical smog
----	air	substances that react to form hydrogen ions (H+)	acidification
----	air	air particulates (PM_{10}, TSP) [a]	air quality (air particulates)
----	water	substances that contain available nitrogen or phosphorus	water eutrophication (nutrient enrichment)
----	water	BOD [a]	water quality: BOD
----	water	TSS [a]	water quality: TSS
---	radioactivity to air, water, or land	radioactive substance (isotope)	radioactivity
		Human Health and Ecotoxicity	
material	----	toxic material	chronic human health effects - occupational
----	air, water	toxic material	chronic human health effects - public
----	air	odorous material	aesthetic impacts (odor)
----	water	toxic material	aquatic ecotoxicity
----	air, water	toxic material	terrestrial ecotoxicity

[a] Acronyms: Resource Conservation and Recovery Act (RCRA); particulate matter with average aerodynamic diameter less than 10 micrometers (PM_{10}); total suspended particulates (TSP); biological oxygen demand (BOD); total suspended solids (TSS).

3.1.2 Characterization

The characterization step of LCIA includes the conversion and aggregation of LCI results to common units within an impact category. Different assessment tools are used to quantify the magnitude of potential impacts, depending on the impact category. Three types of approaches are used in the characterization method for the CDP:

- **Loading** - An impact score is based on the inventory amount.
- **Equivalency** - An impact score is based on the inventory amount weighed by a certain effect, equivalent to a reference chemical.
  - *Full equivalency* - all substances are addressed in a unified, technical model.
  - *Partial equivalency* - a subset of substances can be converted into equivalency factors.
- **Scoring of inherent properties** - An impact score is based on the inventory amount weighed by a score representing a certain effect for a specific material (e.g., toxicity impacts are weighed using a toxicity scoring method).

Table 3-2 lists the characterization approach used with each impact category. The loading approach either uses the direct inventory amount to represent the impact or slightly modifies the inventory amount to change the units into a meaningful loading estimate. Two examples are nonrenewable resource depletion and landfill use. Use of nonrenewable resources are directly estimated as the mass (loading) of that material consumed (input amount). Use of landfill space applies the mass loading of an output of hazardous, nonhazardous, or radioactive waste and converts that loading into a volume to estimate the amount of landfill space consumed.

The equivalency method uses equivalency factors that exist for certain impact categories. Equivalency factors are values that provide a relative measure or weighting that relate an inventory output amount to some impact category relative to a certain chemical. For example, to relate an atmospheric release to the global warming impact category, chemical-specific global warming potential (GWP) equivalency factors are used. GWPs are a measure of the possible warming effect on the earth's surface arising from the emission of a gas relative to carbon dioxide (CO_2). They are based on atmospheric lifetimes and radiative forcing of different greenhouse gases.

The scoring of inherent properties method is applied to impact categories that may have different effects for the same amount of various chemicals, but for which equivalency factors do not exist or are not widely accepted. The scores are meant to normalize the inventory data to provide measures of potential impacts. Scoring methods are employed for the human and ecological toxicity impact categories, based on the CHEMS-1 method described by Swanson et al. (1997), and presented below. The scoring method provides a hazard value (HV) for each potentially toxic material, which is then multiplied by the inventory amount to calculate the toxicity impact score. The aesthetics category directly applies an inherent chemical property (i.e., odor threshold concentration), but does not convert that value into a relative score, or HV.

Using the various approaches, the UT LCIA method calculates impact scores for each inventory item for each applicable impact category. Impact scores are therefore based on either a direct measure of the inventory amount or some modification (e.g., equivalency or scoring) of that amount based on the potential effect the inventory item may have on a particular impact

category. Impact scores are then aggregated within each impact category to calculate the various life-cycle impact category indicators.

Inventory amounts are identified on a functional unit basis and then used to calculate impact scores. For each inventory item, an individual score is calculated for each applicable impact category. The equations presented in the subsections that follow calculate impacts for individual inventory items that could later be aggregated as defined by the user. Impact scores represent relative and incremental changes rather than absolute effects or threshold levels.

Table 3-2. LCIA characterization approaches for the CDP

Impact Category	Characterization Approach
Natural Resource Impacts	
Renewable resource use	loading
Nonrenewable materials use/depletion	loading
Energy use	loading
Solid waste landfill use	loading
Hazardous waste landfill use	loading
Radioactive waste landfill use	loading
Abiotic Ecosystem Impacts	
Global warming	equivalency (full)
Stratospheric ozone depletion	equivalency (full)
Photochemical smog	equivalency (partial)
Acidification	equivalency (full)
Air quality (particulate matter)	loading
Water eutrophication (nutrient enrichment)	equivalency (partial)
Water quality (BOD, TSS)	loading
Radioactivity	loading
Human Health and Ecotoxicity	
Chronic human health effects - occupational	scoring of inherent properties
Chronic human health effects - public	scoring of inherent properties
Aesthetic impacts (odor)	application of inherent properties
Aquatic ecotoxicity	scoring of inherent properties
Terrestrial ecotoxicity	scoring of inherent properties

3.1.2.1 Renewable and nonrenewable resource use

Natural resources are materials that are found in nature in their basic form rather than being manufactured (e.g., water, minerals, petroleum and wood). Renewable (or flow) resources, which are those that can be regenerated, are typically biotic resources (e.g., forest products, other plants or animals) and water. Nonrenewable (or stock) resources are abiotic, such as mineral ore or fossil fuels. Both of these natural resource impacts are calculated using the loading approach. Renewable and nonrenewable resource consumption impacts use direct consumption values (i.e., material mass) from the inventory.

Renewable resource impact scores are based on the following process inputs in the LCI: primary, ancillary, water, and fuel inputs of renewable materials. To calculate the loading-based impact scores, the following equation is used:

$$(IS_{RR})_i = [Amt_{RR} \times (1 - RC)]_i$$

where:

IS_{RR} equals the impact score for use of renewable resource i (kg) per functional unit;

Amt_{RR} equals the inventory input amount of renewable resource i (kg) per functional unit; and

RC equals the fraction recycled content (post industrial and post consumer) of resource i.

In the CDP LCI, most manufacturers that provided primary data did not report recycled content nor was the recycled content available for material inventories from secondary sources. Therefore, to calculate the impact score for use of renewable resources the recycled content (RC) was assumed to be zero.

Depletion of materials, which results from the extraction of renewable resources faster than they are renewed, may occur but is not specifically modeled or identified in the renewable resource impact score. For the nonrenewable materials use/depletion category, depletion of materials results from the extraction of nonrenewable resources. Nonrenewable resource impact scores are based on the amount of primary, ancillary, and fuel inputs of nonrenewable materials. To calculate the loading-based impact scores the following equation is used:

$$(IS_{NRR})_i = [Amt_{NRR} \times (1 - RC)]_i$$

where:

IS_{NRR} equals the impact score for use of nonrenewable resource i (NRR) (kg) per functional unit;

Amt_{NRR} equals the inventory input amount of nonrenewable resource i (kg) per functional unit; and

RC equals the fraction recycled content (post industrial and post consumer) of resource i.

Due to the lack of data on the recycled content of nonrenewable resources, RC was assumed to be zero.

3.1.2.2 Energy use

General energy consumption is used as an indicator of potential environmental impacts from the entire energy generation cycle. Energy use impact scores are based on *fuel* and *electricity* inputs. The impact category indicator is the sum of electrical energy inputs and fuel energy inputs. Fuel inputs are converted from mass to energy units using the fuel's heat value (H) and the density (D), presented in Appendix K, Table K-1. The impact score is calculated by:

$$(IS_E)_i = Amt_{Ei} \text{ or } [Amt_F \times (H/D)]_i$$

where:

IS_E	equals the impact score for energy use (MJ) per functional unit;
Amt_E	equals the inventory input amount of electrical energy used (MJ) per functional unit;
Amt_F	equals the inventory input amount of fuel used (kg) per functional unit;
H	equals the heat value of fuel i (MJ/L); and
D	equals the density of fuel i (kg/L).

This category addresses energy *use* only. The emissions from energy production are outputs from the energy production process and are classified to applicable impact categories, depending on the disposition and chemical properties of the outputs (see Classification Section 3.1.1).

3.1.2.3 Landfill use

Landfill impacts are calculated using solid, hazardous, or radioactive waste outputs to land as volume of landfill space consumed. Solid waste landfill use pertains to the use of suitable and designated landfill space as a natural resource where municipal waste or construction debris is accepted. A solid waste landfill impact score is calculated using solid waste outputs disposed of in a solid waste (nonhazardous) landfill. Impact characterization is based on the volume of solid waste, determined from the inventory mass amount of waste and material density of each specific solid waste type:

$$(IS_{SWL})_i = (Amt_{SW}/D)_i$$

where:

IS_{SWL}	equals the impact score for solid waste landfill (SWL) use for waste i (m^3) per functional unit;
Amt_{SW}	equals the inventory output amount of solid waste i (kg) per functional unit; and
D	equals density of waste i (kg/m^3).

Hazardous waste landfill use pertains to the use of suitable and designated landfill space as a natural resource where hazardous waste, as designated and regulated under the Resource Conservation and Recovery Act, is accepted. For non-US activities, equivalent hazardous or special waste landfills are considered for this impact category. Impact scores are characterized from hazardous waste outputs with a disposition of landfill. Impact characterization is based on

the volume of hazardous waste, determined from the inventory mass amount of waste and material density of each specific hazardous waste type:

$$(IS_{HWL})_i = (Amt_{HW} / D)_i$$

where:

IS_{HWL} equals the impact score for hazardous waste landfill (HWL) use for waste i (m^3) per functional unit;

Amt_{HW} equals the inventory output amount of hazardous waste i (kg) per functional unit; and

D equals density of waste i (kg/m^3).

Radioactive waste pertains to the suitable and designated landfill space as a natural resource that accepts radioactive waste. Impacts are characterized from radioactive waste outputs with a disposition of landfill. Impact characterization is based on the volume of radioactive waste, determined from the inventory mass amount of waste and material density of each specific waste.

$$(IS_{RWL})_i = (Amt_{RW}/D)_i$$

where:

IS_{RWL} equals the impact score for radioactive waste landfill (RWL) use for waste i (m^3) per functional unit;

Amt_{RW} equals the inventory output amount of radioactive waste i (kg) per functional unit; and

D equals density of waste i (kg/m^3).

3.1.2.4 Global warming impacts

The build up CO_2 and other greenhouse gases in the atmosphere may generate a "greenhouse effect" of rising temperature and climate change. Global warming potential (GWP) refers to the warming (relative to CO_2) that chemicals contribute to this effect by trapping the earth's heat. The impact scores for global warming (global climate change) effects are calculated using the mass of a global warming gas released to air modified by a GWP equivalency factor. The GWP equivalency factor is an estimate of a chemical's atmospheric lifetime and radiative forcing that may contribute to global climate change compared to the reference chemical CO_2. Therefore, GWPs are in units of CO_2 equivalents. GWPs have been published for known global warming chemicals within differing time horizons. The LCIA methodology being presented in this memorandum uses GWPs having effects in the 100-year time horizon. Although LCA does not necessarily have a temporal component of the inventory, these impacts are expected to be far enough into the future that releases occurring throughout the life cycle of a computer monitor would be within the 100-year time frame. Appendix K, Table K-2 presents a current list of GWPs as identified by the Intergovernmental Panel on Climate Change (IPCC) (Houghton et al., 1996). Global warming impact scores are calculated for any chemicals in the LCI that are found in Appendix K, Table K-2. The equation to calculate the impact score for an individual chemical is as follows:

$$(IS_{GW})_i = (EF_{GWP} \times Amt_{GG})_i$$

where:

IS_{GW} equals the global warming impact score for greenhouse gas chemical i (kg CO_2 equivalents) per functional unit;

EF_{GWP} equals the GWP equivalency factor for greenhouse gas chemical i (CO_2 equivalents, 100 year time horizon) (Appendix K, Table K-2); and

Amt_{GG} equals the inventory output amount of greenhouse gas chemical i released to air (kg) per functional unit.

3.1.2.5 Stratospheric ozone depletion

The stratospheric ozone layer filters out harmful ultraviolet radiation from the sun. Chemicals such as chlorofluorocarbons, if released to the atmosphere, may result in ozone-destroying chemical reactions. Stratospheric ozone depletion refers to the release of chemicals that may contribute to this effect. Impact scores are based on the identity and amount of ozone depleting chemicals released to air. Currently identified ozone depleting chemicals are those with ozone depletion potentials (ODPs), which measure the change in the ozone column in the equilibrium state of a substance compared to the reference chemical chlorofluorocarbon (CFC)-11 (Heijungs *et al.*, 1992; CAAA, 1990). The list of ODPs that are used in this methodology are provided in Appendix K, Table K-3. The individual chemical impact score for stratospheric ozone depletion impacts is based on the ODP and inventory amount of the chemical:

$$(IS_{OD})_i = (EF_{ODP} \times Amt_{ODC})_i$$

where:

IS_{OD} equals the ozone depletion impact score for chemical i (kg CFC-11 equivalents) per functional unit;

EF_{ODP} equals the ODP equivalency factor for chemical i (CFC-11 equivalents) (Appendix K, Table K-3); and

Amt_{ODC} equals the amount of ozone depleting chemical i released to air (kg) per functional unit.

3.1.2.6 Photochemical smog

Photochemical oxidants are produced in the atmosphere from sunlight reacting with hydrocarbons and nitrogen oxides. At higher concentrations they may cause or aggravate health problems, plant toxicity, and deterioration of certain materials. Photochemical oxidant creation potential (POCP) refers to the release of chemicals that may contribute to this effect. The POCP is based on simulated trajectories of tropospheric ozone production with and without volatile organic carbons (VOCs) present. The POCP is a measure of a specific chemical compared to the reference chemical ethene (Heijungs *et al.*, 1992). The list of chemicals with POCPs to be used in this methodology are presented in Appendix K, Table K-4. As shown in Table 3-2, photochemical smog impacts are based on partial equivalency because some chemicals cannot be

converted into POCP equivalency factors. For example, nitrogen oxides do not have a POCP. However, VOCs are assumed to be the limiting factor and if VOCs are present, there is a potential impact. Impact scores are based on the identity and amount of chemicals with POCP equivalency factors released to the air and the chemical-specific equivalency factor:

$$(IS_{POCP})_i = (EF_{POCP} \times Amt_{POC})_i$$

where:

IS_{POCP} equals the photochemical smog impact score for chemical i (kg ethene equivalents) per functional unit;

EF_{POCP} equals the POCP equivalency factor for chemical i (ethene equivalents) (Appendix K, Table K-4); and

Amt_{POC} equals the amount of smog-creating chemical i released to the air (kg) per functional unit.

3.1.2.7 Acidification

This refers to the release of chemicals that may contribute to the formation of acid precipitation. Impact characterization is based on the amount of a chemical released to air that would cause acidification and the acidification potentials (AP) equivalency factor for that chemical. The AP equivalency factor is the number of hydrogen ions that can theoretically be formed per mass unit of the pollutant being released compared to sulfur dioxide (SO_2) (Heijungs *et al.*, 1992; Hauschild and Wenzel, 1997). Appendix K, Table K-5 lists the AP values that will be used as the basis of calculating acidification impacts. The impact score is calculated by:

$$(IS_{AP})_i = (EF_{AP} \times Amt_{AC})_i$$

where:

IS_{AP} equals the impact score for acidification for chemical i (kg SO_2 equivalents) per functional unit;

EF_{AP} equals the AP equivalency factor for chemical i (SO_2 equivalents) (Appendix K, Table K-5); and

Amt_{AC} equals the amount of acidification chemical i released to the air (kg) per functional unit.

3.1.2.8 Air particulates

This refers to the release and build up of particulate matter primarily from combustion processes. Impact scores are based on particulate release amounts [particulate matter with average aerodynamic diameter less than 10 micrometers (PM_{10})] to the air. This size of particulate matter is most damaging to the respiratory system. Impact characterization is simply based on the inventory amount of particulates released to air. This loading impact score is calculated by:

$$IS_{PM} = Amt_{PM}$$

where:

IS_{PM} equals impact score for particulates (kg PM_{10}) per functional unit, and

Amt_{PM} equals the inventory output amount of particulate release (PM_{10}) to the air (kg) per functional unit.

In this equation, PM_{10} is used to estimate impacts. However, if only total suspended particulates (TSP) data are available, these data may be used. Note that using TSP data is an overestimation of PM_{10}, which only refers to the fraction of particulates in the size range below 10 micrometers. A common conversion factor (TSP to PM_{10}) is not available because the fraction of PM_{10} varies depending on the type of particulates.

3.1.2.9 Water eutrophication

Eutrophication (nutrient enrichment) impacts to water are based on the identity and concentrations of eutrophication chemicals released to surface water after treatment. Equivalency factors for eutrophication have been developed assuming nitrogen (N) and phosphorus (P) are the two major limiting nutrients of importance to eutrophication. Therefore, the partial equivalencies are based on the ratio of N to P in the average composition of algae ($C_{106}H_{263}O_{110}N_{16}P$) compared to the reference compound phosphate (PO_4^{3-}) (Heijungs *et al.*, 1992; Lindfors *et al.*, 1995). If the wastewater stream is first sent to a publicly owned treatment works (POTW), treatment is considered as a separate process and the impact score would be based on releases from the POTW to surface waters. Impact characterization is based on eutrophication potentials (EP) (Appendix K, Table K-6) and the inventory amount:

$$(IS_{EUTR})_i = (EF_{EP} \times Amt_{EC})_i$$

where:

IS_{EUTR} equals the impact score for regional water quality impacts from chemical i (kg phosphate equivalents) per functional unit;

EF_{EP} equals the EP equivalency factor for chemical i (phosphate equivalents) (Appendix K, Table K-6); and

Amt_{EC} equals the inventory output mass (kg) of chemical i per functional unit of eutrophication chemical in a wastewater stream released to surface water after any treatment, if applicable.

3.1.2.10 Water quality

Water quality impacts are characterized as surface water impacts due to releases of wastes causing oxygen depletion and increased turbidity. Two water quality impact scores are calculated based on the biological oxygen demand (BOD) and total suspended solids (TSS) in the wastewater streams released to surface water. The impact scores are based on releases to surface water following any treatment. Using a loading characterization approach, impact

characterization is based on the amount of BOD and TSS in a wastewater stream. The water quality score equations for each are presented below:

$$(IS_{BOD})_i = (Amt_{BOD})_i$$
and
$$(IS_{TSS})_i = (Amt_{TSS})_i$$

where:

IS_{BOD} equals the impact score for BOD water quality impacts for waste stream i (kg) per functional unit;

Amt_{BOD} equals the inventory output amount of BOD in wastewater stream i released to surface waters (kg) per functional unit;

IS_{TSS} equals the impact score for TSS water quality impacts for waste stream i (kg) per functional unit; and

Amt_{TSS} equals the inventory amount of TSS in wastewater stream i released to surface waters (kg) per functional unit.

3.1.2.11 Radioactivity

Radioactivity inventoried as the quantity of an isotope released to the environment is considered in the radioactivity impact category. These outputs, such as those from the generation of nuclear energy, can be air, water, or land releases. The radioactivity impact is a direct loading score measured in Bequerels of radioactivity, and calculated as follows:

$$(IS_{rad})_i = (Amt_{rad})_i$$

where:

IS_{rad} equals the impact score for radioactivity of isotope i (Bq) per functional unit; and

Amt_{rad} equals the inventory amount of radioactivity of isotope i (Bq) per functional unit.

While this impact category uses a loading approach, further refinement of this impact score calculation in the future could use radioactivity dose conversion factors, which convert radioactivity quantities (e.g., Bq) into human doses equivalents (e.g., sievert or rem).

3.1.2.12 Potential human health impacts

Human health impacts are defined in the context of life-cycle assessment as relative measures of potential adverse health effects to humans. Human health impact categories included in the scope of this LCA are chronic (repeated dose) effects, which include noncarcinogenic and carcinogenic effects, and aesthetics (although not a health effect *per se*, aesthetics pertains to human welfare). Chronic human health effects to both workers and the public are considered. Quantitative measures of consumer impacts are not included in this LCIA methodology because there are no direct outputs quantified in the LCI from the use stage of a computer monitor. The CDP does, however, quantify indirect outputs from energy consumption (i.e., pollutants released from energy production). In addition, Appendix L qualitatively discusses direct consumer impacts, such as electromagnetic radiation or eye strain.

The chemical characteristic that classifies inventory items to the human health effects (and ecotoxicity) categories is toxicity. Toxic chemicals were identified by searching lists of toxic chemicals [e.g., Toxic Release Inventory (TRI)] and if needed, toxicity databases [e.g., Hazardous Substances Data Bank (HSDB)], and Registry of Toxic Effects of Chemical Substances (RTECS), or other literature. Upon review by the EPA DfE Workgroup (see Appendix C), several materials in the CDP inventory were excluded from the toxic list if they are generally accepted as nontoxic. The EPA DfE Workgroup also reviewed the list of chemicals that were included in this project as potentially toxic. The list of potentially toxic chemicals is provided in Appendix K, Table K-8, and chemicals that were excluded from the toxic list that appear in the CDP inventory are presented in Appendix K, Table K-9.

Human (and ecological) toxicity impact scores are calculated based on a chemical scoring method modified from CHEMS-1 found in Swanson *et al.* (1997). To calculate impact scores, chemical-specific inventory data are required. Any chemical that is assumed to be potentially toxic is given a toxicity impact score. If toxicity data are unavailable for a chemical, a mean default toxicity score is given. This is described in further detail below. Ecological toxicity is presented in Section 3.1.2.13.

Chronic human health effects are potential human health effects occurring from repeated exposure to toxic agents over a relatively long period of time (i.e., years). These effects could include carcinogenicity, reproductive toxicity, developmental effects, neurotoxicity, immunotoxicity, behavioral effects, sensitization, radiation effects, chronic effects to other specific organs or body systems (e.g., blood, cardiovascular, respiratory, kidney and liver effects). Impact categories for chronic health effects are divided into worker and public impacts. Occupational impact scores are based on inventory inputs and public impact scores are based on inventory outputs.

Chronic occupational health effects

This refers to potential health effects to workers, including cancer, from long-term repeated exposure to toxic or carcinogenic agents in an occupational setting. For possible occupational impacts, the identity and amounts of materials/constituents as input to a process are used. The inputs represent potential exposures and we could assume that a worker would continue to work at a facility and incur exposures over time. However, the inventory is based on manufacturing one monitor and does not truly represent chronic exposure. Therefore, the chronic health effects impact score is more a ranking of the potential of a chemical to cause chronic effects than a prediction of actual effects.

Chronic occupational health effects scores are based on the identity of toxic chemicals (or chemical ingredients) found in primary and ancillary inputs from materials processing and manufacturing life-cycle stages. The distinction between pure chemicals and mixtures is made implicitly, if possible, by specifying component ingredients of mixtures in the inventory.

The chronic human health impact scores are calculated using hazard values (HVs) for carcinogenic and for noncarcinogenic effects. The former HV uses cancer slope factors or cancer weight of evidence (WOE) classifications assigned by EPA and/or the International Agency for Research on Cancer (IARC) when no slope factor exists. If both an oral and inhalation slope factor exist, the slope factor representing the larger hazard is chosen. Where no slope factor is available for a chemical, but there is a WOE classification, the WOE is used to designate default

hazard values as follows: EPA WOE Groups D (not classifiable) and E (noncarcinogen) and IARC Groups 3 (not classifiable) and 4 (probably not carcinogenic) are given a hazard value of zero. All other WOE classifications (known, probable, and possible human carcinogen) are given a default HV of 1 (representative of a mean slope factor) (Table 3-3). Similarly, materials for which no cancer data exist, but are designated as potentially toxic, are also given a default value of 1.

Table 3-3. Hazard values for carcinogenicity weight-of-evidence if no slope factor is available

EPA Classification	IARC Classification	Description	Hazard Value
Group A	Group 1	known human carcinogen	1
Group B1	Group 2A	Probable human carcinogen (limited human data)	1
Group B2	N/A	Probable human carcinogen (from animal data)	1
Group C	Group 2B	Possible human carcinogen	1
Group D	Group 3	Not classifiable	0
Group E	Group 4	Noncarcinogenic or probably not carcinogenic	0

N/A: not applicable.

The cancer hazard value for chronic occupational health effects is the greater of the following:

$$oral: \quad (HV_{CA_{oral}})_i = \frac{oral\ SF_i}{oral\ SF_{mean}}$$

$$inhalation: \quad (HV_{CA_{inhalation}})_i = \frac{inhalation\ SF_i}{inhalation\ SF_{mean}}$$

where:

HV_{CAoral}	equals the cancer oral hazard value for chemical *i* (unitless);
$oral\ SF_i$	equals the cancer oral slope factor for chemical *i* (mg/kg-day);
$oral\ SF_{mean}$	equals the geometric mean cancer slope factor of all available slope factors (0.71 mg/kg-day);
$HV_{CAinhalation}$	equals the cancer inhalation hazard value for chemical *i* (unitless);
$inhalation\ SF_i$	equals the cancer inhalation slope factor for chemical *i* $(mg/kg\text{-}day)^{-1}$; and
$inhalation\ SF_{mean}$	equals the geometric mean cancer inhalation slope factor of all available inhalation slope factors $(1.70\ mg/kg\text{-}day)^{-1}$.

The oral and inhalation slope factor mean values are the geometric means of a set of chemical data presented in Appendix K, Table K-10.

The noncarcinogen HV is based on either no-observed-adverse-effect levels (NOAELs) or lowest-observed-adverse-effect levels (LOAELs). The noncarcinogen HV is the greater of the inhalation and oral HV:

$$oral: \quad (HV_{NC_{oral}})_i = \frac{1/(oral\ NOAEL_i)}{1/(oral\ NOAEL_{mean})}$$

$$inhalation: \quad (HV_{NC_{inhalation}})_i = \frac{1/(inhal\ NOAEL_i)}{1/(inhal\ NOAEL_{mean})}$$

where:

$HV_{NC\ oral}$	equals the noncarcinogen oral hazard value for chemical *i* (unitless);
$oralNOAEL_i$	equals the oral NOAEL for chemical *i* (mg/kg-day);
$oralNOAEL_{mean}$	equals the geometric mean oral NOAEL of all available oral NOAELs (11.88 mg/kg-day);
$HV_{NC\ inhalation}$	equals the noncarcinogen inhalation hazard value for chemical *i* (unitless);
$inhalNOAEL_i$	equals the inhalation NOAEL for chemical *i* (mg/m^3); and
$inhalNOAEL_{mean}$	equals the geometric mean inhalation NOAEL of all available inhalation NOAELs (68.67 mg/kg-day).

The oral and inhalation NOAEL mean values are the geometric means of a set of chemical data presented in Appendix K, Table K-8. If LOAEL data are available instead of NOAEL data, the LOAEL divided by 10 is used to substitute for the NOAEL. The most sensitive endpoint is used if there are multiple data for one chemical.

The sum of the carcinogen and noncarcinogen HVs for a particular chemical is multiplied by the applicable inventory input to calculate the impact score:

$$(IS_{CHO})_i = [(HV_{CA} + HV_{NC}) \times Amt_{TCinput}]_i$$

where:

IS_{CHO}	equals the impact score for chronic occupational health effects for chemical *i* (tox-kg) per functional unit;
HV_{CA}	equals the hazard value for carcinogenicity for chemical *i*;
HV_{NC}	equals the hazard value for chronic noncancer effects for chemical *i*; and
$Amt_{TCinput}$	equals the amount of toxic inventory input (kg) per functional unit for chemical *i*.

Chronic public health effects

For chronic public health effects, the impact score represents a surrogate for potential health effects to residents living near a facility, including cancer, from long-term repeated exposure to toxic or carcinogenic agents. Impact scores are based on the identity and amount of toxic chemical outputs with dispositions to air and water.[1] As stated above, inventory items do not truly represent long-term exposure; instead, impacts are relative toxicity weightings of the inventory.

The scores for impacts to the public differ from the occupational impacts in that inventory outputs are used as opposed to inventory inputs. Note that this basic screening level scoring does not incorporate the fate and transport of the chemicals. The chronic public health effects impact score is calculated as follows:

$$(IS_{CHP})_i = [(HV_{CA} + HV_{NC}) \, x \, Amt_{TCoutput}]_i$$

where:

IS_{CHP} equals the impact score for chronic human health effects to the public for chemical i (tox-kg) per functional unit; and

$Amt_{TCoutput}$ equals the amount of toxic inventory output of chemical i to air and water (kg) per functional unit.

Aesthetic impacts (odor)

This refers to impacts that detract from the quality of the local environment from a human perspective. Characterization in this project is based on odor. Impact scores are based on the identity and amount of odor-causing chemicals (Heijungs *et al.*, 1992; EPA 1992), released to the air and their odor threshold value (OTV) (Heijungs *et al.*, 1992) (Appendix K, Table K-7). This approach does not score chemicals as is done for toxic chemicals. The OTV is specific to a chemical, but does not use an equivalency factor that is based on a reference chemical or a hazard value based on a mean OTV. In this case, the OTV is a concentration which, when divided into the mass output of a chemical, results in an impact score in units of volume of malodorous air:

$$(IS_{AS})_i = (Amt_{OC} / OTV)_i$$

where:

IS_{AS} equals the aesthetics impact score for chemical i (m^3 malodorous air) per functional unit;

Amt_{OC} equals the amount of odor-causing output for chemical i released to air (mg) per functional unit; and

OTV equals the odor threshold value for chemical i (mg/m^3) (Appendix K, Table K-10).

[1] Disposition could be to groundwater. For example, a landfill model could have releases that go to groundwater.

Note that this impact assessment methodology determines the volume of malodorous air created if there is no dilution. In reality, many of the air releases reported in the LCI may occur at concentrations below the chemical's odor threshold.

3.1.2.13 Ecotoxicity

Ecotoxicity refers to effects of chemical outputs on nonhuman living organisms. Impact categories include ecotoxicity impacts to aquatic and terrestrial ecosystems.

Aquatic toxicity

Toxicity measures for fish are used to represent potential adverse effects to organisms living in the aquatic environment from exposure to a toxic chemical. Impact scores are based on the identity and amount of toxic chemicals as outputs to surface water. Impact characterization is based on CHEMS-1 acute and chronic hazard values for fish (Swanson *et al.*, 1997) combined with the inventory amount. Both acute and chronic impacts are combined into the aquatic toxicity term. The hazard values (HVs) for acute and chronic toxicity are based on LC_{50} and NOAEL toxicity data, respectively, mostly from toxicity tests in fathead minnows (*Pimephales promelas*) (Swanson *et al.*, 1997). The acute fish HV is calculated by:

$$(HV_{FA})_i = \frac{1/(LC_{50})_i}{1/(LC_{50})_{mean}}$$

where:

HV_{FA} equals the hazard value for acute fish toxicity for chemical *i* (unitless);
LC_{50i} equals the lethal concentration to 50% of the exposed fish population for chemical *i*; and
LC_{50mean} equals the geometric mean LC_{50} of available fish LC_{50} values in Appendix K, Table K-8 (23.45 mg/L).

The chronic fish HV is calculated by:

$$(HV_{FC})_i = \frac{1/NOAEL_i}{1/NOAEL_{mean}}$$

where:

HV_{FC} equals the hazard value for chronic fish toxicity for chemical *i*;
$NOAEL_i$ equals the no observed adverse affect level for fish for chemical *i*; and
$NOAEL_{mean}$ equals the geometric mean NOAEL of available fish NOAEL values in Appendix K, Table K-7 (3.90 mg/L).

The aquatic toxicity impact score is calculated as follows:

$$(IS_{AQ})_i = [(HV_{FA} + HV_{FC}) \times Amt_{TCoutput,water}]_i$$

where:

IS_{AQ} equals the impact score for aquatic ecotoxicity for chemical i (tox-kg) per functional unit; and

$Amt_{TCoutput,water}$ equals the toxic inventory output amount of chemical i to water (kg) per functional unit.

Terrestrial toxicity

Toxicity measures for mammals (primarily rodents) are used to represent potential adverse effects to organisms living in the terrestrial environment from exposure to a toxic chemical. Impact scores are based on the identity and amount of toxic chemicals as outputs to air and surface water. Impact characterization is based on chronic toxicity hazard values combined with the inventory amount. The terrestrial toxicity impact score is based on the same noncancer chronic data used for human health because underlying data are from the same mammal studies (see Section 2.1.2.12 for the HV_{NC} term). The cancer hazard value was not included in the terrestrial impact score as it is based on ranking for potential human carcinogenicity. The terrestrial toxicity impact score is as follows:

$$(IS_{TER})_i = (HV_{NC} \times Amt_{TCoutput})_i$$

where:

IS_{TER} equals the impact score for terrestrial toxicity for chemical i (tox-kg) per functional unit; and

$Amt_{TCoutput}$ equals the toxic inventory output amount of chemical i (kg) per functional unit.

3.1.2.14 Summary of impact score equations

Table 3-4 summarizes the impact categories, associated impact score equations, and the input or output data required for calculating natural resource impacts. Each of these characterization equations are loading estimates.

Table 3-4. Summary of natural resources impact scoring

Impact Category	Impact Score Approach	Data Required from Inventory (per functional unit)	
		Inputs	Outputs
Use of renewable resources	$IS_{RR} = Amt_{RR} \times (1 - RC)$	Material mass (kg) (e.g., water)	none
Use/depletion of nonrenewable materials	$IS_{NRR} = Amt_{NRR} \times (1 - RC)$	Material mass (kg)	none
Energy use, general energy consumption	$IS_E = Amt_E$ or $(Amt_F \times H/D)$	Energy (MJ) (electricity, fuel)	none
Solid waste landfill use	$IS_{SWL} = Amt_{SW} / D$	none	solid waste mass (kg) and density (i.e., volume, m^3)
Hazardous waste landfill use	$IS_{HWL} = Amt_{HW} / D$	none	hazardous waste mass (kg) and density (i.e., volume, m^3)
Radioactive waste landfill use	$IS_{RWL} = Amt_{RW} / D$	none	radioactive waste mass (kg) and density (i.e., volume, m^3)

Abbreviations: RC = recycled content; H = heat value of fuel *i*; D = density of fuel *i*.

The term abiotic ecosystem refers to the nonliving environment that supports living systems. Table 3-5 presents the impact categories, impact score equations, and inventory data requirements for abiotic environmental impacts to atmospheric resources.

Table 3-5. Summary of atmospheric resource impact scoring

Impact Category	Impact Score Approach	Data Required from Inventory (per functional unit)	
		Inputs	Outputs
Global warming	$IS_{GW} = EF_{GWP} \times Amt_{GG}$	none	amount of each greenhouse gas chemical released to air
Stratospheric ozone depletion	$IS_{OD} = EF_{ODP} \times Amt_{ODC}$	none	amount of each ozone depleting chemical released to air
Photochemical smog	$IS_{POCP} = EF_{POCP} \times Amt_{POC}$	none	amount of each smog-creating chemical released to air
Acidification	$IS_{AP} = EF_{AP} \times Amt_{AC}$	none	amount of each acidification chemical released to air
Air quality (particulate matter)	$IS_{PM} = Amt_{PM}$	none	amount of particulates: PM_{10} or TSP released to air [a]

[a] Assumes PM_{10} and TSP are equal; however, using TSP will overestimate PM_{10}.

Table 3-6 presents the impact categories, impact score equations, and required inventory data for abiotic environmental impacts to water resources.

Table 3-6. Summary of water resource impact scoring

Impact Category	Impact Score Approach	Data Required from Inventory (per functional unit)	
		Inputs	Outputs
Water eutrophication	$IS_{EUTR} = EF_{EP} \times Amt_{EC}$	none	amount of each eutrophication chemical released to water
Water quality (BOD)	$IS_{BOD} = Amt_{BOD}$	none	amount of BOD in each wastewater stream released to surface water
Water quality (TSS)	$IS_{TSS} = Amt_{TSS}$	none	amount of suspended solids (TSS) in each wastewater stream released to surface water

Table 3-7 summarizes the human health and ecotoxicity impact scoring approaches. The impact categories, impact score equations, the type of inventory data, and the chemical properties required to calculate impact scores are presented. The human health effects and ecotoxicity impact scores are based on the scoring of inherent properties approach to characterization.

Table 3-7. Summary of human health and ecotoxicity impact scoring

Impact Category	Impact Score Equations	Data Required from Inventory (per functional unit)		Chemical Properties Data Required
		Inputs	Outputs	
Chronic human health effects - occupational	$IS_{CHO} = (HV_{CA} + HV_{NC}) \times Amt_{TCinput}$	mass of each primary and ancillary toxic chemical	none	WOE or SF and/or mammal NOAEL or LOAEL
Chronic human health effects - public	$IS_{CHP} = (HV_{CA} + HV_{NC}) \times Amt_{TCoutput}$	none	mass of each toxic chemical released to air and surface water	WOE or SF and/or mammal NOAEL or LOAEL
Aesthetic impacts (odor)	$IS_{AS} = Amt_{OC} / OTV$	none	mass of odorous chemicals released to air	human odor threshold values
Aquatic toxicity	$IS_{AQ} = (HV_{FA} + HV_{FC}) \times Amt_{TCoutput,water}$	none	mass of each toxic chemical released to surface water	fish LC_{50} and/or fish NOAEL
Terrestrial toxicity	$IS_{TER} = HV_{NC} \times Amt_{TCoutput}$	none	mass of each toxic chemical released to air or surface water	mammal NOAEL

3.1.2.15 Aggregation of impact scores

Individual impact scores are calculated for inventory items for a certain impact category and can be aggregated by inventory item (e.g., a certain chemical), process, life-cycle stage, or entire product profile. For example, global warming impacts can be calculated for one inventory item (e.g., CO_2 releases), for one process that could include contributions from several inventory items (e.g., electricity generation), for a life-cycle stage that may consist of several process steps (e.g., product manufacturing), or for an entire profile (e.g., a CRT desktop monitor over its life).

The following example illustrates how impacts are calculated. If two toxic chemicals [e.g., toluene and benzo(a)pyrene] are included in a waterborne release to surface water from Process A, impact scores would be calculated for the following impact categories (based on the classification shown in Table 3-1):

- Chronic public health effects;
- Aquatic toxicity; and
- Terrestrial toxicity.

Despite the output types being waterborne releases, the water eutrophication and water quality impact categories are not applicable here because the chemical properties criteria in Table 3-1 are not met. That is, these chemicals do not contain N or P and are not themselves wastewater streams.

Using chronic public health effects as an example, impact scores are then calculated for each chemical as follows:

$$IS_{CHP:toluene} = (HV_{CA:toluene} + HV_{NC:toluene}) \times Amt_{TCoutput:toluene}$$

$$IS_{CHP:benzo(a)pyrene} = (HV_{CA:benzo(a)pyrene} + HV_{NC:benzo(a)pyrene}) \times Amt_{TCoutput:benzo(a)pyrene}$$

Table 3-8 presents toxicity data for the example chemicals from Appendix K, Table K-8. Using benzo(a)pyrene as an example, the hazard values are calculated as follows:

Table 3-8. Toxicity data used in example calculations

Chemical	Cancer		Chronic noncancer effects	
	Weight of evidence	Slope factor (SF) $(mg/kg\text{-}day)^{-1}$	Oral (mg/kg-day)	Inhalation (mg/m^3)
Toluene	D, 3	none	100[b]	411.1[b]
Benzo(a)pyrene	B2, 2A	3.1[a] 7.3[c]	no data	no data

[a] inhalation SF
[b] NOAEL
[c] oral SF

Cancer effects:

$$oral: \quad (HV_{CA_{oral}})_i = \frac{oral\ SF_i}{oral\ SF_{mean}}$$

$HV_{CAoral:benzo(a)pyrene}$ $= 7.3\ (mg/kg\text{-}day)^{-1} \div 0.71\ (mg/kg\text{-}day)^{-1}$
$= 10.3$

$$inhalation: \quad (HV_{CA_{inh}})_i = \frac{inhalation\ SF_i}{inhalation\ SF_{mean}}$$

$HV_{CAinhalation:benzo(a)pyrene}$ $= 3.1\ (mg/kg\text{-}day)^{-1} \div 1.7\ (mg/kg\text{-}day)^{-1}$
$= 1.82$

Thus, the cancer HV is 10.3, the greater of the two values.

Noncancer effects:

Since no data are available for noncancer effects, a default HV of one is assigned, representative of mean toxicity.

Total HV:

Thus the total hazard value for benzo(a)pyrene is given by:

$HV_{benzo(a)pyrene}$ $= HV_{CA} + HV_{NC}$
$= 10.3 + 1$
$= 11.3$

Similarly, the HV for toluene is found to be 0.12. Given the following hypothetical output amounts:

$Amt_{TC\text{-}O:TOLUENE}$ = 1.3 kg of toluene per functional unit
$Amt_{TC\text{-}O:BENZO(A)PYRENE}$ = 0.1 kg of benzo(a)pyrene per functional unit

the resulting impact scores are as follows:

$IS_{CHP\text{-}W:TOLUENE}$ = 0.12 x 1.3 = 0.16 tox-kg of toluene per functional unit
$IS_{CHP\text{-}W:BENZO(A)PYRENE}$ = 11.3 x 0.1 = 1.13 tox-kg of benzo(a)pyrene per functional unit

If these were the only outputs from Process A relevant to chronic public health effects, the total impact score for this impact category for Process A would be:

$$IS_{CHP:PROCESS_A} = IS_{CHP\text{-}W:TOLUENE} + IS_{CHP\text{-}W:BENZO(A)PYRENE}$$
$$= 0.16 + 1.13$$
$$= 1.29 \text{ tox-kg per functional unit for Process A.}$$

If the product system Y contained three processes altogether (Processes A, B, and C), and the impact scores for Process B and C were 2.5 and 3.0, respectively, impact scores would be added together to yield a total impact score for the product system relevant to chronic public health effects:

$$IS_{CHP:PROFILE_Y} = IS_{CHP:PROCESS_A} + IS_{CHP:PROCESS_B} + IS_{CHP:PROCESS_C}$$
$$= 1.29 + 2.5 + 3.0$$
$$= 6.8 \text{ tox-kg per functional unit for Profile Y.}$$

An environmental profile would then be the sum of all the processes within that profile for each impact category.

3.1.3 Data Sources and Data Quality

Data that are used to calculate impacts are from: (1) equivalency factors or parameters used to identify hazard values; and (2) LCI items. Equivalency factors and data used to develop hazard values, which have been presented in this methodology, include GWP, ODP, POCP, AP, EP, WOE, SF, mammalian LOAEL/NOAEL, OTV, fish LC_{50}, and fish NOAEL. Published lists of the chemical-specific parameter values exist for GWP, ODP, POCP, AP, EP and OTV (see Appendix K). The other parameters may exist for a large number of chemicals and several data sources must be searched to identify the appropriate parameter values. Priority is given to peer-reviewed databases (e.g., HEAST, IRIS, HSDB), then other databases (e.g., RTECS), other studies or literature, and finally estimation methods [e.g., structure-activity relationships (SARs) or quantitative structure-activity relationships (QSARs)]. The specific toxicity data that are used in the CDP are presented in Appendix K, Table K-8. The sources of each parameter presented in this report, and the basis for their values, are presented in Table 3-9. Data quality is affected by the type of data source (e.g., primary versus secondary data), the currency of the data, and the accuracy and precision of the data, and will depend on the source. The sources and quality of the LCI data used to calculate impact scores were discussed in Chapter 2. Data sources and data quality for each impact category are discussed further in Section 3.3, Baseline LCIA Results.

3.1.4 Limitations and Uncertainties

This section summarizes some of the limitations and uncertainties in LCIA methodology, in general. Specific limitations and uncertainties in each impact category are discussed in Section 3.3 with the baseline LCIA results.

The purpose of an LCIA is to evaluate the *relative potential* impacts of a product system for various impact categories. There is no intent to measure the *actual* impacts or provide spatial

or temporal relationships linking the inventory to specific impacts. The LCIA is intended to provide a screening-level evaluation of impacts. More detailed characterization of exposure and toxicity has been conducted on selected materials for the CDP in Chapter 4.

Table 3-9. Data sources for equivalency factors and hazard values

Parameter	Basis of Parameter Values	Source
Global warming potential (GWP)	atmospheric lifetimes and radiative forcing compared to CO_2	Houghton *et al.*, 1996
Ozone depletion potential (ODP)	the change in the ozone column in the equilibrium state of a substance compared to CFC-11	Heijungs *et al.*, 1992; CAAA, 1990
Photochemical oxidant creation potential (POCP)	simulated trajectories of ozone production with and without VOCs present compared to ethene	Heijungs *et al.*, 1992
Acidification potential (AP)	number of hydrogen ions that can theoretically be formed per mass unit of the pollutant being released compared to SO_2	Heijungs *et al.*, 1992; Hauschild and Wenzel, 1997
Nutrient enrichment/eutrophication potential (EP)	ratio of N to P in the average composition of algae ($C_{106}H_{263}O_{110}N_{16}P$) compared to phosphate (PO_4^{3-})	Heijungs *et al.*, 1992; Lindfors *et al.*, 1995
Weight-of-evidence (WOE)	classification of carcinogenicity by EPA or IARC based on human and/or animal toxicity data	EPA, 1999; IARC, 1998
Slope factor (SF)	measure of an individual's excess risk or increased likelihood of developing cancer if exposed to a chemical, based on dose-response data	IRIS and HEAST as cited in Risk Assessment Information System (RAIS) online database
Mammalian: Lowest observed adverse effect level / No observed adverse effect level (LOAEL/NOAEL)	mammalian (primarily rodent) toxicity studies	IRIS, HEAST and various literature sources provided by EPA contractor
Fish lethal concentration to 50% of the exposed population (LC_{50})	fish (primarily fathead minnow) toxicity studies	Various literature sources and Ecotox database
Fish NOAEL	fish (primarily fathead minnow) toxicity studies	Literature sources and Ecotox database
Odor threshold value (OTV)	measured odor thresholds in humans	EPA, 1992

In addition to lacking temporal or spatial relationships and providing only relative impacts, LCA is also limited by the availability and quality of the inventory data. Data collection can be very time consuming and expensive. Confidentiality issues may also inhibit the availability of primary data.

Uncertainties are inherent in each parameter described in Table 3-9 and the reader is referred to each source for more information on associated uncertainties. For example, toxicity data require extrapolations from animals to humans and from high to low doses (for chronic effects) and can have a high degree of uncertainty.

Uncertainties also are inherent in chemical ranking and scoring systems, such as the scoring of inherent properties approach used for human health and ecotoxicity effects. In particular, systems that do not consider the fate and transport of chemicals in the environment can contribute to misclassifications of chemicals with respect to risk. Also, uncertainty is introduced where it was assumed that all chronic endpoints are equivalent, which is likely not the case. In addition, when LOAELs were not available but NOAELs were, a factor of ten was applied to the NOAEL to estimate the LOAEL, introducing uncertainty. The human health and ecotoxicity impact characterization methods presented here are screening tools that cannot substitute for more detailed risk characterization methods. However, it should be noted that in LCA, chemical toxicity is often not considered at all. This methodology is an attempt to consider chemical toxicity where it is often ignored.

Uncertainty in the inventory data depends on the responses to the data collection questionnaires and other limitations identified during inventory data collection. These uncertainties are carried into impact assessment. In this LCA, there was uncertainty in the inventory data, which included but was not limited to the following:

- missing individual inventory items,
- missing processes or sets of data,
- measurement uncertainty,
- estimation uncertainty,
- allocation uncertainty/working with aggregated data, and
- unspeciated chemical data.

The goal definition and scoping process helped reduce the uncertainty from missing data, although it is certain that some (missing data) still exist. As far as possible, the remaining uncertainties were reduced primarily through quality assurance/quality control measures (e.g., performing systematic double-checks of all calculations on manipulated data). The limitations and uncertainties in the inventory data were discussed further in Chapter 2.

3.2 DATA MANAGEMENT AND ANALYSIS SOFTWARE

The inventory and chemical characteristics data for the CDP are stored in a database within a software package developed by UT, using the Microsoft Visual FoxPro application programming language, under a cooperative agreement with the EPA Office of Research and Development. The software package calculates impact scores based on the stored inventory and chemical data and on the appropriate formulas for each impact category, as presented in Section 3.1.

3.3 BASELINE LCIA RESULTS

This section presents the baseline LCIA results calculated using the impact assessment methodology presented in Section 3.1. As noted in the section on baseline LCI results (Section 2.7.1), the baseline scenario meets the following conditions:

- uses the effective life use stage scenario (e.g., use stage calculations are based on the actual amount of time a monitor is used by one or multiple users before it reaches its final disposition);
- uses the average value of all the energy inputs from the primary data for glass manufacturing;
- removes two outliers from the primary data for energy inputs during LCD panel/module manufacturing and then uses the average of the remaining energy inputs;
- excludes transportation in the manufacturing stage, but includes any transportation embedded in upstream data sets;
- includes the manufacturing processes of materials used as fuels (e.g., natural gas, fuel oil) in the manufacturing stage instead of in the upstream, materials processing stage. In cases where materials normally considered to be fuels are used as ancillary materials, their manufacturing processes are included with other upstream processes; and
- assumes LCD glass manufacturing processes use the same amounts of energy as CRT glass manufacturing per kilogram of glass produced.

Section 3.3.1 summarizes the baseline life cycle impact category indicators for both the CRT and LCD. Sections 3.3.2 through 3.3.14 present a breakdown of the impact category indicators by life-cycle stage, list the materials that contribute 99% of the total for both monitor types, and discuss limitations and uncertainties in each impact category. Each of the tables in this report shows the top contributors to the impacts because the complete tables, which are provided in Appendix J, are often lengthy. Section 3.3.15 summarizes the top contributors to each impact category, and Appendix M presents complete LCIA results.

3.3.1 Summary of Baseline LCIA Results

Table 3-10 presents the baseline CRT and LCD LCIA indicator results for each impact category, calculated using the impact assessment methodology presented in Section 3.1. The indicator results presented in the table are the result of the characterization step of LCIA methodology where LCI results are converted to common units and aggregated within an impact category. Note that the impact category indicator results are in a number of different units and therefore can not be summed or compared across impact categories. Note also that the CDP LCIA methodology does not perform the optional LCIA steps of normalization (calculating the magnitude of category indicator results relative to a reference value), grouping (sorting and possibly ranking of indicators), or weighting (converting and possibly aggregating indicator results across impact categories). Ranking and weighting, in particular, are subjective steps that depend on the values of the different individuals, organizations, or societies performing the analysis. Since the CDP involves a variety of stakeholders from different geographic regions and with different values, these more subjective steps were intentionally excluded from the CDP LCIA methodology.

Table 3-10. Baseline life-cycle impact category indicators[a]

Impact category	Units per monitor	CRT	LCD
Renewable resource use	kg	**1.31E+04**	2.80E+03
Nonrenewable resource use	kg	**6.68E+02**	3.64E+02
Energy use	MJ	**2.08E+04**	2.84E+03
Solid waste landfill use	m^3	**1.67E-01**	5.43E-02
Hazardous waste landfill use	m^3	**1.68E-02**	3.61E-03
Radioactive waste landfill use	m^3	**1.81E-04**	9.22E-05
Global warming	kg-CO_2 equivalents	**6.95E+02**	5.93E+02
Ozone depletion	kg-CFC-11 equivalents	2.05E-05[b,c]	1.37E-05[b]
Photochemical smog	kg-ethene equivalents	**1.71E-01**	1.41E-01
Acidification	kg-SO_2 equivalents	**5.25E+00**	2.96E+00
Air particulates	kg	**3.01E-01**	1.15E-01
Water eutrophication	kg-phosphate equivalents	4.82E-02	**4.96E-02**
Water quality, BOD	kg	**1.95E-01**	2.83E-02
Water quality, TSS	kg	**8.74E-01**	6.15E-02
Radioactivity	Bq	**3.85E+07**[d]	1.22E+07[d]
Chronic health effects, occupational	tox-kg	**9.34E+02**	6.96E+02
Chronic health effects, public	tox-kg	**1.98E+03**	9.02E+02
Aesthetics (odor)	m^3	**7.58E+06**	5.04E+06
Aquatic toxicity	tox-kg	2.25E-01	**5.19E+00**
Terrestrial toxicity	tox-kg	**1.97E+03**	8.94E+02

[a] Bold indicates the larger value within an impact category when comparing the CRT and LCD.

[b] Several of the substances included in this category were phased out of production by January 1, 1996. Excluding phased out substances decreases the CRT ozone depletion indicator to 1.09E-05 kg CFC-11 equivalents per monitor and the LCD ozone depletion indicator to 1.18E-05 kg CFC-11 equivalents per monitor. These ozone depletion indicators are probably more representative of the CDP temporal boundaries and current operating practices. See Section 3.3.6 for details.

[c] Although the CRT indicator appears larger than the LCD indicator, uncertainties in the inventory make it difficult to determine which monitor has the greater value. Therefore, this value is not shown in bold.

[d] Radioactivity impacts are being driven by radioactive releases from nuclear fuel reprocessing in France, which are included in the electricity data in some of the upstream, materials processing data sets. See Section 3.3.12 for details.

As shown in the table, under the baseline conditions the CRT indicators are greater than the LCD indicators in the following categories: renewable resource use, nonrenewable resource use, energy use, solid waste landfill use, hazardous waste landfill use, radioactive waste landfill use, global warming, photochemical smog, acidification, air particulates, biological oxygen demand (BOD), total suspended solids (TSS), radioactivity, chronic public health effects, chronic occupational health effects, aesthetics, and terrestrial toxicity. The LCD indicators are greater than the CRT indicators in the following categories: water eutrophication and aquatic toxicity. In addition, as noted in Table 3-10, the CRT ozone depletion indicator is greater than that of the LCD when phased out substances are left in the CRT and LCD inventories. However, if phased

out substances are removed from the CRT and LCD inventories, the LCD ozone depletion indicator would exceed that of the CRT.

A number of the impact results for both monitor types, and for the CRT in particular, are being driven by a few data points with relatively high uncertainty. Therefore, sensitivity analyses of the baseline results are presented in Section 3.4.

3.3.2 Renewable and Nonrenewable Resource Use

3.3.2.1 Renewable resource use

Figure 3-2 presents the CRT and LCD impact category indicators for renewable resource use by life-cycle stage, based on the impact assessment methodology presented in Section 3.1.2.1. Tables M-1 and M-2 in Appendix M present complete renewable resource results for the CRT and LCD, respectively. A renewable resource is one that is being replenished at a rate greater than or equal to its rate of depletion. Note that several of the resources listed in the Appendix and in the tables that follow are not renewable or can not be replenished, *per se*, but are considered renewable since they can be restored or are present in nearly infinite, non-depletable amounts. For example, water is typically considered a renewable resource since it can be restored to potable quality and is therefore being "replenished" at a rate greater than or equal to its rate of depletion. However, current trends toward shortages of potable water suggest that water might be more appropriately classified as a nonrenewable resource.

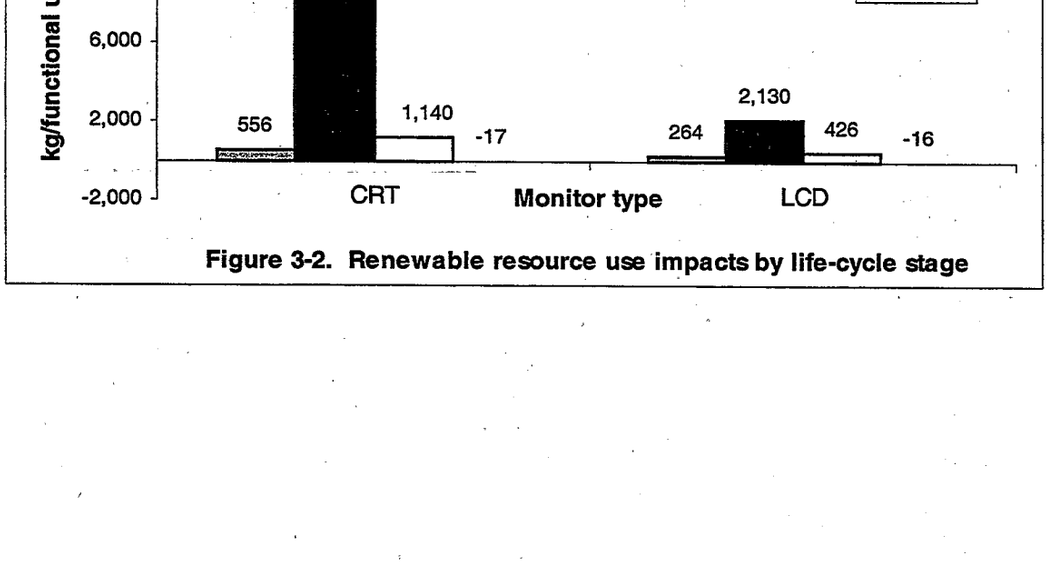


Figure 3-2. Renewable resource use impacts by life-cycle stage

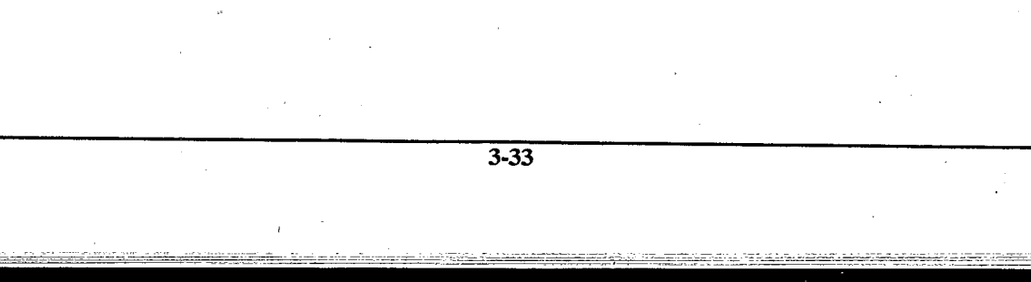


Figure 3-3. Nonrenewable resource use impacts by life-cycle stage

As shown in Figure 3-2, the baseline life-cycle impact category indicator for renewable resource use is 13,100 kg per monitor for the CRT and 2,800 kg per monitor for the LCD. Both the CRT and LCD renewable resource use results are dominated by the manufacturing life-cycle stage, with manufacturing accounting for 87% and 76% of the CRT and LCD totals, respectively.

Table 3-11 presents the life-cycle inventory items that contribute to the top 99% of the CRT renewable resource use total. It also lists the LCI data type (primary, secondary, or model/secondary). As shown in Table 3-11, water used in the production of LPG clearly dominates the CRT renewable resource use impact score. LPG is primarily used as an energy source in CRT glass manufacturing, indicating that the glass/frit process group is ultimately the greatest contributor to the CRT renewable resource use impact score. Other significant contributors include water used to produce electricity in the United States during the use of the monitor, water used in CRT tube manufacturing, and water used in the production of steel. The LCI data for LPG production and steel manufacturing are from secondary sources, while the LCI

the end of its effective life. The latter value is based on the assumption that 50% of LCDs are sent to a solid waste landfill at the end of their effective lives.

Table 3-19. Top 99% of the LCD solid waste landfill use impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Use	U.S. electric grid	Coal waste	Model/secondary	44%
Use	U.S. electric grid	Dust/sludge	Model/secondary	13%
Use	U.S. electric grid	Fly/bottom ash	Model/secondary	11%
Materials processing	Steel production, cold-rolled, semi-finished	Unspecified solid waste	Secondary	9.9%
Materials processing	Natural gas production	Slag and ash	Secondary	7.7%
Manufacturing	LCD monitor/module mfg.	Waste water treatment sludge	Primary	5.6%
Manufacturing	Japanese electric grid	Coal waste	Model/secondary	5.0%
End-of-Life	LCD landfilling	EOL LCD monitor, landfilled	Primary	3.5%

*Column adds to greater than 100% due to a credit from incineration with energy recovery during the EOL life-cycle stage.

LCI data for LCD monitor/module manufacturing were collected by the CDP, and LCD solid waste disposal volumes were estimated by the CDP based on the amounts and density of LCD materials assumed to be disposed of in a solid waste landfill. Like the CRT, data for other process groups either were modeled by the CDP from secondary data sources or came from secondary sources. As discussed above for the CRT, the materials processing inventories from secondary sources (i.e., *Ecobilan*) include electricity generation within the materials manufacturing processes. The different inventories used in this project have varying nomenclature and some of the solid waste materials listed in the table may indeed overlap.

3.3.4.2 Hazardous waste landfill use

Figure 3-6 presents the CRT and LCD LCIA results for the hazardous waste landfill use impact category, based on the impact assessment methodology presented in Section 3.1.2.3. Tables M-9 and M-10 (see Appendix M) present complete hazardous waste landfill use results for the CRT and LCD, respectively. Hazardous waste landfill use impacts are characterized from hazardous waste outputs with a disposition of landfill, which includes about 83% of the 9.46 kg of hazardous waste/functional unit generated by the CRT life cycle and about 27% of the 6.3 kg/functional unit generated by the LCD life cycle. This consumes approximately 0.017 m^3 of hazardous waste landfill space for the CRT and 0.036 m^3 for the LCD, based on the mass and densities of the various materials. The results for both monitor types are dominated by monitor disposal at the end of its effective life. Approximately 46% of CRTs and 5% of LCDs are assumed to be landfilled as hazardous waste (see Section 2.5 and Appendix I).

out substances are removed from the CRT and LCD inventories, the LCD ozone depletion indicator would exceed that of the CRT.

A number of the impact results for both monitor types, and for the CRT in particular, are being driven by a few data points with relatively high uncertainty. Therefore, sensitivity analyses of the baseline results are presented in Section 3.4.

3.3.2 Renewable and Nonrenewable Resource Use

3.3.2.1 Renewable resource use

Figure 3-2 presents the CRT and LCD impact category indicators for renewable resource use by life-cycle stage, based on the impact assessment methodology presented in Section 3.1.2.1. Tables M-1 and M-2 in Appendix M present complete renewable resource results for the CRT and LCD, respectively. A renewable resource is one that is being replenished at a rate greater than or equal to its rate of depletion. Note that several of the resources listed in the Appendix and in the tables that follow are not renewable or can not be replenished, *per se*, but are considered renewable since they can be restored or are present in nearly infinite, non-depletable amounts. For example, water is typically considered a renewable resource since it can be restored to potable quality and is therefore being "replenished" at a rate greater than or equal to its rate of depletion. However, current trends toward shortages of potable water suggest that water might be more appropriately classified as a nonrenewable resource.

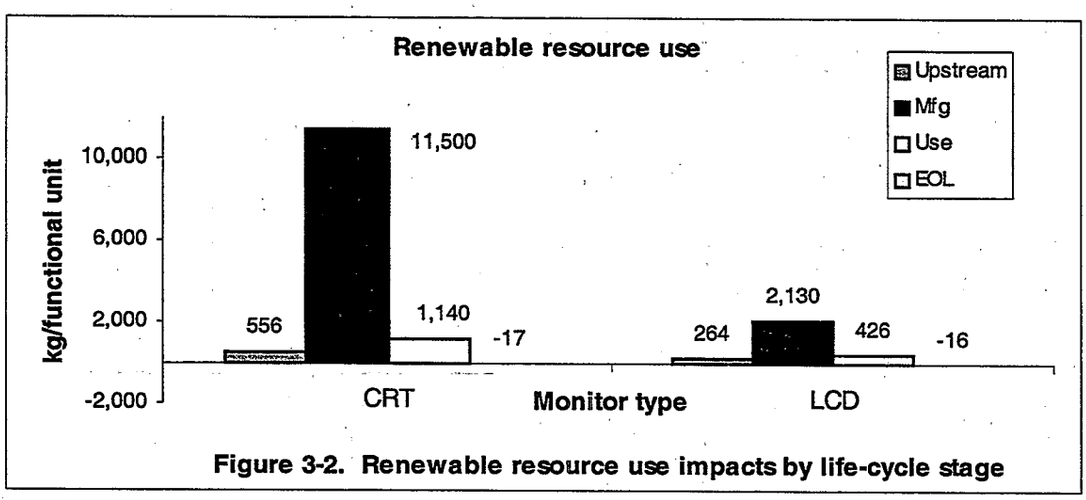


Figure 3-2. Renewable resource use impacts by life-cycle stage

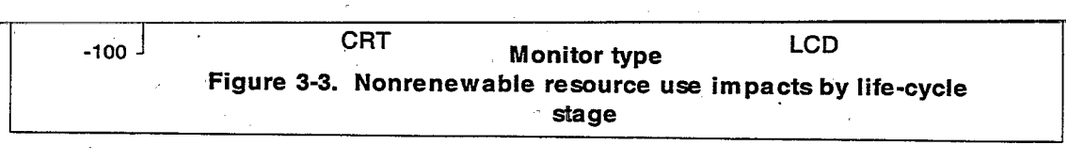


Figure 3-3. Nonrenewable resource use impacts by life-cycle stage

As shown in Figure 3-2, the baseline life-cycle impact category indicator for renewable resource use is 13,100 kg per monitor for the CRT and 2,800 kg per monitor for the LCD. Both the CRT and LCD renewable resource use results are dominated by the manufacturing life-cycle stage, with manufacturing accounting for 87% and 76% of the CRT and LCD totals, respectively.

Table 3-11 presents the life-cycle inventory items that contribute to the top 99% of the CRT renewable resource use total. It also lists the LCI data type (primary, secondary, or model/secondary). As shown in Table 3-11, water used in the production of LPG clearly

the end of its effective life. The latter value is based on the assumption that 50% of LCDs are sent to a solid waste landfill at the end of their effective lives.

Table 3-19. Top 99% of the LCD solid waste landfill use impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Use	U.S. electric grid	Coal waste	Model/secondary	44%
Use	U.S. electric grid	Dust/sludge	Model/secondary	13%
Use	U.S. electric grid	Fly/bottom ash	Model/secondary	11%
Materials processing	Steel production, cold-rolled, semi-finished	Unspecified solid waste	Secondary	9.9%
Materials processing	Natural gas production	Slag and ash	Secondary	7.7%
Manufacturing	LCD monitor/module mfg.	Waste water treatment sludge	Primary	5.6%
Manufacturing	Japanese electric grid	Coal waste	Model/secondary	5.0%
End-of-Life	LCD landfilling	EOL LCD monitor, landfilled	Primary	3.5%

*Column adds to greater than 100% due to a credit from incineration with energy recovery during the EOL life-cycle stage.

LCI data for LCD monitor/module manufacturing were collected by the CDP, and LCD solid waste disposal volumes were estimated by the CDP based on the amounts and density of LCD materials assumed to be disposed of in a solid waste landfill. Like the CRT, data for other process groups either were modeled by the CDP from secondary data sources or came from secondary sources. As discussed above for the CRT, the materials processing inventories from secondary sources (i.e., *Ecobilan*) include electricity generation within the materials manufacturing processes. The different inventories used in this project have varying nomenclature and some of the solid waste materials listed in the table may indeed overlap.

3.3.4.2 Hazardous waste landfill use

Figure 3-6 presents the CRT and LCD LCIA results for the hazardous waste landfill use impact category, based on the impact assessment methodology presented in Section 3.1.2.3. Tables M-9 and M-10 (see Appendix M) present complete hazardous waste landfill use results for the CRT and LCD, respectively. Hazardous waste landfill use impacts are characterized from hazardous waste outputs with a disposition of landfill, which includes about 83% of the 9.46 kg of hazardous waste/functional unit generated by the CRT life cycle and about 27% of the 6.3 kg/functional unit generated by the LCD life cycle. This consumes approximately 0.017 m^3 of hazardous waste landfill space for the CRT and 0.036 m^3 for the LCD, based on the mass and densities of the various materials. The results for both monitor types are dominated by monitor disposal at the end of its effective life. Approximately 46% of CRTs and 5% of LCDs are assumed to be landfilled as hazardous waste (see Section 2.5 and Appendix I).

out substances are removed from the CRT and LCD inventories, the LCD ozone depletion indicator would exceed that of the CRT.

A number of the impact results for both monitor types, and for the CRT in particular, are being driven by a few data points with relatively high uncertainty. Therefore, sensitivity analyses of the baseline results are presented in Section 3.4.

3.3.2 Renewable and Nonrenewable Resource Use

3.3.2.1 Renewable resource use

Figure 3-2 presents the CRT and LCD impact category indicators for renewable resource use by life-cycle stage, based on the impact assessment methodology presented in Section 3.1.2.1. Tables M-1 and M-2 in Appendix M present complete renewable resource results for the CRT and LCD, respectively. A renewable resource is one that is being replenished at a rate greater than or equal to its rate of depletion. Note that several of the resources listed in the Appendix and in the tables that follow are not renewable or can not be replenished, *per se*, but are considered renewable since they can be restored or are present in nearly infinite, non-depletable amounts. For example, water is typically considered a renewable resource since it can be restored to potable quality and is therefore being "replenished" at a rate greater than or equal to its rate of depletion. However, current trends toward shortages of potable water suggest that water might be more appropriately classified as a nonrenewable resource.

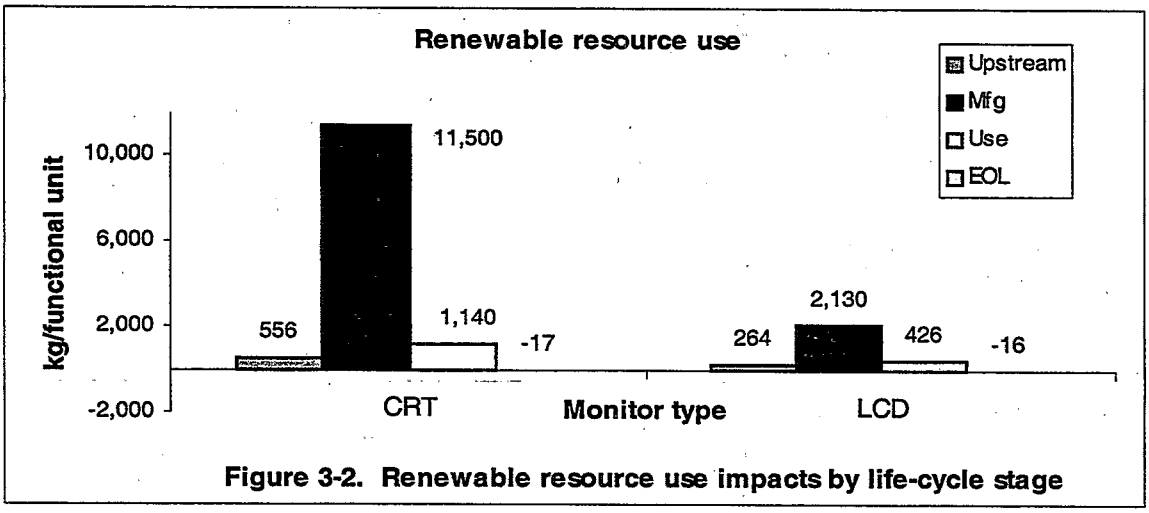


Figure 3-2. Renewable resource use impacts by life-cycle stage

As shown in Figure 3-2, the baseline life-cycle impact category indicator for renewable resource use is 13,100 kg per monitor for the CRT and 2,800 kg per monitor for the LCD. Both the CRT and LCD renewable resource use results are dominated by the manufacturing life-cycle stage, with manufacturing accounting for 87% and 76% of the CRT and LCD totals, respectively.

Table 3-11 presents the life-cycle inventory items that contribute to the top 99% of the CRT renewable resource use total. It also lists the LCI data type (primary, secondary, or model/secondary). As shown in Table 3-11, water used in the production of LPG clearly dominates the CRT renewable resource use impact score. LPG is primarily used as an energy source in CRT glass manufacturing, indicating that the glass/frit process group is ultimately the greatest contributor to the CRT renewable resource use impact score. Other significant contributors include water used to produce electricity in the United States during the use of the monitor, water used in CRT tube manufacturing, and water used in the production of steel. The LCI data for LPG production and steel manufacturing are from secondary sources, while the LCI data for the U.S. electric grid are based on the model developed by the CDP for the amount of electricity consumed by a CRT during use combined with data from secondary sources on the inputs and outputs from U.S. power plants. CRT tube manufacturing LCI data are primary data collected by the CDP.

Table 3-11. Top 99% of the CRT renewable resource use impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Manufacturing	LPG production	Water	Secondary	79%
Use	U.S. electric grid	Water	Model/secondary	8.7%
Manufacturing	CRT tube manufacturing	Water	Primary	6.2%
Materials processing	Steel production, cold-rolled, semi-finished	Water	Secondary	3.6%
Manufacturing	Japanese electric grid	Water	Model/secondary	0.34%
Manufacturing	PWB manufacturing	Water	Primary	0.32%

* Column may not add to 99% due to rounding.

Table 3-12 presents the inventory items contributing to the top 99% of the LCD renewable resource use total and the LCI data types (primary, secondary, or model/secondary). As shown in the table, water used in LCD module/monitor manufacturing is the greatest contributor to the LCD renewable resource use impact score. Other significant contributors include water used in the production of LPG, water used by the U.S. electric grid during the use life-cycle stage, and water used in steel production. It is LCD glass manufacturing that consumes the LPG responsible for the high LCD renewable resource use score. The LCI data for LCD module manufacturing are primary data collected by the CDP. LPG production and steel manufacturing are from secondary sources, while the LCI data for the U.S electric grid are based on the model developed by the CDP for the amount of electricity consumed by an LCD during the use stage combined with data from secondary sources.

Table 3-12. Top 99% of the LCD renewable resource use impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Manufacturing	LCD module/monitor mfg.	Water	Primary	38%
Manufacturing	LPG production	Water	Secondary	18%
Use	U.S. electric grid	Water	Model/secondary	15%
Materials processing	Steel production (cold-rolled, semi-finished)	Water	Secondary	8.2%
Manufacturing	LCD panel components	Water	Primary	6.4%
Manufacturing	Backlight	Water	Primary	6.8%
Manufacturing	Japanese electric grid	Water	Model/secondary	5.3%
Manufacturing	PWB Manufacturing	Water	Primary	0.66%

* Column may not add to 99% due to rounding.

3.3.2.2 Nonrenewable resource use

Figure 3-3 presents the CRT and LCD impact category indicators for nonrenewable resource use by life-cycle stage, based on the impact assessment methodology presented in Section 3.1.2.1. Tables M-3 and M-4 in Appendix M present complete nonrenewable resource results for the CRT and LCD, respectively. The total nonrenewable resource use indicator was 668 kg per monitor for the CRT and 364 kg per monitor for the LCD. As shown in Figure 3-3, the CRT nonrenewable resource use results are dominated by the manufacturing life-cycle stage, which contributed 68% of the total. The LCD nonrenewable resource use score is dominated by the upstream materials processing stages, which contributed 69% of the total.

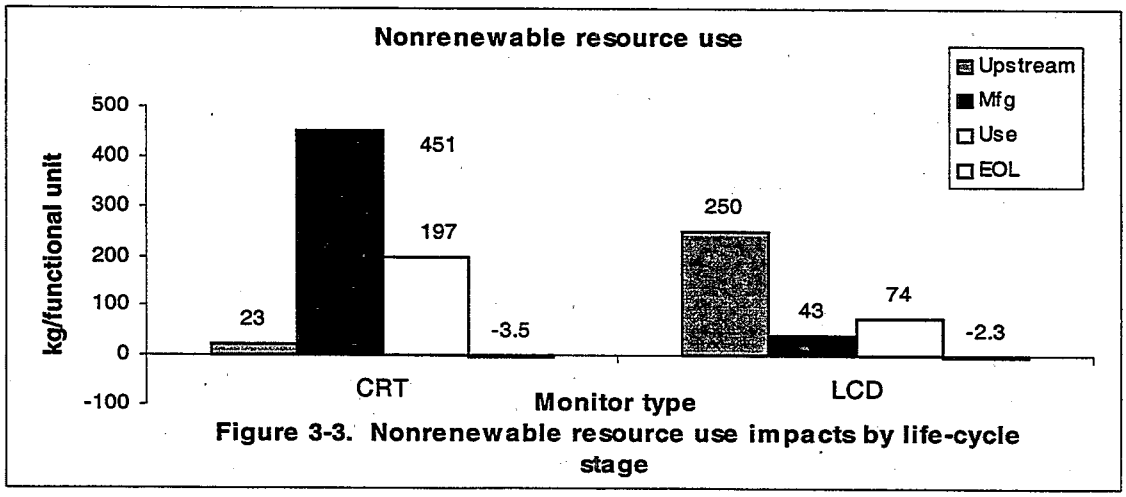


Figure 3-3. Nonrenewable resource use impacts by life-cycle stage

Table 3-13 presents the inventory items contributing to the top 99% of the CRT nonrenewable resource use impact score. It also lists the LCI data type (primary, secondary, or model/secondary). Similar to the renewable resource use LCIA results, the LPG production process, which mainly supports the CRT glass manufacturing process, clearly dominates the CRT nonrenewable resource use impact score. Petroleum used to make LPG is the non-renewable resource being consumed by the LPG production process in the greatest amounts, followed by natural gas, and coal. Note that the LPG actually consumed during CRT glass manufacturing does not appear in the nonrenewable resource use results. This is because it was accounted for in the nonrenewable resource use score for the LPG production process when it was extracted from the ground.

Fuels (coal and natural gas) consumed by the U.S. electric grid during monitor use are also among the greatest contributors to the CRT nonrenewable resource use impact scores. The LCI data for LPG production are from secondary sources, while the LCI data for the U.S. electric grid are based on the model developed by the CDP for the amount of electricity consumed by a CRT during use combined with data from secondary sources on the inputs and outputs from U.S. power plants.

Table 3-13. Top 99% of the CRT nonrenewable resource use impact score

Life-cycle stage	Process group	Material*	LCI data type	Contribution to impact score*
Manufacturing	LPG production	Petroleum (in ground)	Secondary	56%
Use	U.S. electric grid	Coal, average (in ground)	Model/secondary	27%
Manufacturing	LPG production	Natural gas (in ground)	Secondary	6.7%
Use	U.S. electric grid	Natural gas	Model/secondary	2.1%
Manufacturing	LPG production	Coal, average (in ground)	Secondary	2.0%
Materials processing	Steel production, cold-rolled, semi-finished	Iron Ore	Secondary	0.99%
Materials processing	Steel production, cold-rolled, semi-finished	Coal, average (in ground)	Secondary	0.60%
Manufacturing	Fuel oil #6 production	Petroleum (in ground)	Secondary	0.58%
Use	U.S. electric grid	Petroleum (in ground)	Model/secondary	0.57%
Manufacturing	Natural gas production	Natural gas (in ground)	Secondary	0.51%
Manufacturing	U.S. electric grid	Coal, average (in ground)	Model/secondary	0.43%
Manufacturing	Japanese electric grid	Coal, average (in ground)	Model/secondary	0.34%
Materials processing	Aluminum production	Bauxite	Secondary	0.20%
Manufacturing	Japanese electric grid	Petroleum (in ground)	Model/secondary	0.19%
Materials processing	Polycarbonate production	Natural gas (in ground)	Secondary	0.19%
Manufacturing	Japanese electric grid	Natural gas	Model/secondary	0.19%

* Column may not add to 99% due to rounding.

Table 3-14 presents the inventory items contributing to the top 99% of the LCD non-renewable resource use impact score. In this case, the impact score is dominated by the natural gas extracted to produce natural gas in the upstream, materials processing life-cycle stage. Liquified natural gas (LNG) from this production process is used as an ancillary material in the LCD module/monitor manufacturing process group, indicating LCD module/monitor manufacturing is ultimately responsible for this non-renewable resource use. However, only one of the seven companies that provided data for the LCD module/monitor manufacturing process group reported this use of LNG. Note that the actual use of LNG in the LCD module/manufacturing process group does not appear in the nonrenewable resource results. Similar to the LPG results discussed above for the CRT, this is because it has been accounted for in the natural gas production process results.

Other primary contributors to this impact score include coal used to produce electricity for the U.S. electric grid, and petroleum used to produce LPG. The LCI data for all of the primary contributors to the LCD non-renewable resource use score were either from secondary sources or CDP models combined with secondary sources.

Table 3-14. Top 99% of the LCD nonrenewable resource use impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Materials processing	Natural gas production	Natural gas (in ground)	Secondary	65%
Use	U.S. electric grid	Coal, average (in ground)	Model/secondary	18%
Manufacturing	LPG production	Petroleum (in ground)	Secondary	4.9%
Manufacturing	Japanese electric grid	Coal, average (in ground)	Model/secondary	2.1%
Manufacturing	Natural gas production	Natural gas (in ground)	Secondary	1.5%
Use	U.S. electric grid	Natural gas	Model/secondary	1.4%
Manufacturing	Japanese electric grid	Petroleum (in ground)	Model/secondary	1.2%
Manufacturing	Japanese electric grid	Natural gas	Model/secondary	1.2%
Materials processing	Steel production (cold-rolled, semi-finished)	Iron ore	Secondary	0.89%
Manufacturing	LPG production	Natural gas (in ground)	Secondary	0.59%
Materials processing	Steel production (cold-rolled, semi-finished)	Coal (in ground)	Secondary	0.54%
Materials processing	Natural gas production	Coal (in ground)	Secondary	0.45%
Use	U.S. electric grid	Petroleum (in ground)	Model/secondary	0.39%

*Column may not add to 99% due to rounding

3.3.2.3 Limitations and uncertainties

The renewable and nonrenewable resource use results presented here are based on the mass of a material consumed. Depletion of renewable materials, which results from the extraction of renewable resources faster than they are renewed, may occur but is not specifically modeled or identified in the renewable resource impact scores. This may be particularly important for water, which, while considered a renewable resource, is in shorter and shorter supply as world population grows and more of the world's water resources become degraded.

For the nonrenewable materials use category, depletion of materials results from the extraction of nonrenewable resources. However, the impact scores do not directly relate consumption rates to the earth's ability to sustain that consumption.

The CRT and LCD impact scores for renewable resource use, and the CRT impact score for nonrenewable resources use, are being driven by the fuels consumed during CRT or LCD glass manufacturing. However, as discussed in Section 2.3.3.3, there is a high degree of variability in the three sets of CRT glass manufacturing energy data received by the CDP. Furthermore, as discussed in Section 2.3.3.1, LCD glass manufacturing data were developed from the CRT data because no companies were willing to supply the LCD data. Therefore, glass energy use inputs are uncertain for both the CRT and the LCD and were the subject of a sensitivity analysis, discussed in Section 3.4.

The LCD impact score for nonrenewable resource use is being driven by LNG used as an ancillary material during LCD module/monitor manufacturing. However, only one LCD module/monitor manufacturer reported using LNG as an ancillary material, which was confirmed by CDP researchers in follow-up communications. Given the fact that only one of seven manufacturers reported the ancillary use of LNG, the LCD nonrenewable resource use indicator may not be representative of the industry as a whole. If we remove this application of LNG from the LCD inventory, the LCD nonrenewable resource result is reduced by 66%, from 364 kg per monitor to 125 kg per monitor.

Inventory data for most of the materials contributing 99% of the CRT and LCD impact scores come from secondary sources, and were not developed specifically for the CDP. The limitations and uncertainties associated with secondary data sources are summarized in Section 2.2.2. Table 3-15 looks more closely at the LPG and natural gas production geographic and temporal boundaries. These are the production processes that are driving a large part of the CRT and LCD resources use indicators. As shown in the table, most of the LPG and natural gas production data are for the United States, although the LPG data set includes some data from other countries. Both data sets rely on several different sources and have different temporal boundaries. In particular, LPG production data are less recent, and may not accurately reflect current production practices. All of these factors create some inconsistencies among the data sets and reduce the data quality when used for the purposes of the CDP. However, this is a common difficulty with LCA, which often uses data from secondary sources to avoid the tremendous amount of time and resources required to collect all the needed data.

Table 3-15. LPG and natural gas production geographic and temporal boundaries

Production Process	Location	Source	Year
LPG production	Mainly U.S., but includes some other countries	Seven sources cited	1983 to 1993
Natural gas production	U.S.	Six sources cited	1987 to 1998

3.3.3 Energy Use

Figure 3-4 presents the CRT and LCD impact results for energy use by life-cycle stage, based on the impact assessment methodology presented in Section 3.1.2.2. Tables M-5 and M-6 in Appendix M list complete energy use results for the CRT and LCD, respectively. The total indicator for this impact category was 20,800 MJ per monitor for the CRT, and 2,840 MJ per monitor for the LCD.

CRTs generally are assumed to have greater life-cycle energy use impacts than the LCDs due to the high energy requirements in the use stage. This is borne out by the results in Figure 3-4, which show that CRT energy consumption during use is roughly 2.7 times that of the LCD. However, contrary to expectations, CRT energy use impacts are driven by the manufacturing life-cycle stage, which contributes about 88% of the total score. The use stage, which was expected to be responsible for a large amount of energy consumption impacts, only contributes about 11% of the total score. LCD energy consumption impacts are also largest in the manufacturing life-cycle stage which accounts for almost 51% of the impacts in this category. Both the use and upstream (materials processing) life-cycle stages are also significant contributors to LCD life-cycle energy use, accounting for 30 and 22%, respectively. Note that the sum of the upstream, manufacturing, and use life-cycle stages is greater than 100% due to an energy credit for incineration with energy recovery at the end of a monitor's useful life.

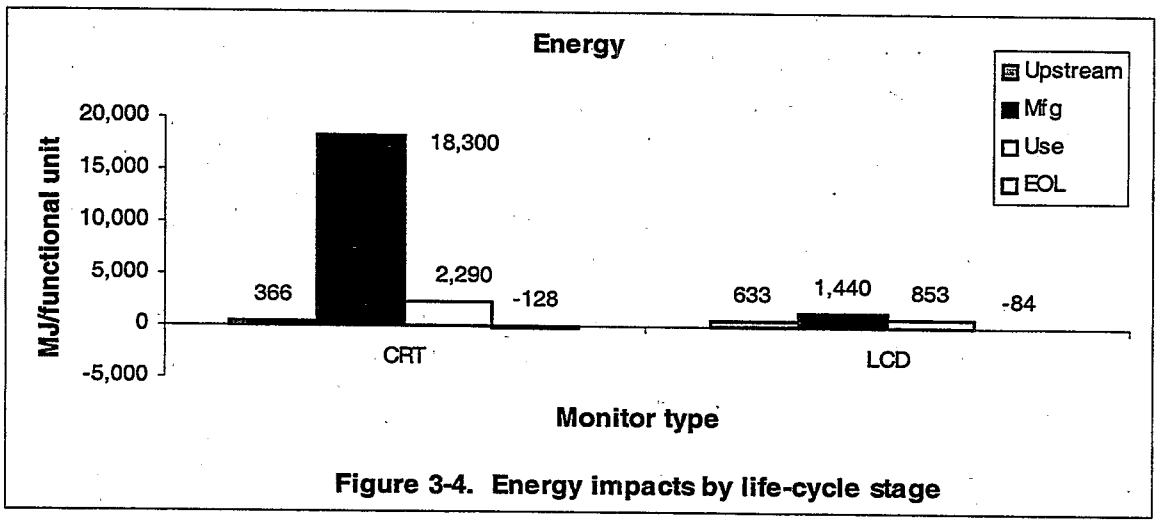


Figure 3-4. Energy impacts by life-cycle stage

3.3.3.1 Major contributors to the CRT energy use results

Table 3-16 presents the life-cycle inventory items contributing to the top 99% of the CRT energy use results and the LCI data type (primary, secondary, or model/secondary). As shown in the table, LPG used in the glass/frit process group, primarily from CRT glass manufacturing, clearly dominates the CRT energy use result, followed by electricity consumed during use of a CRT monitor, and natural gas, petroleum, and coal consumed during LPG production. Since LPG is used primarily as an energy source during CRT glass manufacturing, most of the sum of the glass/frit manufacturing and LPG production energy use impacts—roughly 87% of the CRT life-cycle energy use impacts—can be attributed to the CRT glass manufacturing process.

Table 3-16. Top 99% of the CRT energy use impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Manufacturing	Glass/frit manufacturing	Liquified petroleum gas	Primary	72%
Use	CRT monitor use	Electricity	Model/secondary	11%
Manufacturing	LPG production	Natural gas (in ground)	Secondary	10%
Manufacturing	LPG production	Petroleum (in ground)	Secondary	2.0%
Manufacturing	LPG production	Coal, average (in ground)	Secondary	1.4%
Manufacturing	CRT tube manufacturing	Fuel oil #6	Primary	0.72%
Manufacturing	Glass/frit manufacturing	Natural gas	Primary	0.26%
Manufacturing	Glass/frit manufacturing	Fuel oil # 2	Primary	0.24%
Manufacturing	Glass/frit manufacturing	Electricity	Primary	0.23%
Manufacturing	CRT tube manufacturing	Natural gas	Primary	0.18%
Materials processing	Polycarbonate production	Natural gas (in ground)	Secondary	0.16%
Manufacturing	LPG production	Uranium (U, ore)	Secondary	0.16%
Manufacturing	CRT tube manufacturing	Electricity	Primary	0.15%
Manufacturing	Glass/frit manufacturing	Electricity	Primary	0.13%

*Column may not add to 99% due to rounding.

3.3.3.2 Major contributors to the LCD energy use results

Table 3-17 lists the inventory items contributing to the top 99% of the LCD life-cycle energy use results. Electricity consumed during use of the LCD monitor by the consumer is the single largest contributor to LCD energy use impacts, closely followed by LPG utilized to produce LCD glass. Other major contributors include natural gas consumed during natural gas production, electricity and LNG used as a fuel during LCD monitor/module manufacturing, and natural gas consumed during LPG production. Note that the LNG used as an ancillary material in LCD module/monitor manufacturing is not included in the LCD energy use impact calculations since it is not used as a source of energy. However, natural gas used as an energy source to produce the LNG is included (the third item listed in the table).

Table 3-17. Top 99% of the LCD energy use impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Use	LCD monitor use	Electricity	Model/ secondary	30%
Manufacturing	LCD glass manufacturing	Liquified petroleum gas	Primary	25%
Materials processing	Natural gas production	Natural gas (in ground)	Secondary	14%
Manufacturing	LCD module/monitor mfg.	Electricity	Primary	8.9%
Manufacturing	LCD module/monitor mfg.	Liquified natural gas	Primary	5.8%
Manufacturing	LPG production	Natural gas (in ground)	Secondary	3.4%
Manufacturing	LCD panel components	Electricity	Primary	1.4%
Manufacturing	LCD module/monitor mfg.	Natural gas	Primary	1.3%
Materials processing	Natural gas production	Coal (in ground)	Secondary	1.3%
Materials processing	Natural gas production	Petroleum (in ground)	Secondary	0.89%
Manufacturing	LCD module/monitor mfg.	Liquified petroleum gas	Primary	0.88%
Manufacturing	LPG production	Petroleum (in ground)	Secondary	0.69%
Materials processing	Polycarbonate production	Natural gas (in ground)	Secondary	0.67%
Manufacturing	LPG production	Coal (in ground)	Secondary	0.51%
Manufacturing	LCD module/monitor mfg.	Kerosene	Primary	0.46%
Materials processing	PMMA sheet production	Petroleum (in ground)	Secondary	0.42%
Materials processing	PMMA sheet production	Natural gas (in ground)	Secondary	0.41%
Materials processing	Steel production (cold-rolled, semi-finished)	Petroleum (in ground)	Secondary	0.36%
Materials processing	Steel production (cold-rolled, semi-finished)	Natural gas (in ground)	Secondary	0.35%
Manufacturing	Natural gas production	Natural gas (in ground)	Secondary	0.32%
Materials processing	PMMA sheet production	Electricity	Secondary	0.32%
Materials processing	Steel production (cold-rolled, semi-finished)	Electricity	Secondary	0.31%
Manufacturing	LCD module/monitor mfg.	Fuel oil # 4	Primary	0.31%
Materials processing	Styrene-butadiene copolymer production	Natural gas (in ground)	Secondary	0.29%
Materials processing	Aluminum production	Coal (in ground)	Secondary	0.29%

*Column may not add to 99% due to rounding.

3.3.3.3 Limitations and uncertainties

Some of the limitations and uncertainties in the energy use indicators are similar to those in the renewable and nonrenewable resource use categories. First, as discussed in Section 3.3.1.1, the energy data for both CRT and LCD glass manufacturing are uncertain due to the variability in the primary glass data received by the CDP from three glass manufacturers. Glass manufacturing energy data are the subject of a sensitivity analysis in Section 3.4. Second, data for LPG production and natural gas production, which are among the largest contributors to the

energy use indicators, are from secondary sources and are therefore subject to the limitations and uncertainties associated with secondary data (see Section 2.2.2 and 3.3.1.1). Not counting the use stage data, note that about 14% of the CRT energy use impacts shown in Table 3-16, above, are from secondary sources, compared to about 24% of the LCD energy use impacts (Table 3-17).

The amount of electricity consumed during use of a monitor was modeled by the CDP from secondary sources on the amount of electricity consumed during different power modes and the amount of time a monitor spends in each mode. Data quality for the effective life scenario (the baseline scenario presented here) is considered to be excellent, based on the source and quality information detailed in Appendix H and discussed in Sections 2.4.2 and 2.4.3.

3.3.4 Landfill Use

3.3.4.1 Solid waste landfill use

Figure 3-5 presents the CRT and LCD LCIA results for the solid waste landfill use impact category, based on the impact assessment methodology presented in Section 3.1.2.3. Tables M-7 and M-8 in Appendix M present complete results for the CRT and LCD, respectively. Life-cycle solid waste landfill use was 0.17 m^3 for the CRT and 0.054 m^3 for the LCD. The solid waste landfill indicators for both monitor types are dominated by waste disposal during the use stage—which contributes 59% of the total for the CRT and 68% for the LCD—primarily from wastes generated as a by-product of electricity production. Both monitor types have negative solid waste impact scores during the end-of-life stage. This is due to an energy credit from incineration processes, which offsets some of the solid waste impacts from electricity generation.

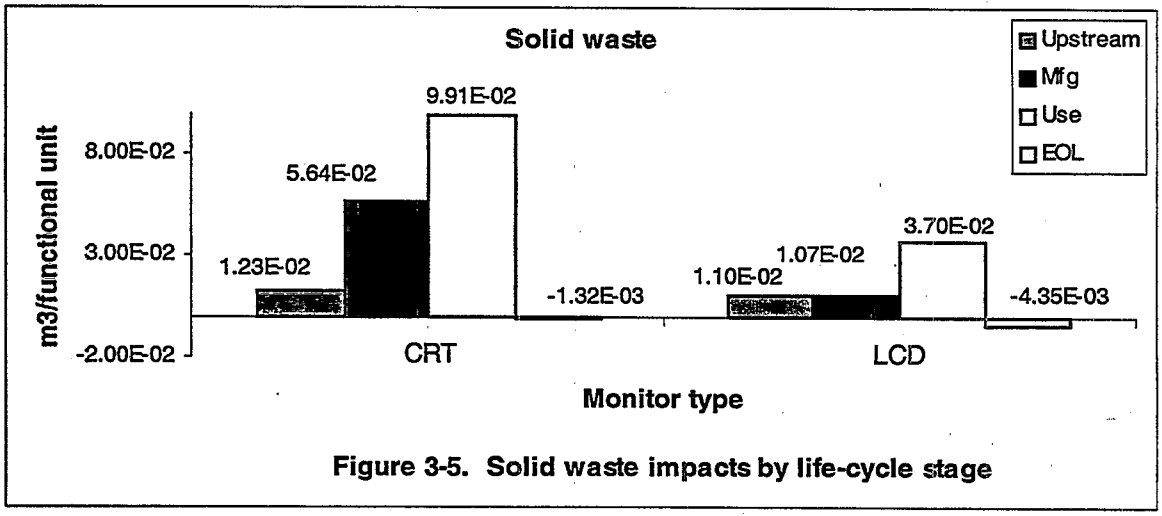


Figure 3-5. Solid waste impacts by life-cycle stage

Table 3-18 presents the materials that contribute to the top 99% of the CRT solid waste landfill use impact score. Note that the material contributions actually add to greater than 100% due to the energy credit from incineration processes, discussed above. Coal waste from U.S. electricity production is the single largest contributor to CRT impacts in this impact category, followed by slag and ash from LPG production, and dust/sludge and fly bottom ash from U.S. electricity production. Electricity is used to power the monitor during the use stage, while LPG is primarily used in the production of CRT glass during manufacturing. LPG production also

results in an unspecified solid waste that contributes 4.5% of the CRT solid waste impact score, while the CRT glass/frit process group generates a wastewater treatment sludge that contributes 5% of the score. Thus, the CRT glass/frit process group contributes about 30% of the CRT solid waste impact score, either directly (as a result of the glass manufacturing process itself) or indirectly (from LPG production). Other processes that are significant contributors include steel production and the landfilling of a CRT at the end of its effective life. The latter value is based on the assumption that 25% of CRTs that have reached their end of life are disposed of in a solid waste landfill (see Section 2.5 and Appendix I).

Table 3-18. Top 99% of the CRT solid waste landfill use impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Use	U.S. electric grid	Coal waste	Model/secondary	38%
Manufacturing	LPG production	Slag and ash	Secondary	21%
Use	U.S. electric grid	Dust/sludge	Model/secondary	12%
Use	U.S. electric grid	Fly bottom ash	Model/secondary	10%
Materials processing	Steel production, cold-rolled, semi-finished	Unspecified solid waste	Secondary	6.6%
End-of-Life	CRT landfilling	EOL CRT monitor, landfilled	Primary	5.0%
Manufacturing	LPG production	Unspecified waste	Secondary	4.5%
Manufacturing	CRT glass/frit mfg.	Waste water treatment sludge	Primary	4.4%

*Column adds to greater than 100% due to a credit from incineration with energy recovery during the EOL life-cycle stage.

CRT glass manufacturing data were collected specifically for the CDP, while data for other process groups were either modeled by the CDP from secondary sources (e.g., U.S. electric grid data) or are entirely from secondary sources (e.g., LPG and steel production data). The mass and volume of CRT materials that are landfilled were developed for the CDP based on the mass reported in each inventory data set (collected as primary data) and the density of CRT materials assumed to be disposed of in a solid waste landfill. Note that the upstream inventories, which were derived from secondary sources (i.e., *Ecobilan*), include electricity generation within the materials manufacturing processes. These inventories do not include coal waste as an output, but list "slag and ash" as an output. The different inventories used in this project have varying nomenclature and some of the solid waste materials listed in the table may indeed overlap.

Table 3-19 presents the materials that contribute to the top 99% of the LCD solid waste landfill use results. Like the CRT solid waste results, the material contributions in the table are actually greater than 100% due to some negative values at end-of-life from an incinerator energy credit. Coal waste, dust/sludge, and fly/bottom ash from U.S. electricity during the use stage dominate the LCD solid waste impacts, contributing 68% of the impact score. Other significant contributors include the following: (1) an unspecified solid waste from producing steel used in the manufacture of the monitor, (2) slag and ash generated during the production of natural gas which is then used by one LCD module/monitor manufacturer as an ancillary material (LNG) during LCD module/monitor manufacture, (3) a wastewater treatment sludge from LCD module/monitor manufacturing, (4) coal waste from the generation of electricity in Japan during manufacturing, and (5) landfilling of non-hazardous or non-recovered components of the LCD at

the end of its effective life. The latter value is based on the assumption that 50% of LCDs are sent to a solid waste landfill at the end of their effective lives.

Table 3-19. Top 99% of the LCD solid waste landfill use impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Use	U.S. electric grid	Coal waste	Model/secondary	44%
Use	U.S. electric grid	Dust/sludge	Model/secondary	13%
Use	U.S. electric grid	Fly/bottom ash	Model/secondary	11%
Materials processing	Steel production, cold-rolled, semi-finished	Unspecified solid waste	Secondary	9.9%
Materials processing	Natural gas production	Slag and ash	Secondary	7.7%
Manufacturing	LCD monitor/module mfg.	Waste water treatment sludge	Primary	5.6%
Manufacturing	Japanese electric grid	Coal waste	Model/secondary	5.0%
End-of-Life	LCD landfilling	EOL LCD monitor, landfilled	Primary	3.5%

*Column adds to greater than 100% due to a credit from incineration with energy recovery during the EOL life-cycle stage.

LCI data for LCD monitor/module manufacturing were collected by the CDP, and LCD solid waste disposal volumes were estimated by the CDP based on the amounts and density of LCD materials assumed to be disposed of in a solid waste landfill. Like the CRT, data for other process groups either were modeled by the CDP from secondary data sources or came from secondary sources. As discussed above for the CRT, the materials processing inventories from secondary sources (i.e., *Ecobilan*) include electricity generation within the materials manufacturing processes. The different inventories used in this project have varying nomenclature and some of the solid waste materials listed in the table may indeed overlap.

3.3.4.2 Hazardous waste landfill use

Figure 3-6 presents the CRT and LCD LCIA results for the hazardous waste landfill use impact category, based on the impact assessment methodology presented in Section 3.1.2.3. Tables M-9 and M-10 (see Appendix M) present complete hazardous waste landfill use results for the CRT and LCD, respectively. Hazardous waste landfill use impacts are characterized from hazardous waste outputs with a disposition of landfill, which includes about 83% of the 9.46 kg of hazardous waste/functional unit generated by the CRT life cycle and about 27% of the 6.3 kg/functional unit generated by the LCD life cycle. This consumes approximately 0.017 m^3 of hazardous waste landfill space for the CRT and 0.036 m^3 for the LCD, based on the mass and densities of the various materials. The results for both monitor types are dominated by monitor disposal at the end of its effective life. Approximately 46% of CRTs and 5% of LCDs are assumed to be landfilled as hazardous waste (see Section 2.5 and Appendix I).

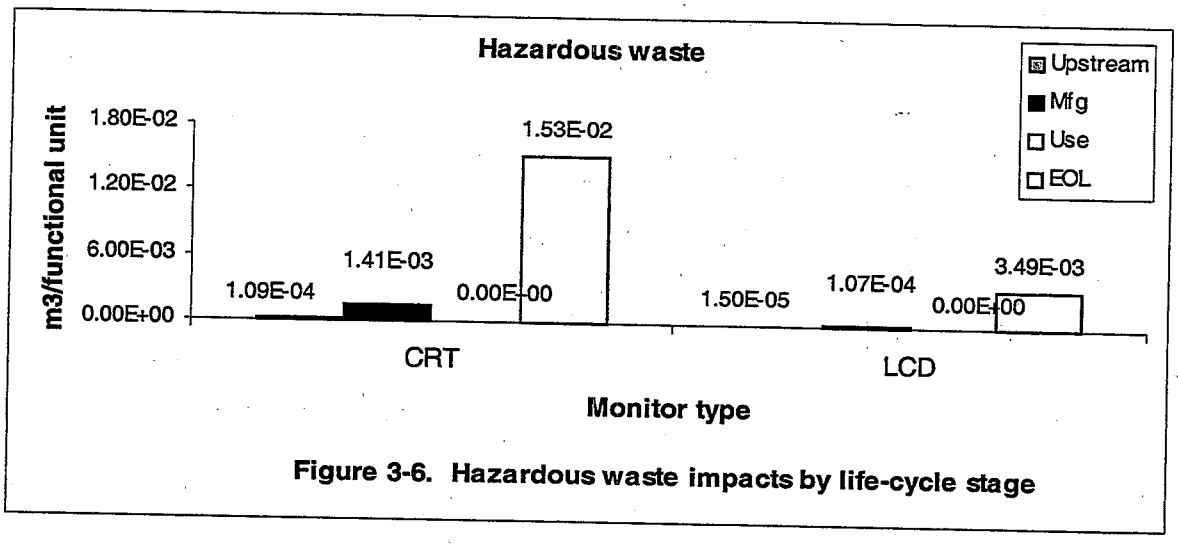


Figure 3-6. Hazardous waste impacts by life-cycle stage

Table 3-20 presents the materials that contribute to the top 99% of the CRT hazardous waste landfill use results. About 91% of the total hazardous waste landfill space consumed throughout the life-cycle of the CRT is from the amount of the monitor that is assumed to be disposed of as hazardous waste. The next largest contributor is an unspecified hazardous waste from LPG production. Most of this LPG is used to manufacture CRT glass. CRT outputs to a hazardous waste landfill at the end-of-life were estimated by the CDP. The LPG inventory is from secondary sources.

Table 3-20. Top 99% of the CRT hazardous waste landfill use impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score
End-of-Life	CRT landfilling	EOL CRT monitor, landfilled	Primary	91%
Manufacturing	LPG production	Hazardous waste	Secondary	8.1%

Table 3-21 lists the top contributors to the LCD hazardous waste landfill use results. LCD results are also dominated by landfilling of the LCD monitor at the end of its effective life, even though only 5% of LCDs are assumed to be landfilled. Other significant contributors include an unspecified hazardous waste from LPG production, and acetic acid from LCD monitor/module manufacturing. LPG is used in the manufacture of LCD glass. LCD outputs to a hazardous waste landfill at the end-of-life were estimated by the CDP. The LPG inventory is from secondary sources.

Table 3-21. Top 99% of the LCD hazardous waste landfill use impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score
End-of-Life	LCD landfilling	EOL LCD monitor, landfilled	Primary	97%
Manufacturing	LPG production	Hazardous waste	Secondary	1.8%
Manufacturing	LCD monitor/module mfg.	Acetic acid	Primary	0.88%

3.3.4.3 Radioactive waste landfill use

Figure 3-7 presents the CRT and LCD LCIA results for the radioactive waste landfill use impact category, based on the impact assessment methodology presented in Section 3.1.2.3. Tables M-11 and M-12 in Appendix M present complete results for the CRT and LCD, respectively. Life-cycle radioactive waste landfill use indicators for the CRT are 1.81E-04 m^3 per monitor for the CRT and 9.22E-05 m^3 per monitor for the LCD. As shown in the figure, CRT radioactive waste landfill impacts are dominated by radioactive waste disposal in the use stage, which contributes about 79% of the total impacts. This result is to be expected, given the relatively large amount of electricity consumed by a CRT during use and the associated radioactive waste from nuclear power plants. The use stage also contributes the greatest amount of LCD impacts (58%), but the manufacturing stage is also a significant contributor (33%) due to electricity consumed during manufacturing. LCD manufacturing electricity is linked to the Japanese electric grid, which derives 31% of its power from nuclear sources. By comparison, about 20% of the U.S. electric grid is powered by nuclear sources.

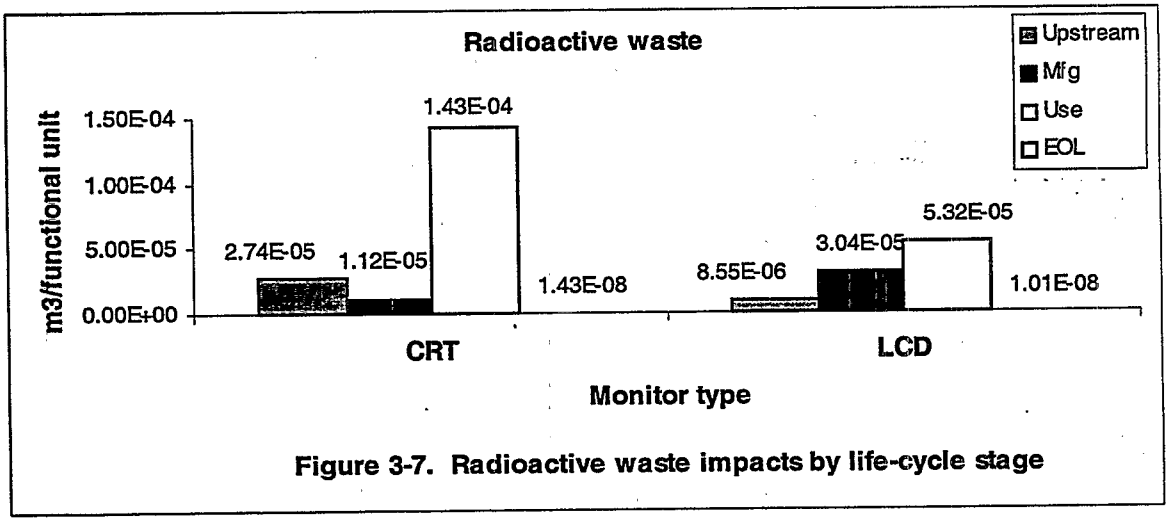


Figure 3-7. Radioactive waste impacts by life-cycle stage

Table 3-22 lists the materials that contribute to the top 99% of the CRT radioactive waste landfill use score and the LCI data type. Note that the LCI data for all of the materials in the table are from secondary sources or models. Low-level radioactive waste and depleted uranium from the U.S. electric grid are the radioactive materials being landfilled in the greatest quantities, followed by low-level radioactive waste from the production of steel used in the monitor. The latter radioactive waste is a byproduct of electricity production used in the manufacture of steel. It should be noted that the electricity generation data utilized in the steel inventory are from France (Glazebrook, 2001), where a large percentage of electricity is derived from nuclear sources. Therefore, these emissions may not be representative of emissions from steel production in some parts of Asia or in the United States. This issue is discussed further in the section on limitations and uncertainties, below.

Table 3-22. Top 99% of the CRT radioactive waste landfill use impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Use	U.S. electric grid	Low-level radioactive waste	Model/secondary	61%
Use	U.S. electric grid	Uranium, depleted	Model/secondary	18%
Materials processing	Steel production, cold-rolled, semi-finished	Low-level radioactive waste	Secondary	9.0%
Manufacturing	Japanese electric grid	Low-level radioactive waste	Model/secondary	3.8%
Materials processing	Invar	Low-level radioactive waste	Secondary	2.6%
Materials processing	Ferrite manufacturing	Low-level radioactive waste	Secondary	2.5%
Manufacturing	Japanese electric grid	Uranium, depleted	Model/secondary	1.1%
Manufacturing	U.S. electric grid	Low-level radioactive waste	Model/secondary	0.97%

*Column may not add to 99% due to rounding.

Other significant contributors to the CRT radioactive waste score include low-level radioactive waste from electricity used in Japan during manufacturing, and low-level radioactive waste from invar and ferrite manufacturing. Invar is an alloy of nickel and iron. Like the steel data discussed above, the invar and ferrite manufacturing data also include emissions from electricity production. Finally, low-level radioactive waste from U.S. electricity consumed during the manufacturing stage contributes slightly less than 1% of the CRT radioactive waste landfill use impacts. The frit and PWB manufacturing processes consume this electricity. These are the only CRT components linked to the U.S. grid.

Table 3-23 lists the materials that contribute to the top 99% of the LCD radioactive waste landfill use results and the LCI data type. Note that LCI data for all of the primary contributors to this impact category are from secondary sources or modeled from secondary sources. Together, low-level radioactive waste and depleted uranium disposal from electricity consumed during use of the monitor account for about 57% of the LCD radioactive waste landfill use indicator, followed by low-level radioactive waste and depleted uranium disposal from electricity used during manufacturing (roughly 32%). Waste disposal from steel production is also a significant contributor at 8.7%. Like the CRT data discussed above, these emissions occur from electricity production in France and may not be representative of U.S. or some Asian practices.

Table 3-23. Top 99% of the LCD radioactive waste disposal impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Use	U.S. electric grid	Low-level radioactive waste	Model/secondary	44%
Manufacturing	Japanese electric grid	Low-level radioactive waste	Model/secondary	25%
Use	U.S. electric grid	Uranium, depleted	Model/secondary	13%
Materials processing	Steel production, cold-rolled, semi-finished	Low-level radioactive waste	Secondary	8.7%
Manufacturing	Japanese electric grid	Uranium, depleted	Model/secondary	7.5%

*Column may not add to 99% due to rounding.

3.3.4.4 Limitations and uncertainties

Landfill use pertains to the use of suitable and designated landfill space as a natural resource where the specified type of waste (solid, hazardous, or radioactive) is accepted. Landfill use impacts are characterized from solid, hazardous, or radioactive waste outputs with a disposition of landfill. Impact characterization is based on the volume of waste determined from the inventory mass amount of waste and materials density of each specific waste. Note that different countries may have different landfill designations for the final disposition of similar waste streams (e.g., a waste considered hazardous in the U.S. may be accepted in a solid waste landfill elsewhere). However, where possible, equivalent landfills (e.g., special waste landfills and hazardous waste landfills) were considered for these impact categories.

CRT and LCD impact results for the solid and radioactive waste landfill use categories were driven almost entirely by waste outputs reported in inventories from secondary sources. These inventories were not developed specifically for the CDP and therefore are subject to the limitations and uncertainties associated with secondary data (see Section 2.2.2 and 3.3.2). In particular, radioactive waste disposal from some of the upstream materials processing data may not be representative of conditions in the U.S. or parts of Asia. These data include emissions from electricity production within the materials inventory, which are the primary source of radioactive waste streams. For example, steel production data include the French electric grid, where a large percentage of the power supply comes from nuclear power plants. In addition, some of the upstream data may not be representative of current conditions, with steel production data covering the period from 1975 to 1990 and invar production data being from 1991.

CRT and LCD impact results for the hazardous waste landfill use category were dominated by monitor disposal at the end of their effective lives. Hazardous waste landfill disposal volumes were estimated based on the percent of monitors with hazardous waste landfilling as their final disposition, the monitor mass, and the material densities. However, data on the percentage of CRTs that are landfilled are not separated into hazardous and non-hazardous landfilling processes. Therefore, these percentages were estimated by the CDP, as described in Appendix I. Even less is known about the final disposition of LCDs, particulary since very few LCD desktop monitors have reached the end of their effective lives (and then, only if they have been damaged in some way). Therefore, the effect of different LCD EOL dispositions was evaluated in a sensitivity analysis (see Section 3.4.)

3.3.5 Global Warming

Figure 3-8 presents the CRT and LCD LCIA results for the global warming impact category, based on the impact assessment methodology presented in Section 3.1. Tables M-13 and M-14 in Appendix M list complete global warming results for the CRT and LCD, respectively. The life-cycle global warming indicators for the CRT and LCD were 695 and 593 kg of CO_2 equivalents per monitor, respectively. The CRT global warming indicators are driven by the use life-cycle stage, which contributes about 66% of the total. The manufacturing stage, which contributed 88% of the CRT energy consumption impacts, only contributes about 29% of the total global warming score. LCD global warming impacts, on the other hand, have the greatest contribution from the manufacturing life-cycle stage, which accounts for about 40% of the potential impacts in this category. Both the upstream (materials processing) and use

life-cycle stages are also significant contributors to the LCD global warming results, accounting for 31% and 29% of the total, respectively.

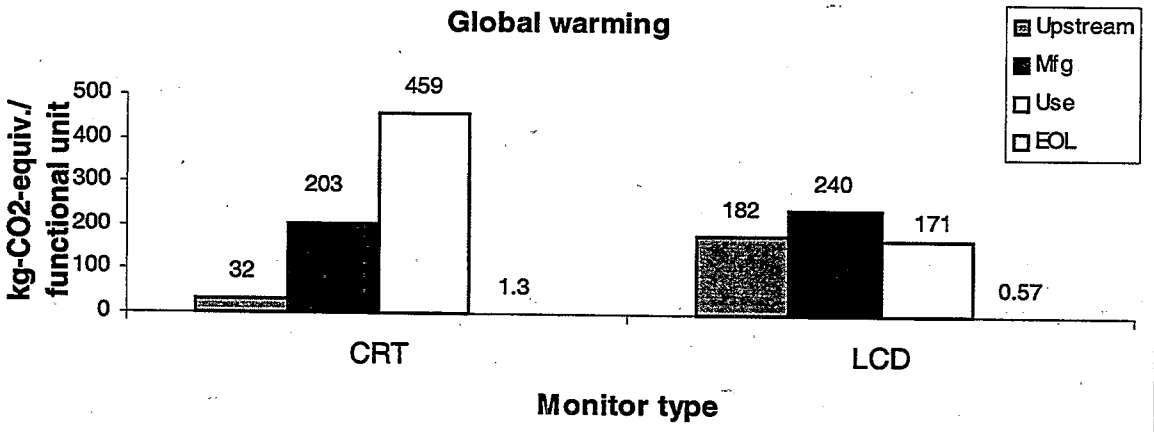


Figure 3-8. Global warming impacts by life-cycle stage

One might expect the distribution of global warming impacts across life-cycle stages to mirror those of energy consumption, as CO_2 is generally a large emission from electricity generation. However, as discussed in Section 3.3.3, CRT energy impacts are greatest in the manufacturing stage due to the large amounts of energy used to manufacture glass. Since the energy used in glass manufacturing is not only from electricity, but more so from other fuels (LPG, natural gas, and fuel oil), there is not a direct correlation between CRT global warming impacts and CRT energy impacts.

The distribution of LCD global warming impacts across life-cycle stages does mirror the distribution of LCD energy use impacts discussed in Section 3.3.3. However, as discussed below, the manufacturing stage global warming impacts for the LCD are being driven more by the use of sulfur hexafluoride (SF_6) in LCD monitor/module manufacturing than by the use of electricity.

3.3.5.1 Major contributors to the CRT global warming results

Table 3-24 presents the life-cycle inventory items contributing to the top 99% of the CRT global warming results and the LCI data type (primary, secondary, or model/secondary). As shown in the table, CRT global warming impacts are dominated by CO_2 emissions from electricity generation during use of the monitor, followed by CO_2 and methane emissions from producing LPG used as fuel in the CRT glass/frit process group. Together these three emissions contribute almost 89% of the CRT life-cycle global warming score. Carbon dioxide and methane emissions from a number of other processes also add to the CRT global warming score, as does nitrous oxide emissions from the LPG production process. It is likely that most of the CO_2 emissions from the materials processing life-cycle stage can be attributed to emissions from electricity generation or fuel combustion. As discussed in Section 2.2.2.1, the upstream materials processing inventories used in this study include data from electricity generation.

Note that almost all of the LCI data for global warming emissions are from secondary sources. This is because the CRT global warming results are dominated by CO_2 emissions from electricity generation, and electric grid data were either developed by the CDP from secondary sources or already included in the upstream, materials processing inventories from secondary sources.

Table 3-24. Top 99% of the CRT global warming impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Use	U.S. electric grid	Carbon dioxide	Model/secondary	64%
Manufacturing	LPG production	Carbon dioxide	Secondary	22%
Manufacturing	LPG production	Methane	Secondary	2.5%
Manufacturing	Japanese electric grid	Carbon dioxide	Model/secondary	2.2%
Use	U.S. electric grid	Methane	Model/secondary	1.9%
Materials processing	Steel production, cold-rolled, semi-finished	Carbon dioxide	Secondary	1.9%
Manufacturing	U.S. electric grid	Carbon dioxide	Model/secondary	1.0%
Manufacturing	LPG production	Nitrous oxide	Secondary	0.72%
Materials processing	Polycarbonate production	Carbon dioxide	Secondary	0.66%
Materials processing	Aluminum production	Carbon dioxide	Secondary	0.52%
End-of-Life	CRT incineration	Carbon dioxide	Secondary	0.51%
Manufacturing	CRT glass/frit mfg.	Carbon dioxide	Primary	0.40%
Materials processing	Invar	Carbon dioxide	Secondary	0.33%
Materials processing	Styrene-butadiene copolymer production	Carbon dioxide	Secondary	0.24%

*Column may not add to 99% due to rounding.

3.3.5.2 Major contributors to the LCD global warming results

Table 3-25 presents the life-cycle inventory items contributing to the top 99% of the LCD global warming results and the LCI data type (primary, secondary, or model/secondary). Sulfur hexafluoride used in LCD module manufacturing is the single largest contributor to LCD global warming impacts, followed by CO_2 emissions from electricity generation during the use stage, CO_2 and methane emissions from natural gas production, and CO_2 emissions from the generation of electricity used during manufacturing in Japan.

Table 3-25. Top 99% of the LCD global warming impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Manufacturing	LCD monitor/module mfg.	Sulfur hexafluoride	Primary	29%
Use	U.S. electric grid	Carbon dioxide	Model/secondary	28%
Materials processing	Natural gas production	Carbon dioxide	Secondary	16%
Materials processing	Natural gas production	Methane	Secondary	12%
Manufacturing	Japanese electric grid	Carbon dioxide	Model/secondary	8.7%
Manufacturing	LPG production	Carbon dioxide	Secondary	1.2%
Materials processing	Steel production, cold-rolled, semi-finished	Carbon dioxide	Secondary	1.1%
Use	U.S. electric grid	Methane	Model/secondary	0.85%
Materials processing	PMMA sheet production	Carbon dioxide	Secondary	0.45%
Materials processing	Polycarbonate production	Carbon dioxide	Secondary	0.43%
Manufacturing	Natural gas production	Carbon dioxide	Secondary	0.35%
End-of-Life	LCD incineration	Carbon dioxide	Secondary	0.35%

*Column may not add to 99% due to rounding.

Sulfur hexafluoride is a potent global warming gas, with a global warming potential (GWP) equivalancy factor of 23,900 CO_2 equivalents (see Table K-2 in Appendix K). It is used as an etchant in a dry-etching process of amorphus silicon and SiNx films. The CO_2 and methane emissions from natural gas production can be attributed to the use of LNG as an ancillary material in LCD monitor/module manufacturing. However, as discussed in the section on non-renewable resource use (Section 3.3.2), only one LCD module manufacturer reported this use of LNG.

Carbon dioxide emissions (and, in one case, methane emissions) round out the remainder of the primary contributors to the LCD global warming indicator. Most of the carbon dioxide emissions occur from upstream processes and are due to electricity generation. With the exception of the SF_6 data, the LCI data for all of the top LCD global warming emissions are from secondary sources. Sulfur hexaflouride emissions data were developed by the CDP based on an emissions factor (0.45) applied to SF_6 inputs reported by LCD monitor/module manufacturers. The emissions factor is from the Intergovernmental Panel on Climate Change publication, *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (Penman *et al.*, 2000.)

3.3.5.3 Limitations and uncertainties

Global warming potential (GWP) refers to the warming that emissions of certain gases may contribute by building up in the atmosphere and trapping the earth's heat. As discussed in Section 3.1.2.4, the LCIA methodology for global warming impacts uses published GWP equivalency factors having effects in the 100-year time horizon. These effects are expected to be far enough into the future that releases occurring throughout the life cycle of a computer monitor would be within the 100-year timeframe.

The effects of the buildup of global warming gases in the atmosphere is still the subject of scientific debate, but in 1995 the Intergovernmental Panel on Climate Change (IPCC), representing the consensus of most climate scientists worldwide, concluded that "... the balance of evidence...suggests that there is a discernible human influence on global climate (IPCC, 1995)." Other than the limitations and uncertainties inherent in predicting future effects, most of the limitations and uncertainties in the CRT and LCD global warming results have to do with the LCI data on greenhouse gas emissions, which occur primarily from electricity generation processes.

As noted above, the U.S. and Japan electric grid inventories used in the CDP were developed by the CDP, and electric grids used with upstream processes are embedded in the upstream inventories. U.S. electric grid emissions of CO_2 are based on data in the EPA publication, *National Air Quality and Emissions Trends Report, 1997* (EPA, 1998), which were the best data available when the electric grid inventory data was developed and are expected to be reasonably accurate. However, the Japanese electric grid inventory was derived from the U.S. inventory based on the mix of fuels used in Japan. Because Japanese power plants may employ different pollution control devices, use fuels of different quality, or other factors, their greenhouse gas emissions could actually be higher or lower than those reported in the inventory.

Similarly, the electric grid inventories embedded in upstream, materials processing inventories may have differing geographic and temporal boundaries or may be representative of older technologies. Therefore, actual emissions of greenhouse gases could be higher or lower than reported. This is a common limitation of LCAs, which must often rely on secondary data sources to avoid the considerable time and resources required to collect primary data for every process.

3.3.6 Stratospheric Ozone Depletion

Figure 3-9 presents the CRT and LCD LCIA results for the stratospheric ozone depletion impact category by life-cycle stage, based on the impact assessment methodology presented in Section 3.1.2.5. Note that most of the CRT ozone depletion impacts occur from the use stage (50%) and the upstream, materials processing stages (45%), while most of the LCD ozone depletion impacts occur from the manufacturing stage (63%). As will be shown later, this is important because upstream and use stage data are primarily from secondary data sources, whereas manufacturing data were collected by the CDP. Tables M-15 and M-16 in Appendix M list complete stratospheric ozone depletion results for the CRT and LCD, respectively.

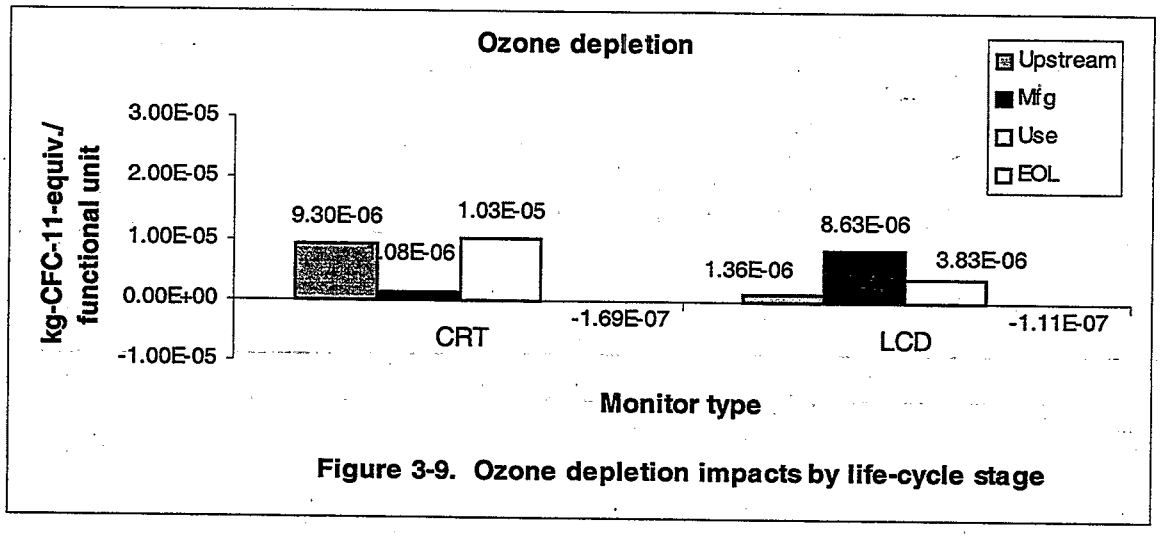


Figure 3-9. Ozone depletion impacts by life-cycle stage

The ozone depletion impact category indicator was 2.05E-05 kg of CFC-11 equivalents per monitor for the CRT and 1.37E-05 kg of CFC-11 equivalents per monitor for the LCD. However, for both the CRT and the LCD, many of the materials contributing to this impact category are listed as Class I ozone depleting substances in Title VI of the 1990 Clean Air Act Amendments, and therefore were required to be phased out of U.S. production by January 1, 1996. Production of these substances was also phased out in other developed countries under the Montreal Protocol and its Amendments and Adjustments, but continues today in some developing countries. An exception is bromomethane, which is a Class I substance that will not be completely phased out of production until 2005 (EPA, 2001a).

For a few of the phased out substances, a significant amount of inventory remained after production was phased out. However, most of these inventories are now exhausted, and Class I ozone depleting substances are rarely used by manufacturers in developed countries. If we delete the phased out substances from the CRT and LCD inventories, the CRT ozone depletion indicator is reduced 47% from 2.05E-05 to 1.09E-05 kg of CFC-11 equivalents per monitor, and the LCD result is reduced 14% from 1.37E-05 to 1.18E-05 kg of CFC-11 equivalents per monitor. These latter values are probably more representative of the temporal boundaries for primary data collected in the CDP LCA. Thus, when all data are included in the ozone depletion calculations, the CRT has a greater ozone depletion impact score than the LCD, but the results are switched (LCD greater than CRT) when phased out substances are removed from the inventory.

3.3.6.1 Major contributors to the CRT ozone depletion results

Table 3-26 lists the materials that contribute to the top 99% of the CRT life-cycle ozone depletion impact score and the LCI data type. Bromomethane emissions from electricity generated in the use stage are the single largest contributor to the CRT ozone depletion indicator, accounting for almost half of the total score. Most of the other materials in the table are emitted from materials production processes in the upstream, materials processing life-cycle stage. Exceptions are bromomethane emissions from the LPG production process (used to produce LPG

for the glass/frit process group), 1,1,1-trichloroethane emissions from electricity generation in the use stage, and bromomethane emissions from electricity used in manufacturing.

Table 3-26. Top 99% of the CRT stratospheric ozone depletion impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score[a]
Use	U.S. electric grid	Bromomethane[b]	Model/secondary	49%
Materials processing	ABS production	HALON-1301[b]	Secondary	20%
Materials processing	Aluminum production	HALON-1301[b]	Secondary	14%
Materials processing	Invar	HALON-1301[b]	Secondary	5.9%
Manufacturing	LPG production	Bromomethane[b]	Secondary	3.7%
Materials processing	Lead	HALON-1301[b]	Secondary	2.6%
Materials processing	Steel production, cold-rolled, semi-finished	HALON-1301[b]	Secondary	2.0%
Use	U.S. electric grid	1,1,1-Trichloroethane[b]	Model/secondary	1.1%
Manufacturing	U.S. electric grid	Bromomethane[b]	Model/secondary	0.78%

[a] Column may not add to 99% due to rounding.
[b] Class I substance as listed in Title VI of the Clean Air Act Amendments.

Note that all of the materials listed in Table 3-26 are Class I ozone depleting substances. As discussed above, all of these substances except bromomethane were phased out of production by January 1, 1996. Note also that all of the LCI data for the materials in the table are from secondary sources. For both of these reasons, the LCI data for the materials in the table are highly uncertain. This is discussed further under limitations and uncertainties, below.

3.3.6.2 Major contributors to the LCD ozone depletion results

Table 3-27 lists the top contributors to the LCD life-cycle stratospheric ozone depletion indicator and the LCI data type. Together HCFC-225cb and HCFC 225ca used in the LCD panel components process group account for 59% of the LCD ozone depletion indicator. Note that HCFC 225cb and HCFC 225ca are Class II ozone depleting substances that are not scheduled for phaseout until 2015. [Under U.S. regulations and the Montreal Protocol and its Amendments and Adjustments these substances can not be produced or imported after 2015, except for use as refrigerants in equipment manufactured before January 1, 2020 (EPA, 2001b).] Also note that the impact scores for these materials are based on primary LCI data collected from manufacturers. Therefore, these data are considered to be more reliable than data for Phase I substances from secondary sources.

Table 3-27. Top 99% of the LCD stratospheric ozone depletion use impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score[a]
Manufacturing	LCD panel components	HCFC-225cb[b]	Primary	34%
Use	U.S. electric grid	Bromomethane[c]	Model/secondary	27%
Manufacturing	LCD panel components	HCFC-225ca[b]	Primary	25%
Materials processing	Aluminum production (virgin)	HALON-1301[c]	Secondary	7.8%
Manufacturing	Japanese electric grid	Bromomethane[c]	Model/secondary	3.1%
Materials processing	Steel production, cold-rolled, semi-finished	HALON-1301[c]	Secondary	1.4%

[a] Column may not add to 99% due to rounding.
[b] Class II substance as listed in Title VI of the Clean Air Act Amendments.
[c] Class I substance as listed in Title VI of the Clean Air Act Amendments.

Other significant contributors to the LCD ozone depletion score include bromomethane emissions from electricity generation in the United States and Japan, and halon emissions from upstream, materials processing stages. As noted above in the discussion of CRT ozone depletion results, the halons were phased out of production in 1996, which suggests that these data are not representative of current conditions. Bromomethane is still being produced, but bromomethane emissions data are also uncertain as will be discussed in the section on limitations and uncertainties, below.

3.3.6.3 Limitations and uncertainties

Both the CRT and LCD life-cycle stratospheric ozone depletion results are highly uncertain due to the inclusion of a number of Class I ozone depleting substances in inventories from secondary sources. As discussed above, except for bromomethane, developed countries that are parties to the Montreal Protocol and its Amendments and Adjustments phased out the production of Class I substances by 1996. To better assess the uncertainties in these results, Table 3-28 lists the geographic and temporal boundaries for the life-cycle inventories of the process groups listed in tables 3-26 and 3-27, above.

Table 3-28. Geographic and temporal boundaries of inventories contributing to the CRT and/or LCD ozone depletion indicator results

Process group	Geographic boundaries	Temporal boundaries
ABS production	Germany, Italy, Netherlands	1997
Aluminum production	Not provided	Not provided
Invar production	Multiple countries	1991 (nickel), Not provided (lead)
Japanese electric grid	U.S. and Japan[a]	1993[b]
LCD panel components	Japan	1998
Lead production	Not provided	Not provided
LPG production	Mainly U.S.	1983-1993
Steel production	Multiple countries	1975-1990
U.S. electric grid	U.S.	1993[b]

[a] Based on the U.S. electric grid inventory modified to account for the fuel mix used in Japan.
[b] Date of stack tests from which bromomethane emission factor was developed (from EPA Web site: Emission Factor Documentation for AP-42 Section 1.1: Bituminous and Subbituminous Coal Combustion. http://www.epa.gov/ttn/chief/ap42/ch01/bgdocs/b01s01.pdf.)

The most recent data are for LCD panel components manufacturing, which are primary data collected from manufacturers in Japan by the CDP and expected to be of better quality than older data from secondary sources. Data for ABS production are also fairly recent, dating from 1997. However, the temporal boundaries for most of the data are either not listed in the inventories, or pre-date the Class I substance production phase out. In addition, most of the data are from Europe and/or the United States, where very few Class I ozone depleting substances are currently used. Thus, we suspect that emissions of Class I substances reported in the inventories no longer occur, indicating that the CRT and LCD life-cycle impact results should be reduced to 2.05E-05 kg of CFC-11 equivalents per monitor for the CRT, and 1.37E-05 kg of CFC-11 equivalents per monitor for the LCD.

Bromomethane is a Class I ozone depleting substance that has not yet been phased out of production and is emitted during coal combustion to produce electricity. Bromoethane emissions from electricity production are estimated from an emission factor reported in AP-42, the EPA compilation of air pollutant emission factors (EPA, 1996). EPA (1996) provides an emission factor rating that is, "an overall assessment of how good a factor is, based on both the quality of the test(s) or information that is the source of the factor and on how well the factor represents the emission source." The bromomethane emissions factor rating is "D," or below average, indicating CDP data quality for bromomethane emissions from electricity generation is also below average.

In conclusion, it appears that most of the Class I substance emissions data are highly uncertain or of below average quality. Manufacturing data collected by the CDP, which includes emissions of Class II substances, are of better quality and expected to be more representative of current conditions. When all data are included in the ozone depletion calculations, the CRT has a greater ozone depletion impact score than the LCD. However, if we remove phased out substances from the inventory, the results are switched with the LCD having a greater score in this category than the CRT.

3.3.7 Photochemical Smog

Figure 3-10 presents the CRT and LCD LCIA results for the photochemical smog impact category by life-cycle stage. These results were calculated using the impact assessment methodology presented in Section 3.1.2.6. Tables M-17 and M-18 in Appendix M list complete results for the CRT and LCD, respectively. One 17" CRT monitor produces 0.171 kg of ethene equivalents throughout its life cycle, while a functionally equivalent 15" LCD monitor produces 0.141 of ethene equivalents. The CRT photochemical smog impact score is dominated by emissions during the manufacturing stage (71% of total); the LCD impact score is dominated by emissions during the upstream, materials processing stages (91% of total). However, as discussed below, it is fossil fuel production processes that emit the majority of smog forming emissions during the life-cycle of either monitor type. Both the CRT and LCD receive a slight credit on emissions of smog forming chemicals at the end of their effective lives due to energy recovery from incineration processes.

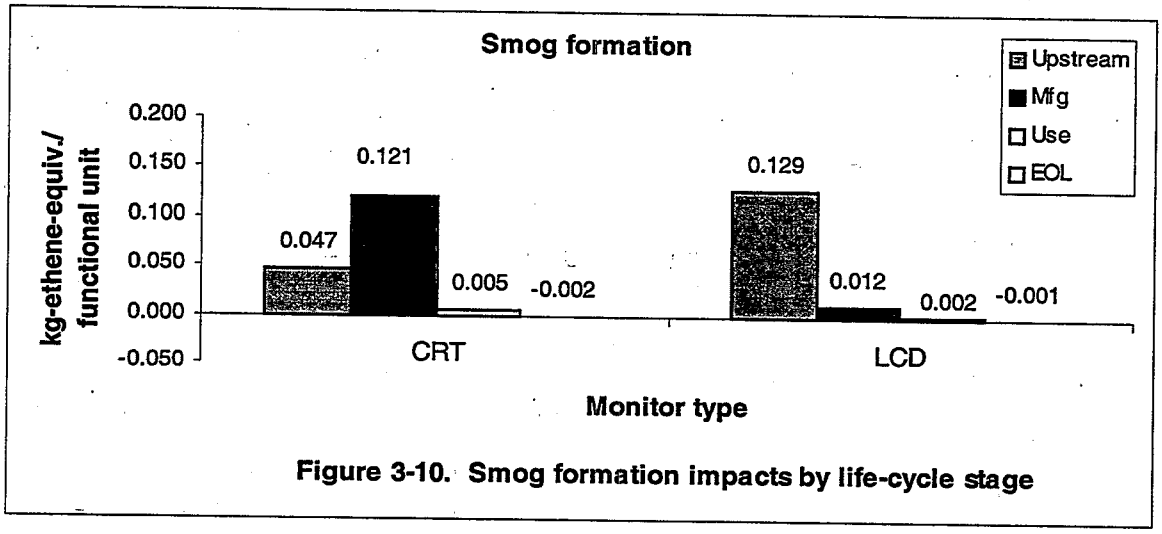


Figure 3-10. Smog formation impacts by life-cycle stage

3.3.7.1 Major contributors to the CRT photochemical smog results

Table 3-29 lists the materials that contribute to the top 99% of the CRT photochemical smog indicator result. The LPG production process alone, which emits various unspeciated hydrocarbons, benzene, aldehydes, ethane, and formaldehyde, accounts for almost 67% of CRT photochemical smog impacts. As noted earlier in the discussion of other impact category indicators, most of this LPG is used as a fuel source in CRT glass manufacturing. However, CRT glass energy data reported in the three data sets received by the CDP were highly variable and therefore the subject of a sensitivity analysis (see Section 3.4).

Other materials responsible for more than 1% of the CRT photochemical smog score include the following: (1) hydrocarbon (methane and nonmethane) emissions associated with steel production, (2) methane emissions from electricity generation during the use stage, (3) toluene emissions from CRT tube manufacturing, (4) nonmethane hydrocarbon emissions associated with ABS production, and (5) nonmethane hydrocarbon emissions associated with polycarbonate production. Note that the inventory for each upstream material (e.g., steel

production, ABS production, etc.) contains data from the raw materials extraction, materials manufacture, and (usually) electricity generation processes. Therefore, hydrocarbon emissions associated with steel production, for example, could be from one of many individual processes, such as the steel production process itself, from fuels consumed during the mining of ore, or from the combustion of fuels as an energy source during steel manufacturing.

Table 3-29. Top 99% of the CRT photochemical smog impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Manufacturing	LPG production	Hydrocarbons, unspeciated	Secondary	36%
Manufacturing	LPG production	Nonmethane hydrocarbons, unspeciated	Secondary	25%
Materials processing	Steel production, cold-rolled, semi-finished	Nonmethane hydrocarbons, unspeciated	Secondary	19%
Manufacturing	LPG production	Methane	Secondary	3.4%
Use	U.S. electric grid	Methane	Model/secondary	2.6%
Materials processing	Steel production, cold-rolled, semi-finished	Hydrocarbons, unspeciated	Secondary	2.0%
Manufacturing	LPG production	Benzene	Secondary	1.6%
Manufacturing	CRT tube mfg.	Toluene	Primary	1.3%
Materials processing	ABS production	Nonmethane hydrocarbons, unspeciated	Secondary	1.3%
Materials processing	Polycarbonate production	Nonmethane hydrocarbons, unspeciated	Secondary	1.1%
Materials processing	Aluminum production	Nonmethane hydrocarbons, unspeciated	Secondary	0.86%
Manufacturing	Natural gas production	Nonmethane hydrocarbons, unspeciated	Secondary	0.53%
Materials processing	ABS production	Nonmethane hydrocarbons, unspeciated	Secondary	0.41%
Manufacturing	LPG production	Aldehydes	Secondary	0.39%
Materials processing	Stryene-butadiene copolymer production	Hydrocarbons, remaining unspeciated	Secondary	0.39%
Materials processing	Invar	Nonmethane hydrocarbons, unspeciated	Secondary	0.32%
Manufacturing	Fuel oil #6 production	Hydrocarbons, unspeciated	Secondary	0.31%
Manufacturing	LPG production	Formaldehyde	Secondary	0.29%
Materials processing	Lead	Nonmethane hydrocarbons, unspeciated	Secondary	0.21%
Manufacturing	Fuel oil #6 production	Nonmethane hydrocarbons, unspeciated	Secondary	0.21%
Manufacturing	Natural gas production	Methane	Secondary	0.21%
Manufacturing	LPG production	Ethane	Secondary	0.18%
Manufacturing	CRT tube mfg.	Xylene (mixed isomers)	Primary	0.17%

Table 3-29. Top 99% of the CRT photochemical smog impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Manufacturing	LPG production	Pentane	Secondary	0.16%
Manufacturing	Natural gas production	Benzene	Secondary	0.14%

*Column may not add to 99% due to rounding.

3.3.7.2 Major contributors to the LCD photochemical smog results

Table 3-30 lists the materials that contribute to the top 99% of the LCD life-cycle photochemical smog results. LCD results are dominated by unspeciated hydrocarbon emissions, methane emissions, and benzene emissions from natural gas production in the materials processing life-cycle stage, which together account for about 75% of the total. This natural gas is used as an ancillary material by one LCD monitor/module manufacturer. Other LCD monitor/module manufacturers reported using LNG as a fuel, but not as an ancillary number. A number of other materials and processes contribute more than 1% of the total LCD photochemical smog score, most notably unspeciated, nonmethane hydrocarbon emissions associated with steel production. As noted above under the CRT results, the latter hydrocarbon emissions could occur from any one of various processes (e.g., ore mining, steel production, electricity generation, etc.) wrapped into the steel production inventory.

Table 3-30. Top 99% of the LCD photochemical smog impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Materials processing	Natural gas production	Nonmethane hydrocarbons, unspeciated	Secondary	45%
Materials processing	Natural gas production	Methane	Secondary	17%
Materials processing	Natural gas production	Benzene	Secondary	12%
Materials processing	Steel production, cold-rolled, semi-finished	Nonmethane hydrocarbons, unspeciated	Secondary	11%
Manufacturing	LCD monitor/module mfg.	Isopropyl alcohol	Primary	2.5%
Manufacturing	LPG production	Hydrocarbons, unspeciated	Secondary	2.1%
Manufacturing	LPG production	Nonmethane hydrocarbons, unspeciated	Secondary	1.4%
Materials processing	Natural gas production	Hydrocarbons, unspeciated	Secondary	1.2%
Materials processing	Steel production, cold-rolled, semi-finished	Hydrocarbons, unspeciated	Secondary	1.2%
Use	U.S. electric grid	Methane	Model/secondary	1.2%
Manufacturing	Natural gas production	Nonmethane hydrocarbons, unspeciated	Secondary	1.0%
Materials processing	PMMA sheet production	Nonmethane hydrocarbons, unspeciated	Secondary	0.87%

Table 3-30. Top 99% of the LCD photochemical smog impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Materials processing	Polycarbonate production	Nonmethane hydrocarbons, unspeciated	Secondary	0.73%
Manufacturing	Natural gas production	Methane	Secondary	0.39%
Materials processing	Aluminum production	Nonmethane hydrocarbons, unspeciated	Secondary	0.39%
Materials processing	PET resin production	Nonmethane hydrocarbons, unspeciated	Secondary	0.36%

*Column may not add to 99% due to rounding.

3.3.7.3 Limitations and uncertainties

Photochemical smog indicators are calculated using the mass of a chemical released to air per functional unit and the chemical-specific partial equivalency factor. The equivalency factor is a measure of the chemical's photochemical oxidant creation potential (POCP) compared to the reference chemical ethylene. As noted in Section 3.1.2.6, photochemical smog impacts are based on partial equivalency because some chemicals cannot be converted into POCP equivalency factors (e.g., nitrogen oxide). The inability to develop equivalency factors for some chemicals is a limitation of the photochemical smog impact assessment methodology.

The CRT impact score for photochemical smog formation is being driven by the process for producing the large amount of LPG used in CRT glass manufacture. However, as discussed in Section 2.3.3.3 and previous subsections of this Section 3.3, the three sets of glass manufacturing energy data received by the CDP were highly variable, making the average glass energy inputs used in the baseline analysis uncertain. Therefore, the emissions of smog forming chemicals from LPG production, which are based on the glass LPG inputs, are also uncertain. CRT glass energy inputs were subjected to a sensitivity analysis. Sensitivity results are discussed in Section 3.4.

The LCD impact score for photochemical smog formation is being driven by the natural gas production process to produce the large amount of LNG used as an ancillary material during LCD monitor/module manufacturing. However, as discussed earlier, only one LCD monitor/module manufacturer reported this use of LNG, which indicates the average LNG inputs used in the LCD inventory may be unduly high. Therefore, the mass of smog forming chemical emissions from the natural gas production process, which are based on the amount of ancillary LNG inputs, may also by unduly high.

The majority of the CRT and LCD photochemical smog results are based on life-cycle inventories from secondary sources and are therefore subject to the limitations and uncertainties associated with secondary data, discussed previously. In particular, see Section 3.3.1.1 for a detailed discussion of limitations and uncertainties in the LPG and natural gas production data.

3.3.8 Acidification

Figure 3.11 presents the CRT and LCD LCIA results for the acidification impact category, based on the impact assessment methodology presented in Section 3.1.2.7. Tables M-19 and M-20 in Appendix M list complete results for the CRT and LCD, respectively. The life-cycle acidification impact indicator result is 5.25 kg of SO_2 equivalents per monitor for the CRT and 2.96 kg of SO_2 equivalents per monitor for the LCD. As might be expected, acidification impacts are greatest in the use stage for both monitor types, due to the emissions of SO_x and NO_x from U.S. power plants. Use stage impacts are more dominant for the CRT (65% of life-cycle acidification impacts) than the LCD (43%) due to the relatively large amount of power consumed during use by the less energy-efficient CRT.

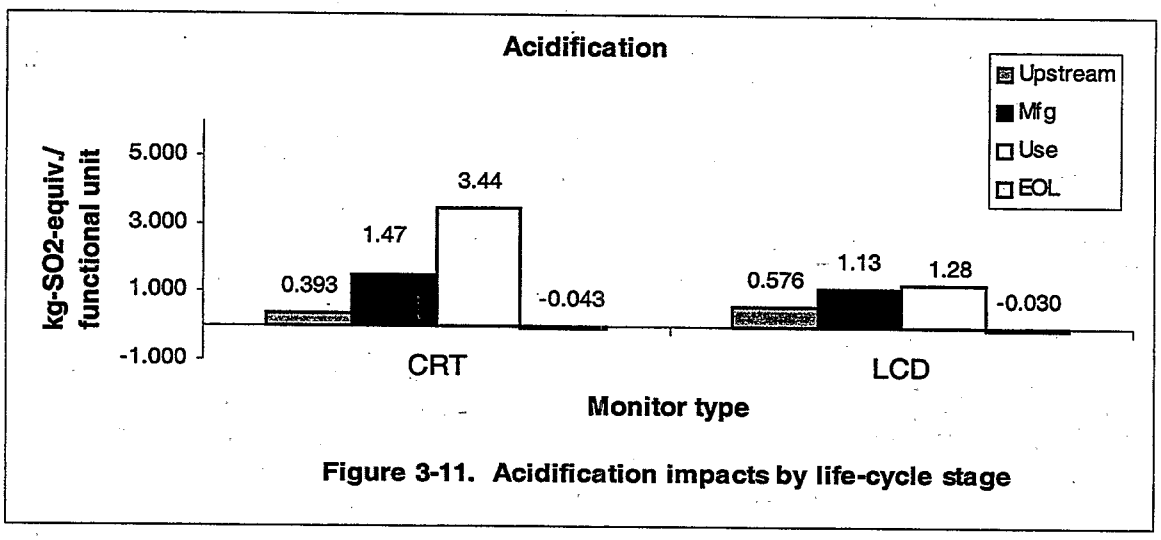


Figure 3-11. Acidification impacts by life-cycle stage

Emissions from manufacturing processes account for 28% of CRT acidification impacts and 38% of LCD acidification impacts. Material processing is responsible for about 7 and 19% of CRT and LCD impacts in this category, respectively. Both technologies receive a slight credit on acidification impacts during the EOL stage due to an energy credit from incineration processes with energy recovery, which offset some of the impacts from electricity production.

3.3.8.1 Major contributors to the CRT acidification results

Table 3-31 lists the materials that contribute to the top 99% of the CRT acidification impacts score and their LCI data type. SO_2 and NO_x emissions from the U.S. electric grid are the two largest contributors to the CRT acidification indicator, together accounting for 63% of the total. SO_x and NO_x emissions from the LPG production process are also significant, contributing about 23%. As noted previously, most of the LPG from this production process is used to manufacture CRT glass, but the mass of LPG inputs is uncertain and the basis of a sensitivity analysis later in this chapter (see Section 3.4).

Other materials that contribute more than one percent of the CRT acidification indicator are SO_2 emissions from invar production, hydrochloric acid emissions from electricity generation during the use stage, and sulfur dioxide emissions from electricity used in manufacturing. Note that most of the LCI data for materials in Table 3-31 are from secondary sources.

Table 3-31. Top 99% of the CRT acidification impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Use	U.S. electric grid	Sulfur dioxide	Model/secondary	47%
Use	U.S. electric grid	Nitrogen oxides	Model/secondary	16%
Manufacturing	LPG production	Sulfur oxides	Secondary	15%
Manufacturing	LPG production	Nitrogen oxides	Secondary	7.6%
Materials processing	Invar	Sulfur dioxide	Secondary	4.8%
Use	U.S. electric grid	Hydrochloric acid	Model/secondary	1.8%
Manufacturing	Japanese electric grid	Sulfur dioxide	Secondary	1.6%
Manufacturing	U.S. electric grid	Sulfur dioxide	Model/secondary	0.76%
Materials processing	Steel production, cold-rolled, semi-finished	Sulfur dioxide	Secondary	0.73%
Manufacturing	CRT glass/frit manufacturing	Nitrogen oxides	Primary	0.59%
Manufacturing	Japanese electric grid	Nitrogen oxides	Model/secondary	0.54%
Use	U.S. electric grid	Hydrofluoric acid	Model/secondary	0.41%
Materials processing	Aluminum production	Sulfur dioxide	Secondary	0.40%
Materials processing	Polycarbonate production	Nitrogen dioxide	Secondary	0.26%
Manufacturing	U.S. electric grid	Nitrogen oxides	Model/secondary	0.25%
Materials processing	Polycarbonate production	Sulfur dioxide	Secondary	0.23%
Manufacturing	LPG production	Nitrous oxide	Secondary	0.22%

*Column may not add to 99% due to rounding.

3.3.8.2 Major contributors to the LCD acidification impact results

Table 3-32 lists the materials responsible for the top 99% of the LCD acidification impact results and the LCI data type. Sulfur dioxide emissions from the U.S. electric grid during the use stage are the greatest contributor at 31%, followed by NO_x from natural gas production in the materials processing stage. The latter process produces natural gas used by one LCD monitor/module manufacturer as an ancillary material, indicating the LCD monitor/module manufacturing process group is ultimately responsible for this contribution to the impact score. However, as noted previously, only one LCD monitor/module manufacturer reported the ancillary use of LNG. Other LCD monitor/module manufacturers reported using LNG as a fuel, but not as an ancillary material. NO_x, ammonia, hydrofluoric acid, and hydrochloric acid emissions from LCD monitor/module manufacturing contribute another 22% of the LCD acidification impact score. LCD monitor/module manufacturing data were collected directly by the CDP from manufacturers in Asia.

NO_x emissions from the U.S. electric grid during the use stage, and SO_x and NO_x emissions from the Japanese electric grid during manufacturing are also among the top contributors to the LCD acidification results. LCI data for these process groups were developed by the CDP from secondary sources.

Table 3-32. Top 99% to the LCD acidification impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Use	U.S. electric grid	Sulfur dioxide	Model/secondary	31%
Materials processing	Natural gas prod.	Nitrogen oxides	Secondary	15%
Manufacturing	LCD monitor/module mfg.	Nitrogen oxides	Primary	13%
Use	U.S. electric grid	Nitrogen oxides	Model/secondary	10%
Manufacturing	Japanese electric grid	Sulfur dioxide	Model/secondary	9.8%
Manufacturing	LCD monitor/module mfg.	Ammonia	Primary	4.0%
Manufacturing	Japanese electric grid	Nitrogen oxides	Model/secondary	3.2%
Manufacturing	LCD monitor/module mfg.	Hydrofluoric acid	Primary	2.8%
Manufacturing	LCD monitor/module mfg.	Hydrochloric acid	Primary	1.8%
Manufacturing	LPG production	Sulfur oxides	Secondary	1.3%
Use	U.S. electric grid	Hydrochloric acid	Model/secondary	1.2%
Manufacturing	LCD backlight	Nitrogen oxides	Primary	0.70%
Materials processing	Natural gas production	Ammonia	Secondary	0.69%
Materials processing	Natural gas production	Sulfur oxides	Secondary	0.65%
Manufacturing	LPG production	Nitrogen oxides	Secondary	0.65%
Materials processing	Steel production, cold-rolled, semi-finished	Sulfur oxides	Secondary	0.64%
Materials processing	PMMA sheet production	Sulfur oxides	Secondary	0.44%
Manufacturing	Natural gas production	Nitrogen oxides	Secondary	0.35%
Use	U.S. electric gird	Hydrofluoric acid	Model/secondary	0.27%

*Column may not add to 99% due to rounding.

3.3.8.3 Limitations and uncertainties

Acidification impact characterization is a function of the mass of an acid-forming chemical emitted to air and the acidification potential (AP) equivalency factor for that chemical. The AP equivalency factor is the number of hydrogen ions that can theoretically be formed per mass unit of the pollutant being released compared to SO_2. This is a full equivalency approach to impact characterization where all substances are addressed in a unified, technical model, which lends more certainty to the characterization results than partial equivalency factors discussed with regard to photochemical smog (Section 3.3.7).

For the CRT, and less so for the LCD, impact results are being driven primarily by SO_2 and NO_x emissions from U.S. power plants during use of the monitor by the consumer. As discussed in Section 3.3.5 and noted above, the U.S. and Japanese electric grid inventories were developed by the CDP from secondary sources. U.S. electric grid emissions of the criteria pollutants, including SO_2 and NO_x, are based on data in the EPA publication, *National Air Quality and Emissions Trends Report, 1997* (EPA, 1998), which were the best data available when the electric grid inventory data was developed and are expected to be reasonably accurate. However, the Japanese electric grid inventory was derived from the U.S. inventory based on the mix of fuels used in Japan. Because Japanese power plants may employ different pollution

control devices, use fuels of different quality, or other factors, their emissions could actually be higher or lower than those reported in the inventory.

LCI data for many of the other primary contributors to the CRT acidification impact category are from existing LCI databases. The limitations and uncertainties associated with these data have been discussed extensively in other subsections of this chapter and pertain here. On the other hand, LCI data for many of the other primary contributors to the LCD acidification indicator results were collected directly by the CDP from manufacturers in Asia. These data are considered to be of better quality since they were collected to meet the goals, objectives and temporal and spatial boundaries of the CDP.

3.3.9 Air Particulates

Figure 3-12 presents the CRT and LCD LCIA results for the air particulates impact category by life-cycle stage, based on the impact assessment methodology presented in Section 3.1.2.8. Tables M-21 and M-22 in Appendix M list complete air particulates results for the CRT and LCD, respectively.

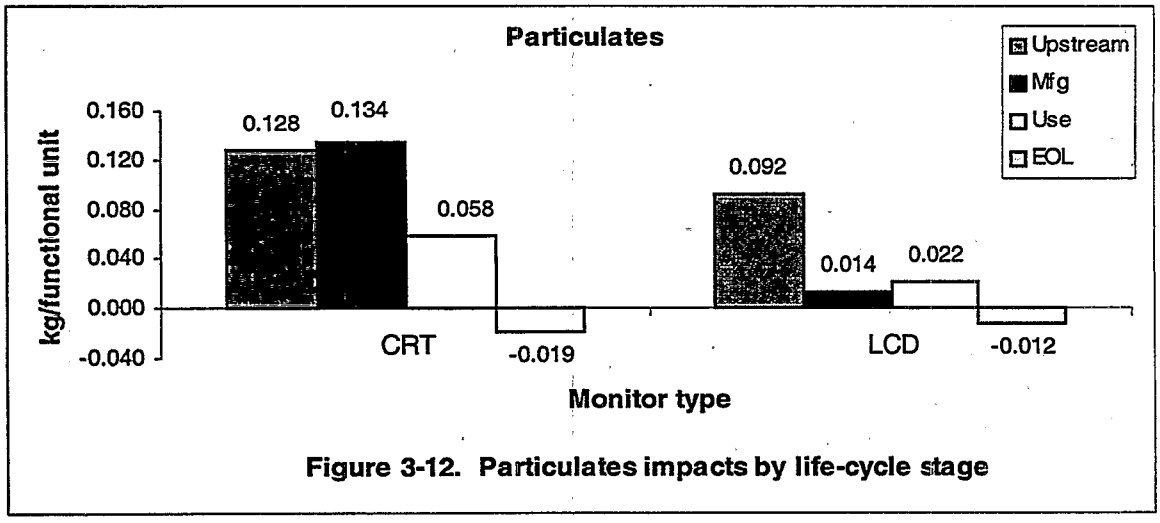


Figure 3-12. Particulates impacts by life-cycle stage

The life-cycle air particulates indicator is 0.30 kg of air particulates per monitor for the CRT and 0.115 kg of air particulates per monitor for the LCD. Recall from Section 3.1.2.8 that air particulates impact results are ideally based on release amounts of particulate matter with average aerodynamic diameter less than 10 micrometers (PM_{10}) to the air. This is the size of particulate matter that is most damaging to the respiratory system. However, as will be shown later in this section, a significant portion of the particulate emissions data for both monitor types do not specify a particulate size. This makes it more difficult to draw conclusions about the relative life-cycle air particulate impacts of the CRT and LCD.

The manufacturing and upstream materials processing stages have almost equal contribution to CRT air particulate impacts, at 45% of the total for the manufacturing stage and 43% of the total for the upstream stages. LCD impacts, on the other hand, are dominated by particulate emissions during the upstream, materials processing stages, which contribute 80% of the total score. Both technologies receive a substantial reduction in life-cycle air particulate impacts at EOL due to an energy credit from incineration with energy recovery. The energy

credit, which is from incineration with energy recovery, is applied to electric power production where it offsets some particulate emissions that would otherwise occur from electrical power production.

3.3.9.1 Major contributors to the CRT air particulates impact results

Table 3-33 lists the materials that contribute to the top 99% of the CRT air particulates impact score and their LCI data type. PM emissions from LPG production are the single largest contributor to the overall score, at 43% of the total. This LPG is primarily an energy source in CRT glass manufacturing, indicating the glass/frit process group is the ultimate source of these air particulate emissions. As noted previously, CRT glass energy inputs are the subject of a sensitivity analysis, discussed in Section 3.4.

Other major contributors to the CRT air particulates impact results are PM emissions from the steel production process group, PM_{10} emissions from the U.S. electric grid during the use stage, and PM emissions from aluminum production processes. Note that the inventories for steel and aluminum production combine data from the raw materials extraction, materials manufacture, and electricity generation processes. The PM emissions reported for the material production process group could be from any one of these individual processes, but particulate matter emissions are most often associated with combustion processes.

Table 3-33. Top 99% of the CRT air particulates impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Manufacturing	LPG production	PM	Secondary	43%
Materials processing	Steel production, cold-rolled, semi-finished	PM	Secondary	35%
Use	U.S. electric grid	PM-10	Model/secondary	19%
Materials processing	Aluminum production	PM	Secondary	3.0%

*Column adds to greater than 99% due to an offset of emissions from incineration with energy recovery at EOL.

As shown in Table 3-33, the impact scores associated with the LPG, steel, and aluminum production process groups—82% of CRT air particulates impacts—are based on emissions of PM instead of emissions of PM_{10}. This could be a matter of different terminology used in the secondary data sets for these process groups (that is, PM is used to represent PM_{10}), or it could represent a broader class of particulate emissions, of which PM_{10} emissions would be a subset. If the latter case is true, it is likely that CRT air particulate impacts are overstated.

3.3.9.2 Major contributors to the LCD air particulates impact results

Table 3-34 lists the materials that contribute to the top 99% of the LCD air particulates impact score and their LCI data type. PM emissions from steel production are the largest contributor to the overall score, followed by PM emissions from natural gas production. Natural gas from this process supplies the LNG used as an ancillary material by one LCD monitor/module manufacturer.

Other major contributors to the LCD air particulates impact results are PM_{10} emissions from the U.S. electric grid during the use stage and from the Japanese electric grid during

manufacturing, and PM emissions from LPG production. LPG from the latter process supplies energy to the LCD glass manufacturing process.

Table 3-34. Top 99% of the LCD air particulates impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Materials processing	Steel production, cold-rolled, semi-finished	PM	Secondary	45%
Materials processing	Natural gas production	PM	Secondary	25%
Use	U.S. electric grid	PM-10	Model/secondary	19%
Manufacturing	Japanese electric grid	PM-10	Model/secondary	5.9%
Manufacturing	LPG production	PM	Secondary	5.4%

*Column adds to greater than 99% due to an offset of emissions from incineration with energy recovery at EOL.

As shown in Table 3-34, the impact scores associated with the steel, natural gas, and LPG production process groups—roughly 75% of LCD air particulates impacts—are based on emissions of PM instead of emissions of PM_{10}. As with the CRT, air particulate impacts should be based on PM_{10} emissions, indicating LCD air particulate impacts may be overstated.

3.3.9.3 Limitations and uncertainties

The CDP LCIA methodology for air particulates is based on emissions of PM_{10} to air, which is the size of particulate matter that is most damaging to the respiratory system. However, as noted in Tables 3-33 and 3-34, the majority of the CRT and LCD impacts were calculated from emissions of "PM" rather than PM_{10}. This could be a matter of different terminology used in the secondary data sets for these process groups, or it could represent a broader class of particulate emissions, of which PM_{10} emissions would be a subset. If the latter case is true, it is likely that both the CRT and LCD air particulate impacts are overstated.

The LCI data for all of the major contributors to both the CRT and LCD were either developed by the CDP from secondary sources (e.g., the U.S. and Japanese electric grids) or are from secondary LCI data sets (e.g., the fuel and upstream materials production processes). The limitations and uncertainties associated with these data have been discussed in other subsections of this chapter and pertain here. Note that U.S. electric grid emissions of the criteria pollutant PM_{10} are based on data in the EPA publication, *National Air Quality and Emissions Trends Report, 1997* (EPA, December, 1998, EPA/454/R-98-016), and are expected to be reasonably accurate.

Finally, the amount of LPG used to produce CRT glass, which is ultimately driving the CRT air particulates results, is also uncertain due to the large variability in CRT glass energy inputs received from glass manufacturers. See Section 3.4 for a sensitivity analysis of CRT glass energy inputs.

3.3.10 Water Eutrophication

Figure 3-13 presents the CRT and LCD LCIA results for the water eutrophication impact category by life-cycle stage, based on the impact assessment methodology presented in Section 3.1.2.9. Tables M-23 and M-24 in Appendix M are complete results for the CRT and LCD, respectively.

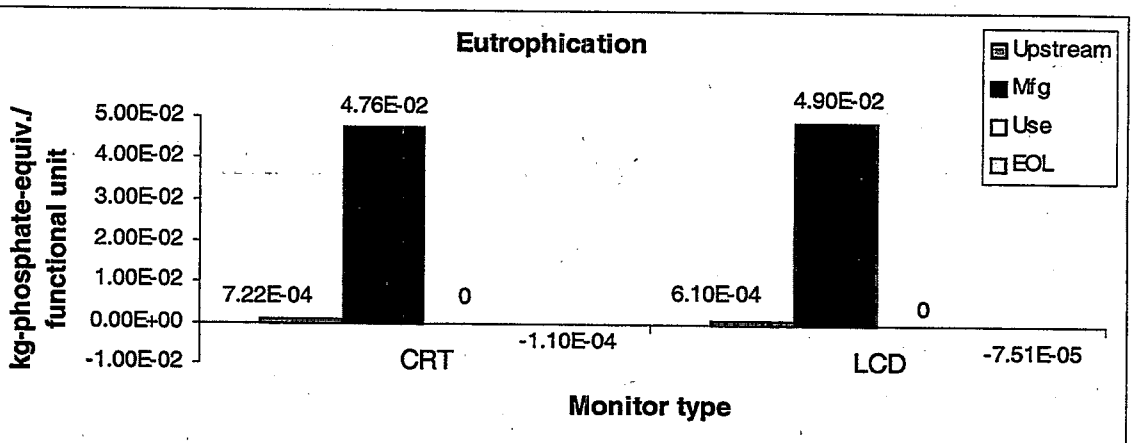


Figure 3-13. Eutrophication impacts by life-cycle stage

The life-cycle water eutrophication indicators are 0.048 kg of phosphate equivalents for the CRT and 0.050 kg of phosphate equivalents for the LCD. Results for both the CRT and LCD are completely dominated by emissions from the manufacturing stage, which accounts for 99% of the indicator for both technologies. Both technologies have negative scores at the end-of-life due to incineration with energy recovery. The energy recovery offsets some of the water emissions from the electricity generation inventory included in the incineration data set.

3.3.10.1 Major contributors to the CRT water eutrophication impact results

Table 3-35 lists the materials that contribute to the top 99% of the CRT water eutrophication results. Together, chemical oxygen demand (COD) and ammonia ions from the LPG production process group account for about 91% of the total score. Most of the LPG from this process is used as an energy source in CRT glass manufacturing (see Section 3.4 for the sensitivity analysis of CRT glass energy inputs). Emissions of nitrogen, COD and phosphorus from the CRT tube manufacturing process group contribute about seven percent of the CRT water eutrophication impacts. COD and other nitrogen emissions from steel production are the remaining top contributors to the CRT eutrophication score. LPG and steel production data are from secondary sources, while the CRT tube manufacturing outputs are primary data collected by the CDP.

Table 3-35. Top 99% of the CRT water eutrophication impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Manufacturing	LPG production	COD	Secondary	72%
Manufacturing	LPG production	Ammonia ions	Secondary	19%
Manufacturing	CRT tube manufacturing	Nitrogen	Primary	6.3%
Materials processing	Steel production, cold-rolled, semi-finished	Other nitrogen	Secondary	0.37%
Materials processing	Steel production, cold-rolled, semi-finished	COD	Secondary	0.33%
Manufacturing	CRT tube manufacturing	COD	Primary	0.33%
Manufacturing	CRT tube manufacturing	Phosphorus (yellow or white)	Primary	0.32%

*Column may not add to 99% due to rounding.

3.3.10.2 Major contributors to the LCD water eutrophication impact results

Table 3-36 lists the materials that contribute to the top 99% of the LCD water eutrophication results. Like the CRT, the LCD water eutrophication indicator is driven by emissions from a single process group, in this case, LCD monitor/module manufacturing. Together, emissions of nitrogen and phosphorus from that process account for 94% of the total score. The LPG production process is the next largest contributor to the LCD water eutrophication score, where water releases of COD and ammonia ions account for more than 4% of the total.

Table 3-36. Top 99% to the LCD water eutrophication impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Manufacturing	LCD monitor/module mfg.	Nitrogen	Primary	67%
Manufacturing	LCD monitor/module mfg.	Phosphorus (yellow or white)	Primary	27%
Manufacturing	LPG production	COD	Secondary	3.4%
Manufacturing	LPG production	Ammonia ions	Secondary	0.88%
Manufacturing	LCD panel components	Phosphorus (yellow or white)	Primary	0.48%
Materials processing	PMMA sheet production	Ammonia	Secondary	0.40%

*Column may not add to 99% due to rounding.

3.3.10.3 Limitations and uncertainties

Eutrophication (nutrient enrichment) impacts are calculated from the mass of a chemical released directly to surface water and the chemical's eutrophication potential (EP). The EP is a partial equivalency factor derived from the ratio of nitrogen and phosphorus in the average

composition of algae compared to the reference compound phosphate (see Section 3.1.2.9). As a partial equivalency approach, only a subset of substances can be converted into equivalency factors, which is a limitation of this LCIA methodology. However, the methodology does take into account nitrogen and phosphorus, which are the two major limiting nutrients of importance to eutrophication.

CRT water eutrophication results are dominated by LCI data from secondary sources, and are therefore subject to the limitations and uncertainties associated with secondary data. Furthermore, these results are ultimately due to the large amount of LPG reported to be used as a fuel in LPG glass production. Because of the large degree of variability in glass energy data received from three CRT glass manufacturers, CRT glass energy inputs are also uncertain and the subject of a sensitivity analysis (see Section 3.4). LCD results, on the other hand, are driven almost entirely by primary LCI data from the manufacturing life-cycle stage, which were collected to meet the goals, objectives, and temporal and geographic boundaries of the CDP and are therefore considered to be of better quality.

3.3.11 Water Quality

3.3.11.1 Biological oxygen demand (BOD)

Figure 3-14 presents the CRT and LCD LCIA results for the BOD water quality impacts category by life-cycle stage, based on the impact assessment methodology presented in Section 3.1.2.10. Complete results are listed in Tables M-25 (CRT) and M-26 (LCD) in Appendix M.

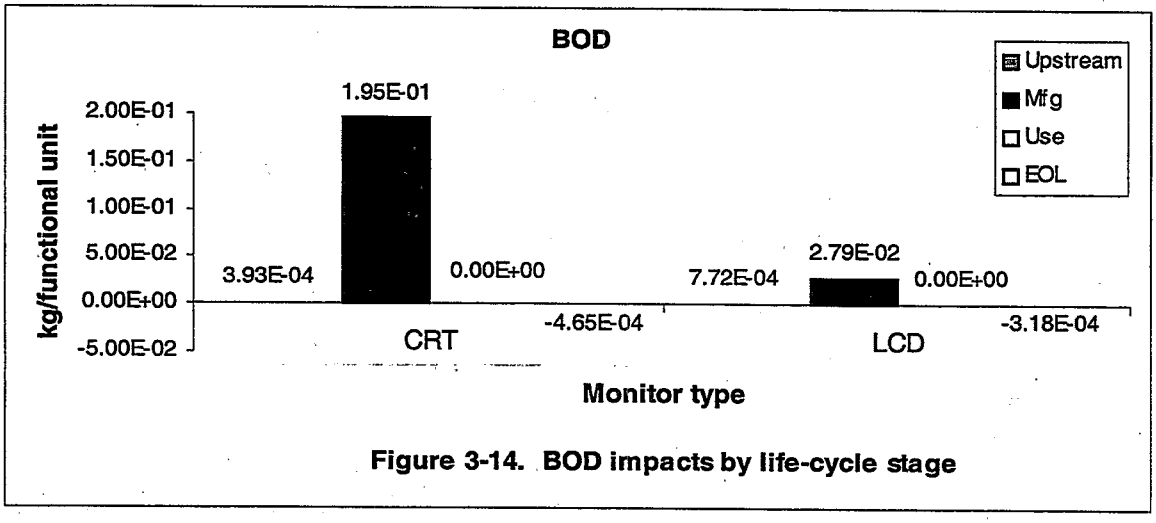


Figure 3-14. BOD impacts by life-cycle stage

During the life-cycle of a 17" CRT monitor, 0.195 kg of BOD are released to surface water. The life-cycle of a functionally equivalent 15" LCD results in 0.0283 kg of BOD surface water releases. As shown in Figure 3-14, BOD impacts for both monitor types are driven by surface water releases in the manufacturing stage, which contribute 100% of CRT impacts and 99% of LCD impacts. Note that small BOD impacts also occur in the upstream, materials processing life-cycle stage for both monitor types. These are almost entirely offset by negative BOD values at end of life due to the offset of electric grid emissions when the monitors are incinerated with energy recovery. Note also that there are no BOD emissions from the U.S.

electric grid during the use stage. The incineration inventory is a secondary data set that contains a different electric grid inventory than the U.S. electric grid inventory developed by the CDP.

Table 3-37 lists the materials responsible for the top 99% of the CRT BOD impacts. CRT impacts in this category are driven by BOD releases from the LPG production process, most of which is used to make LPG employed as fuel in CRT glass manufacturing. BOD releases from CRT tube manufacturing also contribute a small percentage to the total score.

Table 3-37. Top 99% of the CRT BOD impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score
Manufacturing	LPG production	BOD	Secondary	96%
Manufacturing	CRT tube manufacturing	BOD	Primary	3.3%

Table 3-38 lists the materials that contribute to the top 99% of the LCD BOD impacts. As shown in the table, LCD impacts are slightly more distributed among processes than CRT impacts, with BOD releases from four processes or process groups making up the list of top contributors. Note that BOD releases from LPG production (most of which is used to make LPG for LCD glass manufacturing) are much less for the LCD than the CRT, even though the LCD glass manufacturing inventory was derived from the CRT glass manufacturing inventory. This is because the CRT contains approximately ten times more glass than the LCD.

Table 3-38. Top 99% of the LCD BOD impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score
Manufacturing	LCD monitor/module mfg.	BOD	Primary	61%
Manufacturing	LPG production	BOD	Secondary	32%
Manufacturing	LCD panel components	BOD	Primary	4.7%
Materials processing	Natural gas production	BOD	Secondary	0.99%

3.3.11.2 Total suspended solids (TSS)

Figure 3-15 presents the CRT and LCD LCIA results for the TSS water quality impacts category by life-cycle stage, based on the impact assessment methodology presented in Section 3.1.2.10. Tables M-27 and M-28 in Appendix M list complete results for the CRT and LCD, respectively.

The life-cycle TSS impact indicator is 0.874 kg of TSS for the CRT and 0.0615 kg of TSS for the LCD. TSS impacts for both monitor types are driven by the manufacturing stage, where 99 and 94% of impacts occur for the CRT and LCD, respectively. TSS impacts also occur in the upstream, materials processing life-cycle stage for both monitor types. Both technologies receive a credit on TSS impacts at EOL due to an offset of electric grid emissions when the monitors are incinerated with energy recovery.

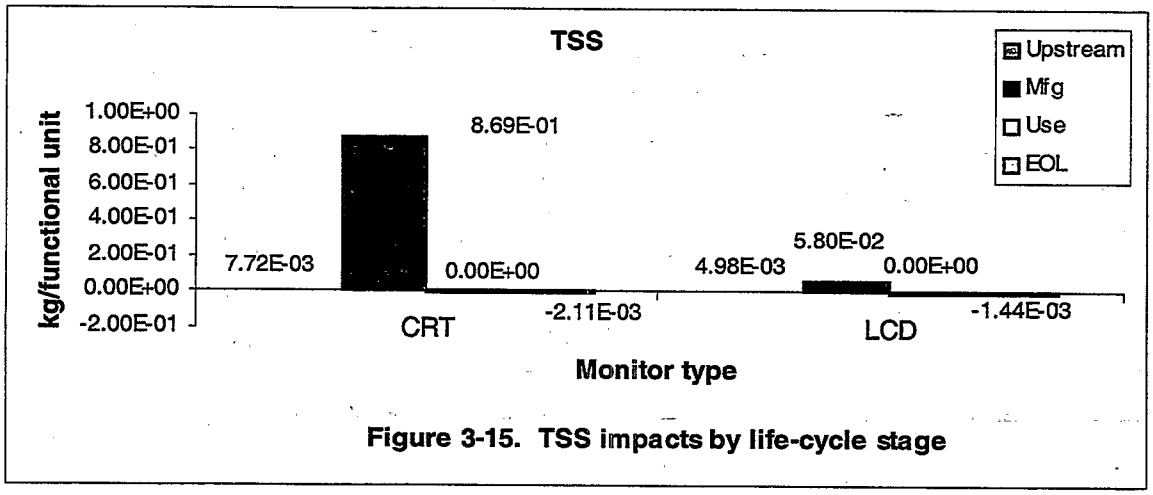


Figure 3-15. TSS impacts by life-cycle stage

Table 3-39 presents the major contributors to the CRT TSS indicator and lists the LCI data type. As with many other impact categories, the LPG production process is the single largest contributor to the CRT TSS indicator, accounting for 97% of the total score. Most of the LPG from this process is used as a fuel to produce CRT glass, but CRT energy inputs are uncertain and evaluated in a sensitivity analysis in Section 3.4. TSS surface water releases from the CRT glass/frit process group, CRT tube manufacturing, and fuel oil #6 production are also top contributors to the CRT TSS score. However, the contribution of these processes or process groups is small compared to that of the LPG production process.

Table 3-39. Top 99% of the CRT TSS impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score
Manufacturing	LPG production	Suspended solids	Secondary	97%
Manufacturing	CRT glass/frit mfg.	Suspended solids	Primary	0.83%
Manufacturing	CRT tube manufacturing	Suspended solids	Primary	0.53%
Manufacturing	Fuel oil # 6 production	Suspended solids	Secondary	0.33%

Table 3-40 presents the top contributors to the LCD TSS impact score. Like the CRT results discussed above, TSS surface water releases from the LPG production process are responsible for the majority of LCD TSS impacts. LPG from this production process is used to produce LCD glass. Note that the actual mass of TSS releases from the LCD-related process is much smaller than those from the CRT-related process. This is because the LCD only uses about 10% as much glass as the CRT. TSS releases from the LCD monitor/module process group also account for a sizeable percentage of LCD TSS impacts.

Table 3-40. Top 99% of the LCD TSS impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Manufacturing	LPG production	Suspended solids	Secondary	66%
Manufacturing	LCD monitor/module mfg.	Suspended solids	Primary	25%
Materials processing	PMMA sheet production	Suspended solids	Secondary	2.2%
Materials processing	Natural gas production	Suspended solids	Secondary	2.0%
Materials processing	Steel production, cold-rolled, semi-finished	Suspended solids	Secondary	1.6%
Materials processing	Aluminum production (all virgin)	Suspended solids	Secondary	1.1%
Manufacturing	LCD panel components	Suspended solids	Primary	1.0%

*Column may not add to 99% due to rounding.

3.3.11.3 Limitations and uncertainties

Both BOD and TSS indicators are calculated using a loading approach (i.e., the impact score is based on the inventory amounts) and are therefore highly sensitive to inventory data quality. CRT impact results are driven almost entirely by the LPG production inventory (a secondary data set) and are therefore subject to the limitations and uncertainties associated with secondary data. In particular, see Section 3.3.2.3 for a detailed discussion of LPG production data quality. In addition, note that LPG production impacts are almost all due to the large amount of LPG reported to be used as a fuel in CRT glass manufacturing. As note previously, CRT glass energy inputs are uncertain and are evaluated in a sensitivity analysis (see Section 3.4).

LCD impact results, on the other hand, are driven by LCI data from both primary and secondary sources and are therefore considered to be of somewhat better quality than the CRT results. However, a significant percentage of LCD water quality impacts also come from the large amount of LPG used as a fuel input to LCD glass manufacturing. These energy inputs are also uncertain and are evaluated in the sensitivity analysis in Section 3.4.

3.3.12 Radioactivity

Figure 3-16 presents the CRT and LCD LCIA results for the radioactivity impact category by life-cycle stage, based on the impact assessment methodology presented in Section 3.1.2.11. Complete CRT and LCD results are presented in Tables M-29 and M-30 in Appendix M, respectively.

The life-cycle radioactivity indicator is 38.5 million Bequerels (Bq) for the CRT and 12.2 million Bq for the LCD. Radioactivity impacts are driven by radioactive emissions from the upstream, materials processing stage for both monitor types, which contributes 99% of CRT life-cycle impacts and 98% of LCD life-cycle impacts. This result was unforeseen, since one might expect the majority of radioactive emissions to occur from the use stage, due to electricity generation at nuclear power plants. As it turns out, radioactivity impacts are being driven by data for nuclear fuel reprocessing that are included in the electric grid inventories for the steel, invar (an alloy of nickel and ferrite), and ferrite production process groups.

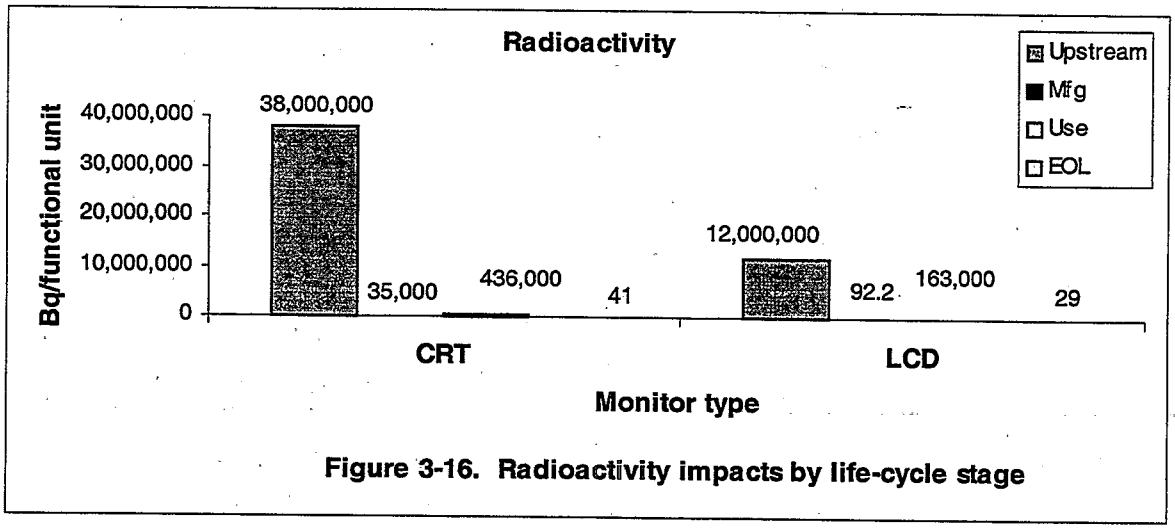


Figure 3-16. Radioactivity impacts by life-cycle stage

The LCIs for steel, invar, and ferrite were obtained from two databases developed by the former *Ecobilan Group,* an LCA consulting firm that was previously headquartered in France (see Section 2.2.1.1 for a discussion of how these databases were selected). Per *Ecobilan*, the ferrite inventory contains older data that may include radioactive emissions from electricity use. For the steel and nickel inventories, the source of both is site data in Europe, with the radioactive emissions coming from electricity in Europe, where nuclear fuel is reprocessed. In fact, the electricity data are from France for both materials, and France is one of the few countries (including Japan and the United Kingdom) that reprocesses nuclear fuel (Glazebrook, 2001). Therefore, the radioactivity impacts calculated from these inventories are more representative of impacts from countries that reprocess nuclear fuel than impacts from countries that do not.

To further illustrate this point, Tables 3-41 and 3-42 lists the materials and process groups that contribute to the top 99% of the CRT and LCD radioactivity indicator results, respectively. As shown in the tables, radioactivity impacts for both monitor types are driven by releases of plutonium-241 from steel (both monitor types), invar (CRT), and ferrite (CRT) production. Plutonium-241 is a byproduct of fuel reprocessing. Xenon -133 releases from the U.S. electric grid contribute slightly to the LCD radioactivity impacts and to a lesser degree to the CRT total impacts. Note that the actual amount of radioactivity from Xenon-133 is greater for the CRT than the LCD, but contributes a smaller percent of total impacts.

Table 3-41. Top 99% of the CRT radioactivity impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Materials processing	Steel production, cold-rolled, semi-finished	Plutonium-241 (isotope)	Secondary	62%
Materials processing	Invar	Plutonium-241 (isotope)	Secondary	18%
Materials processing	Ferrite	Plutonium-241 (isotope)	Secondary	17%
Use	U.S. electric grid	Xenon-133 (isotope)	Model/secondary	0.81%
Materials processing	Steel production, cold-rolled, semi-finished	Plutonium-240 (isotope)	Secondary	0.27%
Materials processing	Steel production, cold-rolled, semi-finished	Cesium-135 (isotope)	Secondary	0.24%

*Column may not add to 99% due to rounding.

Table 3-42. Top 99% of the LCD radioactivity impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Materials processing	Steel production, cold-rolled, semi-finished	Plutonium-241 (isotope)	Secondary	96%
Use	U.S. electric grid	Xenon-133 (isotope)	Model/secondary	0.95%
Manufacturing	Japanese electric grid	Xenon-133M (isotope)	Secondary	0.54%
Materials processing	Steel production, cold-rolled, semi-finished	Plutonium-240 (isotope)	Secondary	0.42%
Materials processing	Steel production, cold-rolled, semi-finished	Cesium-135 (isotope)	Secondary	0.38%

*Column may not add to 99% due to rounding.

Most of the radioactivity impacts are based on LCI data from secondary sources and are therefore subject to the limitations and uncertainties in secondary data, discussed previously. In addition, because radioactivity impacts are being driven by radioactive emissions from fuel reprocessing in France, they may not be representative of radioactivity impacts elsewhere. However, most of the CRT and LCD primary manufacturing data were collected from companies in Japan, where fuel reprocessing also occurs. For example, if Japanese CRT and LCD monitor and/or components manufacturers purchase steel from Japanese steel mills, the radioactivity emissions from electricity used to manufacture the steel could be similar. Japan ranked second in worldwide steel production in 2000 behind Mainland China, and third in 1999 behind Mainland China and the United States (IISI, 2001).

Note that the Japanese electric grid, which is linked to CRT and LCD production inventories, was developed from the U.S. electric grid inventory and therefore does not account for radioactive emissions from fuel reprocessing. This means that radioactive impacts from Japanese manufacturing processes that consume electricity are understated. For example, electricity used in the CRT glass/frit process group was the ninth largest contributor to the CRT energy use score, but the inventory for this process group does not account for fuel reprocessing emissions.

3.3.13 Potential Human Health Impacts

As discussed in Section 3.1.2.12, human health impacts included in the scope of this LCA are chronic (repeated dose) effects, including non-carcinogenic and carcinogenic effects to both workers and the public, and aesthetics. (Although not a health effect *per se*, aesthetics pertains to human welfare.)

Chronic health effect (cancer and noncancer) impacts are calculated using the scoring of inherent properties approach where an impact score is based on the inventory amount weighed by a hazard value (HV). The HV represents the chronic toxicity of a specific material (see Table K-8 in Appendix K for a list of toxicity values used to calculate hazard values). In this manner the inventory amount (the toxic chemical input amount for occupational health effects, and the output amount for public health effects) is used as a surrogate for exposure, while the hazard value represents the inherent toxicity of the chemical for chronic exposure.

The CDP human health effects LCIA methodology does not consider the fate and transport of a toxic chemical in the environment, nor does it evaluate the potential for actual exposures to occur. LCI data do not have the temporal and spatial specificity needed to estimate potential dose rates, for example, nor do they contain information on engineering controls used in an occupational setting to reduce exposure. [It should be noted that more sophisticated models for evaluating human health effects in an LCA framework are being developed that use a multimedia fate, multi-pathway human exposure, and toxicological potency approach (Bare, 1999). However, such models are less comprehensive in terms of the number of chemicals for which there are data.] The limitations and uncertainties in the health effects scores are discussed further below, following the presentation of results.

3.3.13.1 Chronic occupational health effects

Figure 3-17 presents the CRT and LCD LCIA results by life-cycle stage for the chronic occupational health effects impact category, based on the impact assessment methodology presented in Section 3.1.2.12. Complete CRT and LCD results are presented in Tables M-31 and M-32 in Appendix M.

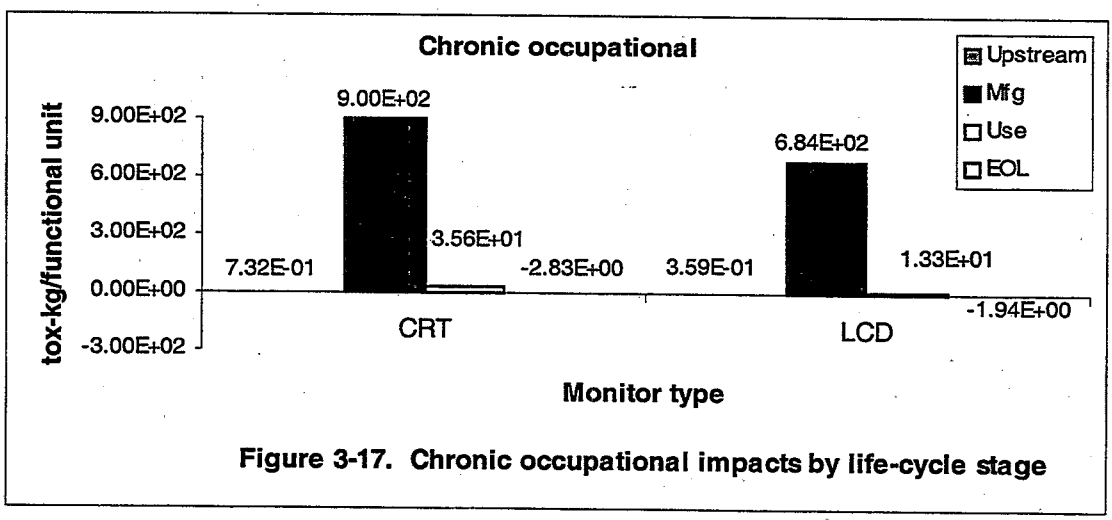


Figure 3-17. Chronic occupational impacts by life-cycle stage

The life-cycle chronic occupational health effects indicator is 934 tox-kg per functional unit for the CRT, and 696 tox-kg per functional unit for the LCD. As shown in the figure, the total score is dominated by toxic chemical inputs to the manufacturing stage, which account for 98% and 96% of CRT and LCD impacts in this category, respectively. This result was expected since inputs to the other life-cycle stages tend to be raw materials (e.g., ores, coal, etc., for the materials processing and use life-cycle stages) or finished products (e.g., the monitors themselves for the EOL stage) that are not classified as toxic materials (see Table K-9 in Appendix K for a l list of materials excluded from the toxic classification). Both the CRT and LCD receive negative chronic occupational health effects scores at end of life due to the offset of electric grid emissions when the monitors are incinerated with energy recovery.

Table 3-43 lists the materials responsible for the top 99% of the CRT chronic occupational health effects score and the LCI data type. LCI data for most of the top contributors are primary data collected from manufacturers by the CDP. In general, these data are expected to be of better quality (for the purposes of the CDP) than data from secondary sources, since they were collected to meet the goals and scope of the CDP.

Table 3-43. Top 99% of the CRT chronic occupational health effects score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Manufacturing	CRT glass/frit mfg.	Liquified petroleum gas	Primary	75%
Manufacturing	PWB manufacturing	Sulfuric acid	Primary	13%
Manufacturing	CRT tube manufacturing	Sulfuric acid	Primary	4.1%
Use	U.S. electric grid	Natural gas	Model/secondary	3.0%
Manufacturing	CRT glass/frit mfg.	Barium carbonate	Primary	1.8%
Use	U.S. electric grid	Petroleum (in ground)	Model/secondary	0.81%
Manufacturing	CRT tube manufacturing	Fuel oil # 6	Primary	0.79%

*Column may not add to 99% due to rounding.

LPG inputs to the glass/frit process group, primarily from CRT glass manufacturing, contribute 75% of the CRT impacts in this category. The high impact score for LPG is mainly due to the large amount of LPG inputs to the glass/frit process group (351 kg/functional unit), which results in a high score when multiplied by the HV. No toxicity data were available for LPG. Therefore, it was assigned default HVs of one for both cancer and noncancer effects (total HV=2), representative of mean cancer and noncancer toxicity values. As noted previously, glass manufacturing energy data are uncertain and therefore evaluated in a sensitivity analysis (see Section 3.4).

Sulfuric acid used in PWB manufacturing is the next greatest contributor to the CRT chronic occupational health effects results (13%) followed by sulfuric acid used in CRT tube manufacturing (4.1%). The sulfuric acid HV is based on an inhalation NOAEL of 0.1 mg/m^3, which is significantly lower (and therefore more toxic) than the geometric mean inhalation NOAEL of 68.7 mg/m^3. Consequently, sulfuric acid impacts are driven more by its inherent toxicity for noncancer effects than the input amounts (0.18 kg per functional unit for PWB manufacturing and 0.056 kg per functional unit for CRT tube manufacturing). Sulfuric acid has

no cancer slope factor and an IARC weight of evidence (WOE) classification of 3 (not classifiable for carcinogenicity), and therefore received an HV of zero for cancer effects.

Natural gas and petroleum used as fuels in the U.S. electric grid, barium carbonate used in the CRT glass/frit process group and fuel oil #6 used to manufacture the CRT tube round out the top contributors to the CRT chronic occupational health effects score. Barium carbonate has no cancer slope factor and an EPA cancer WOE of D (not classifiable), and therefore has an HV of zero for cancer effects. However, its oral NOAEL is 0.21 mg/kg-day compared to the geometric mean oral NOAEL of 11.9 mg/kg-day, which results in an HV of 57 for noncancer effects. Therefore, like sulfuric acid, the barium carbonate impacts are driven more by its inherent toxicity than the input amount (0.297 kg per functional unit). No specific toxicity data were available for natural gas, petroleum, or fuel oil #6; consequently they were assigned a default HV of one for both cancer and noncancer effects (total HV=2).

Table 3-44 lists the materials that contribute to the top 99% of the LCD chronic occupational health effects score. Like the CRT, LCI data for most of the top contributors are primary data collected from manufacturers by the CDP, and are therefore expected to be of generally better quality (for the purposes of the CDP) than data from secondary sources.

Table 3-44. Top 99% of the LCD chronic occupational health effects score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Manufacturing	LCD monitor/module mfg.	Liquified natural gas	Primary	57%
Manufacturing	LCD monitor/module mfg.	Sulfuric acid	Primary	23%
Manufacturing	PWB manufacturing	Sulfuric acid	Primary	8.0%
Manufacturing	LCD glass manufacturing	Liquified petroleum gas	Primary	4.7%
Manufacturing	LCD monitor/module mfg.	Phosphine	Primary	1.8%
Manufacturing	LCD panel components	Sulfuric acid	Primary	1.6%
Use	U.S. electric grid	Natural gas	Model/secondary	1.5%
Manufacturing	LCD monitor/module mfg.	Dimethylsulfoxide	Primary	1.1%
Manufacturing	LCD monitor/module mfg.	Ethanolamine	Primary	0.62%

*Column may not add to 99% due to rounding.

As shown in the table, LCD impacts in this category are dominated by LNG used in LCD monitor/module manufacturing. The high impact score for LNG is primarily due to the large amount of ancillary LNG inputs (194 kg/functional unit) in the LCD monitor/module manufacturing inventory, which results in a high score when multiplied by the HV. No toxicity data were available for LNG. Therefore, it was assigned a default, mean HV of one for both cancer and noncancer effects (total HV=2). As noted previously, only one of seven LCD module/monitor manufacturers reported using LNG as an ancillary material. Therefore, the total score for LCD chronic occupational health effects may not be representative of the industry as a whole. If we remove this application of LNG from the LCD inventory, the LCD occupational health effects result is reduced by 58 percent, from 683 tox-kg per monitor to 288 tox-kg per monitor. Note, however that other LCD monitor/module manufacturers did report using LNG as a fuel.

Sulfuric acid used in three process groups (LCD module/monitor manufacturing, PWB manufacturing, and LCD panel components) accounts for another 33% of the LCD chronic occupational health effects score. As discussed above for the CRT, sulfuric acid has a relatively low toxicity value, and therefore a high HV, which results in a high impact score for a small input amount. The LCD module/monitor manufacturing process group has the highest impact score for sulfuric acid because it has the greatest input amount (0.229 kg per functional unit).

The remaining top contributors to the LCD chronic occupational health effects score are LPG used in LCD glass manufacturing; and phosphine, dimethylsulfoxide, and ethanolamine used in LCD monitor/module manufacturing; and natural gas used as a fuel by the U.S. electric grid. As discussed earlier, LCD glass energy inputs are uncertain and evaluated in a sensitivity analysis in Section 3.4. The LPG score is based on default HVs (representative of the geometric mean toxicity values) for both cancer and noncancer effects, since no toxicity data were available for LPG.

The phosphine score is driven by its low oral NOAEL value (0.026 mg/kg-day), which is significantly lower than the geometric mean value of 68.7 mg-kg-day. Thus, due to its inherently high toxicity, a relatively small input of phosphine (in this case, 0.027 kg per functional unit) results in a relatively high chronic occupational health effects score. No slope factors or cancer WOE classifications were found for phosphine, indicating a default HV of one was used, which is far outweighed by the non-cancer hazard value.

Dimethylsulfoxide is less toxic than phosphine (oral LOAEL =1.0 mg/kg-day), but has a greater input amount (0.066 kg per functional unit). However, phosphine's greater toxicity outweighs the greater input amount for dimethylsulfoxide, resulting in a higher impact score for phosphine.

No specific toxicity data were available for natural gas; consequently it was assigned a default HV of one for both cancer and noncancer effects (total HV=2).

3.3.13.2 Chronic public health effects

Figure 3-18 presents the CRT and LCD LCIA scores by life-cycle stage for the chronic public health effects category, based on the impact assessment methodology presented in Section 3.1.2.12. Complete results are presented in Tables M-33 and M-34 in Appendix M, respectively.

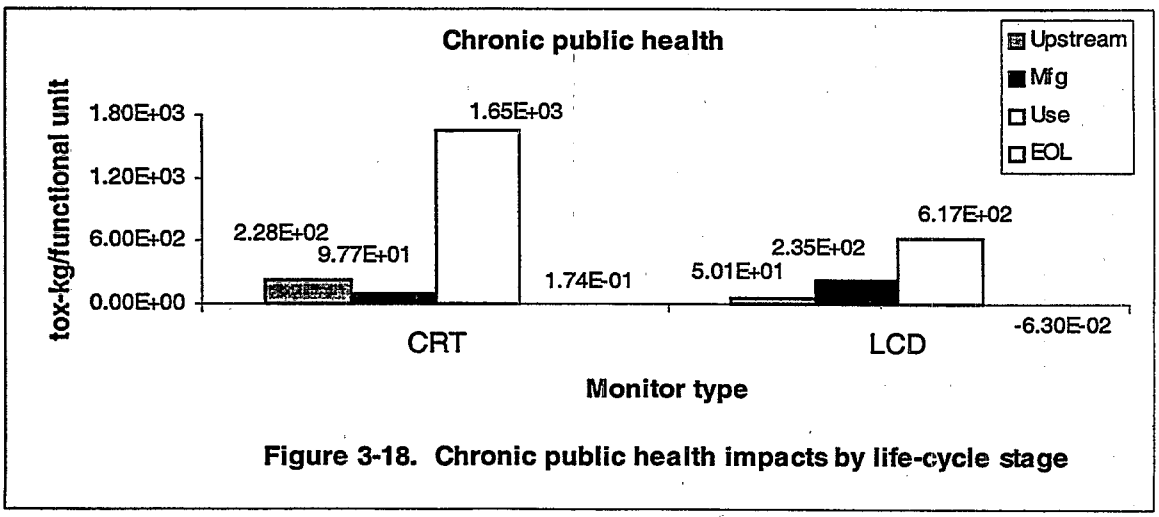


Figure 3-18. Chronic public health impacts by life-cycle stage

The life-cycle chronic public health effects score is 1,980 tox-kg per functional unit for the CRT and 902 tox-kg per functional unit for the LCD. As shown in the figure, the CRT score is dominated by toxic chemical outputs from electricity generation in the use stage, which account for almost 84% of CRT impacts in this category. To a lesser degree, LCD chronic public health effect impacts are also driven by emissions from electricity generation in the use stage, which account for more than 68% of the total. Note that the ratio of CRT to LCD use stage public health impacts is the same as the ratio of CRT to LCD use stage electricity consumption (634 kWh/life for the CRT to 237 kWh/life for the LCD).

The materials processing stage contributes almost 12% of CRT chronic public health effect impacts and almost six percent of LCD impacts. The manufacturing life-cycle stage is responsible for five and 26% of CRT and LCD impacts in this category, respectively. Both monitors receive very small public chronic health effects scores at end of life. This is because most public health effect impacts from CRT and LCD recycling and disposal processes are offset by a credit on electric grid emissions when the monitors are incinerated with energy recovery.

Table 3-45 presents the materials that contribute to the top 99% of the CRT chronic public health effects score. As shown in the table, SO_2 emissions from a number of different process groups almost completely dominate CRT impacts in this category, accounting for more than 98% of the total. All of the SO_2 LCI data shown in the table are either from secondary data sets not developed specifically for the CDP, or from the electric grid inventories developed from secondary sources for this project. Sulfur dioxide has a relatively high HV based on an inhalation NOAEL of 0.104 mg/m^3, compared to the geometric mean inhalation NOAEL of 68.7 mg/m^3. In addition, from a mass loading perspective, SO_2 emissions were the second largest contributor to CRT life-cycle air pollutant emissions, exceeded only by emissions of carbon dioxide (CO_2). Carbon dioxide is not classified as toxic, and therefore does not contribute to the human health effects scores.

Table 3-45. Top 99% of the CRT chronic public health effects score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Use	U.S. electric grid	Sulfur dioxide	Model/secondary	83%
Materials processing	Invar	Sulfur dioxide	Secondary	8.3%
Manufacturing	Japanese electric grid	Sulfur dioxide	Model/secondary	2.9%
Manufacturing	U.S. electric grid	Sulfur dioxide	Model/secondary	1.3%
Materials processing	Steel production, cold-rolled, semi-finished	Sulfur dioxide	Secondary	1.3%
Materials processing	Aluminum production	Sulfur dioxide	Secondary	0.70%
Materials processing	Polycarbonate production	Sulfur dioxide	Secondary	0.40%
Manufacturing	LPG production	Carbon monoxide	Secondary	0.29%
Materials processing	Lead production	Sulfur dioxide	Secondary	0.23%

*Column may not add to 99% due to rounding.

Most of the sulfur dioxide emissions that contribute to the CRT chronic public health effects score are from the combustion of fossil fuels used to generate electricity. For example, the electricity required to power the monitor during the use stage accounts for the vast majority of SO_2 emissions and 83% of the CRT chronic public health effects score. Sulfur dioxide

emissions from electricity consumed in the United States and Japan during the manufacturing life-cycle stage account for another 4.2% of the total score. Much of the SO_2 emissions reported in secondary data sets for the materials processing life-cycle stage may also be from electricity generation since many of these data also contain an electric grid inventory.

Table 3-46 lists the materials that contribute to the top 99% of the LCD chronic public health effects score and the LCI data type. LCD impacts in this category are also dominated by SO_2 emissions, which are responsible for roughly 93% of impacts. Like the CRT, most of these emissions occur from electricity generation, either during the use stage (68%) or manufacturing (21%). As noted previously, SO_2 has a relatively high HV due to its low toxicity value (inhalation NOAEL = 0.104 mg/m^3). Similar to the CRT, from a mass loading perspective, SO_2 emissions were the second largest contributor to LCD life-cycle air pollutant emissions, exceeded only by emissions of CO_2.

Table 3-46. Top 99% of the LCD chronic public health effects score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Use	U.S. electric grid	Sulfur dioxide	Model/secondary	68%
Manufacturing	Japanese electric grid	Sulfur dioxide	Model/secondary	21%
Manufacturing	LCD monitor/module mfg.	Phosphine	Primary	3.2%
Materials processing	Steel production, cold-rolled, semi-finished	Sulfur dioxide	Secondary	1.4%
Materials processing	PMMA sheet production	Sulfur dioxide	Secondary	0.96%
Materials processing	Natural gas production	Methane	Secondary	0.78%
Materials processing	Natural gas production	Benzene	Secondary	0.59%
Materials processing	Aluminum production	Sulfur dioxide	Secondary	0.57%
Materials processing	Natural gas production	Carbon monoxide	Secondary	0.53%
Materials processing	Polycarbonate production	Sulfur dioxide	Secondary	0.49%
Manufacturing	LCD monitor/module mfg.	Phosphorus (yellow or white)	Primary	0.38%
Manufacturing	U.S. electric grid	Sulfur dioxide	Model/secondary	0.35%

*Column may not add to 99% due to rounding.

Other top contributors to the LCD chronic public health effects score include phosphine and phosphorus from LCD monitor/module manufacturing, and methane, benzene, and carbon monoxide from natural gas production. As noted above in the section on chronic occupational health effects, the phosphine score is driven by its low oral NOAEL value (0.026 mg/kg-day), which is significantly lower than the geometric mean value of 68.7 mg-kg-day, resulting in a high HV. Thus, a relatively small output of phosphine (in this case, air emissions of 0.063 kg per functional unit) results in a relatively high chronic public health effects score.

The benzene and phosphorus chronic health effects scores are also driven more by their toxicity than the output amounts. Benzene is a known human carcinogen (EPA WOE Class A) that also causes noncancer health effects. The HV for benzene is based on its oral slope factor [0.055 (mg/kg-day)$^{-1}$] and its inhalation NOAEL for noncancer effects (1.15 mg/m^3), which

together result in a high HV. (Benzene also has an *inhalation* slope factor and an *oral* NOAEL value, but these yield lower hazard values when compared to the geometric mean values.) Phosphorus has an EPA WOE classification of D (not classifiable as to human carcinogenicity), but has a low oral NOAEL value (0.015 mg/kg-day), which also gives it a high HV.

No toxicity data were available for methane. Therefore, it received a default HV of one for both cancer and noncancer effects (HV=2 total). The HV for carbon monoxide is based on an inhalation LOAEL of 55 mg/m^3.

3.3.13.3 Chronic public health effect scores modified to exclude sulfur dioxide

Because the chronic public health effects scores for both the CRT and the LCD are dominated by SO_2 emissions, a secondary analysis was run to identify the top contributors to public health impacts when SO_2 emissions are excluded from the inventories. Results of this analysis may be more useful to manufacturers seeking to identify problematic toxic chemicals within their own manufacturing processes.

Figure 3-19 presents the CRT and LCD chronic public health effects scores by life-cycle stage when SO_2 emissions are excluded from the inventories. Under this scenario, the CRT score is reduced almost 99% from 1980 tox-kg to 26 tox-kg per functional unit, and the LCD score is reduced about 93% from 902 tox-kg to 61 tox-kg per functional unit. Note that these scores should not be used to evaluate which monitor type has higher overall impacts in this category, but they are useful for identifying life-cycle improvement opportunities that were previously obscured by SO_2 impacts.

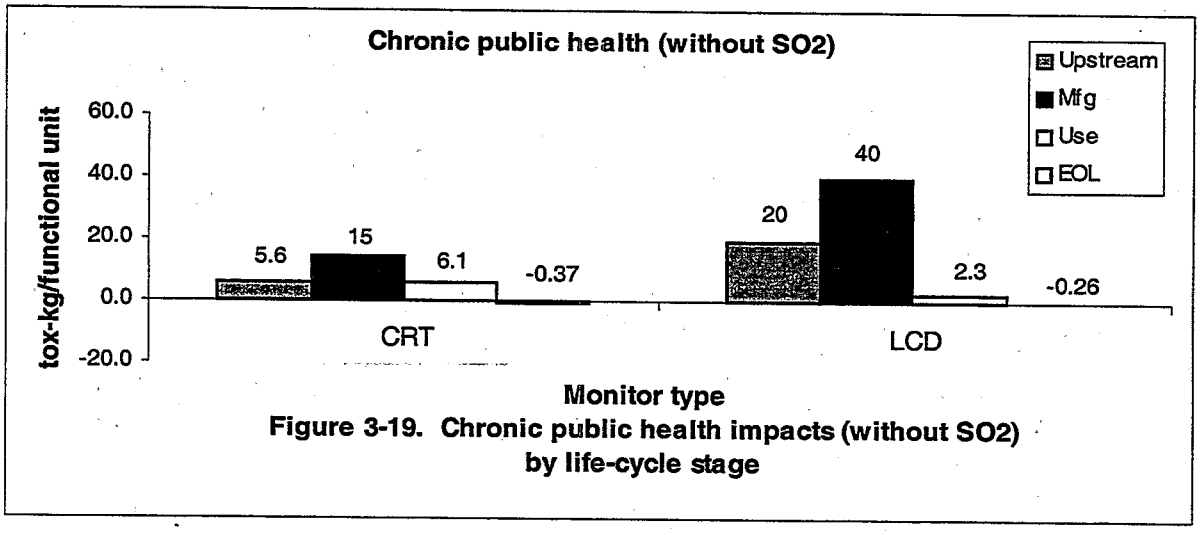


Figure 3-19. Chronic public health impacts (without SO2) by life-cycle stage

With SO_2 emissions removed from the inventories, chronic public health effect impacts are highest in the manufacturing life-cycle stage for both the CRT (56% of impacts) and the LCD (65% of impacts). The use stage is the next largest contributor for the CRT (22%), and the materials processing stage in the next largest contributor for the LCD (32%). As will be shown below, use stage impacts are significant for the CRT, even when SO_2 emissions are excluded, because of the CRT's relatively high electricity consumption during use by the consumer and the associated emissions of pollutants from U.S. power plants.

Table 3-47 presents the materials that contribute greater than one percent of CRT impacts when SO_2 emissions are excluded from the CRT inventory. Under this scenario, CRT chronic public health impacts are still being driven by emissions of criteria air pollutants,[2] including carbon monoxide, nitrogen oxides, and sulfur oxides (assuming that SO_2 emissions comprise a large part of the sulfur oxide emissions shown in the table). As shown in the table, emissions of these three pollutants or pollutant categories are responsible for some 48% of CRT chronic public health impacts when pure SO_2 emissions are excluded from the CRT inventory. Note that the majority of these emissions occur from the LPG production process, and most of this LPG is used as a fuel in CRT glass manufacturing. CRT glass manufacturing energy inputs are uncertain and evaluated in a sensitivity analysis (See Section 3.4). Other significant contributors include arsenic from lead production, methane from LPG production and the U.S. electric grid inventory, vanadium and benzene from LPG production, and titanium tetrachloride from aluminum production.

Table 3-47. Materials contributing greater than 1% of the CRT chronic public health effects score (without SO_2)

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score
Manufacturing	LPG production	Carbon monoxide	Secondary	22.35%
Use	U.S. electric grid	Nitrogen oxides	Modeled/secondary	9.12%
Materials processing	Lead	Arsenic	Secondary	8.55%
Manufacturing	LPG production	Methane	Secondary	6.50%
Manufacturing	LPG production	Sulfur oxides	Secondary	6.21%
Use	U.S. electric grid	Methane	Modeled/secondary	4.99%
Manufacturing	LPG production	Nitrogen oxides	Secondary	4.44%
Use	U.S. electric grid	Carbon monoxide	Modeled/secondary	4.23%
Manufacturing	LPG production	Vanadium	Secondary	4.05%
Manufacturing	LPG production	Benzene	Secondary	3.32%
Materials processing	Aluminum production (virgin)	Titanium tetrachloride	Secondary	2.79%
Manufacturing	CRT glass/frit mfg.	Fluorides (F-)	Primary	2.27%
Use	U.S. electric grid	Arsenic	Modeled/secondary	2.16%
Use	U.S. electric grid	Hydrochloric acid	Modeled/secondary	1.91%
Materials processing	Steel Prod., cold-rolled, semi-finished	Carbon monoxide	Secondary	1.16%

Table 3-48 presents the materials that contribute greater than one percent of LCD impacts when SO_2 emissions are excluded from the LCD inventory. Under this scenario, phosphine emissions from LCD monitor/module manufacturing are the dominant factor in the LCD chronic public health effects score, contributing 47% of the total. Other significant contributors include methane, benzene, carbon monoxide, and nitrogen oxides from natural gas production, and

[2] The criteria air pollutants are those for which U.S. National Ambient Air Quality Standards have been adopted. They are carbon monoxide, lead, nitrogen oxides, ozone, particulate matter, and sulfur dioxide.

phosphorus, fluorides, tetramethyl ammonium hydroxide, and nitrogen oxides from LCD monitor/module manufacturing. Recall that the LCD monitor/module manufacturing process consumes the majority of the natural gas made in the natural gas production process, where LNG is used as an ancillary material. However, only one of the seven LCD monitor/module manufacturers that provided inventory data to the CDP reported the ancillary use of LNG. Other LCD monitor/module manufactures did report the use of LNG as a fuel.

Table 3-48. Materials contributing greater than 1% of the LCD chronic public health effects score (without SO_2)

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score
Manufacturing	LCD monitor/module mfg.	Phosphine	Primary	46.7%
Materials processing	Natural gas production	Methane	Secondary	11.4%
Materials processing	Natural gas production	Benzene	Secondary	8.61%
Materials processing	Natural gas production	Carbon monoxide	Secondary	7.81%
Manufacturing	LCD monitor/module mfg.	Phosphorus (yellow or white)	Primary	5.56%
Manufacturing	LCD monitor/module mfg.	Fluorides (F-)	Primary	4.15%
Materials processing	Natural gas production	Nitrogen oxides	Secondary	2.12%
Manufacturing	LCD monitor/module mfg.	Tetramethyl ammonium hydroxide	Primary	2.09%
Manufacturing	LCD monitor/module mfg.	Nitrogen oxides	Primary	1.78%
Use	U.S. electric grid	Nitrogen oxides	Modeled/secondary	1.43%

3.3.13.4 Limitations and uncertainties: chronic human health effects

Most of the limitations and uncertainties in the chronic human health effects results presented here can be grouped into three categories:

1. *Structural or modeling limitations and uncertainties* associated with the accuracy of the toxic chemical classification method and the chemical scoring approach used to characterize human health effects.
2. *Toxicity data limitations and uncertainties* associated with the availability and accuracy of toxicity data to represent potential human health effects.
3. *LCI data limitations and uncertainties* associated with the accuracy and representativeness of the inventory data.

Each of these are discussed below.

Structural or modeling limitations and uncertainty. The chemical scoring method used in the human health effects impact characterization is a screening tool to identify chemicals of potential concern, not to predict actual effects or characterize risk. A major limitation in the method is that it only measures relative toxicity, combined with inventory amount. It does not take chemical fate, transformation, or degradation into account. In addition, it uses a simple surrogate value (i.e., inventory amount) to evaluate the potential for exposure, when actual

exposure potential involves many more factors, some of which are chemical-specific. Other sources of uncertainty include possible omissions by the CDP researchers in the impact classification process (e.g., potentially toxic chemicals not classified as such) or misrepresentation of chemicals in the impact characterization method itself (e.g., misrepresenting a chemical as a small contributor to total impacts, because of missing or inaccurate toxicity data). Some of these limitations and uncertainties may also be considered limits in the toxicity data which are discussed further below.

It should also be noted, however, that because LCA involves analyzing many processes over the entire life cycle of a product, a comprehensive, quantitative risk assessment of each chemical input or output can not be done. Rather, LCA develops relative impacts that often lack temporal or spatial specificity, but can be used to identify materials for more detailed evaluation. More detailed assessments of the toxicity and potential exposures to selected materials are performed in Chapter 4.

Toxicity data limitations and uncertainties. Major uncertainties in the impact assessment for potentially toxic chemicals result from missing toxicity data and from limitations of the available toxicity data. Uncertainties in the human health hazard data (as typically encountered in a hazard assessment) include the following:

- Using dose-response data from laboratory animals to represent potential effects in humans.
- Using data from homogeneous populations of laboratory animals or healthy human populations to represent the potential effects on the general human populations, with a wide range of sensitivities.
- Using dose-response data from high dose toxicity studies to represent potential effects that may occur at low levels.
- Using data from short-term studies to represent the potential effects of long-term exposures.
- Assuming a linear dose-response relationship.
- Possibly increased or decreased toxicity resulting from chemical interactions.

Regarding uncertainties resulting from missing toxicity data, there is uncertainty associated with using a default HV (i.e., assuming average toxicity for that measure when a chemical could be either more or less toxic than average). However, the use of neutral default values for missing data reduces the bias that typically favors chemicals with little available information. Use of a data-neutral default value to fill data gaps is consistent with principles for chemical ranking and scoring (Swanson and Socha, 1997). Of the 273 chemicals classified as potentially toxic in the CDP LCA, 156 (57%) had no toxicity data for carcinogenic effects and 128 (47%) had no data for noncarcinogenic effects. Ninety-seven chemicals (36%) had no human health toxicity data whatsoever.

LCI data limitations and uncertainty. Limitations and uncertainties in the LCI data have been discussed previously and are generally related to: (1) uncertainties in data from secondary sources that may not be representative of the geographic and temporal boundaries of this LCA, and (2) uncertainties in a few of the primary data points collected specifically for this project. With regard to the latter, glass manufacturing energy inputs are particularly uncertain despite

numerous attempts to resolve the uncertainty, but are responsible for a significant portion of CRT human health impacts. Glass manufacturing energy inputs are evaluated in a sensitivity analysis in Section 3.4. The amount of LNG used as an ancillary material in LCD monitor/module manufacturing is also uncertain (also despite attempts to resolve questions regarding the data), but this material contributes a significant portion of LCD occupational health impacts. As noted previously, removing this application of LNG from the LCD monitor/module manufacturing inventory would reduce the LCD chronic occupational health effects score by 68%.

3.3.13.5 Aesthetic impacts (odor)

Figure 3-20 presents the CRT and LCD LCIA results for the aesthetic impacts (odor) category, based on the impact assessment methodology presented in Section 3.1.2.12. Complete results for the CRT and LCD are presented in Tables M-35 and M-36 in Appendix M, respectively. The life-cycle aesthetic (odor) impact result is 7.58 million m^3 malodorous air per functional unit for the CRT and 5.04 million m^3 malodorous air per functional unit for the LCD. As shown in the figure, this impact category indicator is dominated by air emissions in the manufacturing stage for both the CRT (96% of total) and the LCD (98% of total). Both monitor types receive relatively minor contributions in the use and materials processing life-cycle stages, and negative values at end of life. Negative values are due to the offset of electric power plant emissions from incineration with energy recovery.

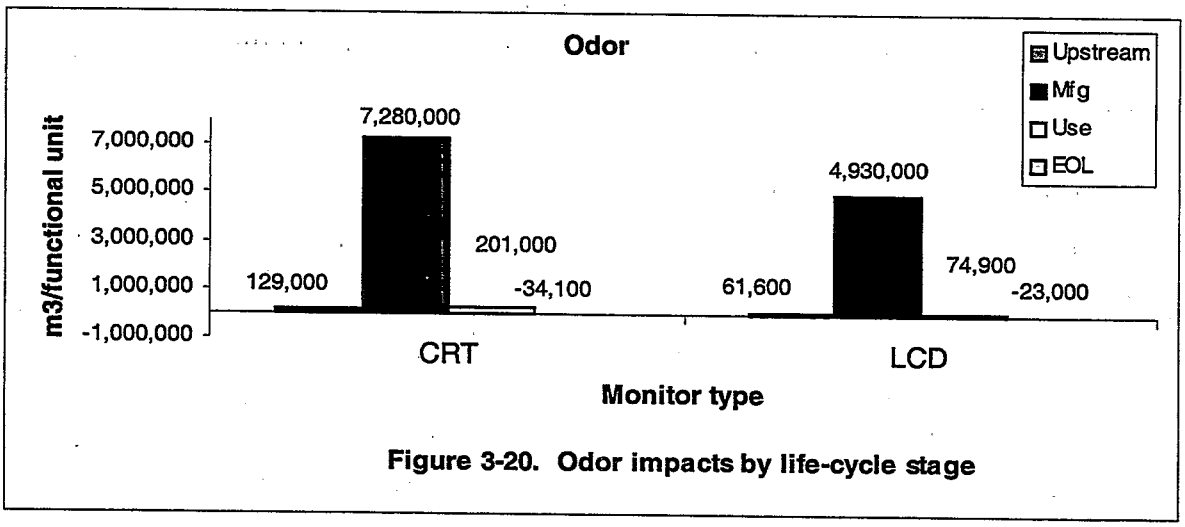


Figure 3-20. Odor impacts by life-cycle stage

Major Contributors to the CRT Aesthetics (Odor) Result

Table 3-49 lists the materials that contribute to the top 99% of the CRT aesthetic impacts result and the LCI data type. Air emissions of hydrogen sulfide from LPG production in the manufacturing life-cycle stage dominate the CRT odor impacts, contributing 94% of the total score. Hydrogen sulfide impacts are calculated based on an odor threshold value (OTV) of 0.00043 mg/m^3. [See Table K-7 in Appendix K for a list of OTVs used to calculate aesthetic (odor) impacts.] As noted previously, most of the LPG produced by this process is used as a fuel in CRT glass manufacturing, but glass manufacturing energy inputs are uncertain. The next largest contributor to the CRT is acetaldehyde emitted from the U.S. electric grid during the use

stage. Acetaldehyde has a lower OTV (0.00027 mg/m^3) than LPG, and is also emitted in smaller quantities. Emissions of hydrogen sulfide from fuel oil #6 production, steel production, and ABS production are the remaining top contributors to the CRT aesthetic impacts score. LCI data for all of the top contributors are either from secondary data sets or developed by CDP researchers from secondary sources.

Table 3-49. Top 99% of the CRT aesthetic (odor) impacts score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Manufacturing	LPG production	Hydrogen sulfide	Secondary	94%
Use	U.S. electric grid	Acetaldehyde	Model/secondary	2.5%
Manufacturing	Fuel oil #6 production	Hydrogen sulfide	Secondary	0.98%
Materials processing	Steel production, cold-rolled, semi-finished	Hydrogen sulfide	Secondary	0.42%
Materials processing	ABS production	Hydrogen sulfide	Secondary	0.31%

*Column may not add to 99% due to rounding.

Major Contributors to the LCD Aesthetics (Odor) Result

Table 3-50 presents the materials that contribute to the top 99% of the LCD aesthetics impact score and the LCI data type. LCD impacts are dominated by air emissions of phosphine from LCD monitor/module manufacturing, which contribute 89% of the total score. OTVs reported for phosphine range from 0.014 to 2.8 mg/m^3. The lower, more sensitive value (0.014 mg/m^3) was used to calculate impacts.

Table 3-50. Top 99% of the LCD aesthetic (odor) impacts score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Manufacturing	LCD monitor/module mfg.	Phosphine	Primary	89%
Manufacturing	LPG production	Hydrogen sulfide	Secondary	6.8%
Use	U.S. electric grid	Acetaldehyde	Model/secondary	1.4%
Manufacturing	LCD monitor/module mfg.	Ammonia	Primary	1.2%
Manufacturing	LCD monitor/module mfg.	Acetic acid	Primary	0.44%

*Column may not add to 99% due to rounding.

Other significant contributors include hydrogen sulfide from LPG production, acetaldehyde from the U.S. electric grid, and ammonia and acetic acid from LCD module/monitor manufacturing. Most of the LPG made in the LPG production process is used as a fuel in LCD glass manufacturing, indicating this process is ultimately responsible for LPG production impacts. However, LCD glass energy inputs are uncertain and evaluated in a sensitivity analysis (Section 3.4). LCD monitor/module manufacturing data were collected directly from manufacturers by the CDP, while the LPG production inventory was obtained from *Ecobilan*. The U.S. electric grid inventory was developed by CDP researchers from secondary sources.

Limitations and Uncertainties

Aesthetic (odor) impact scores are based on the identity and amount of odor-causing chemicals (Heijungs *et al.*, 1992; EPA, 1992), released to the air divided by their chemical-specific OTVs. An OTV is the lowest concentration of a substance in air that can be smelled based on a standardized test. Limitations and uncertainties in the aesthetics impact score stem from structural or model uncertainty (whether or not odor thresholds will actually be exceeded), OTV data uncertainty (how well published OTVs represent the odor threshold of different populations), and LCI data uncertainty.

The aesthetics impact score calculates the mass of malodorous air that could result if a chemical release occurs in a finite volume of air. It does not predict whether actual odor impacts will occur. This is because LCI data do not describe the time rate of release or whether dilution and mixing with ambient air will dilute the concentration of a pollutant to below its odor threshold. In addition, odor thresholds are highly variable because of the differing ability of individuals to detect odors. Therefore, the impact scores may not account for odors perceived by the most sensitive populations or may overstate impacts perceived by less sensitive populations. Finally, the aesthetic impact scores are subject to the limitations and uncertainties in the LCI data, since they are calculated from air emissions data in the inventories. The limitations and uncertainties in LCI data were discussed in Section 2.2.2.2, and have been discussed extensively with LCIA results for other impact categories, above.

3.3.14 Ecotoxicity

Ecotoxicity refers to effects of chemical outputs on non-human living organisms. As discussed in Section 3.1.2.13, ecotoxicity impact categories included in the scope of this LCA include impacts to aquatic and terrestrial organisms.

Ecotoxicity impacts are calculated using the scoring of inherent properties approach where an impact score is based on the inventory amount weighed by a hazard value (HV). The HV represents the toxicity of a specific material to aquatic or terrestrial organisms (see Table K-8 in Appendix K for a list of toxicity values used to calculate hazard values). Aquatic HVs are based on acute and chronic toxicity values for fish, while terrestrial HVs are based on chronic noncancer toxicity values for mammals, usually rodents. Similar to the chronic human health impacts discussed in Section 3.3.13, the inventory amount (the toxic chemical outputs to water for aquatic toxicity effects, and the outputs to air and water for terrestrial toxicity effects) is used as a surrogate for exposure, while the hazard value represents the inherent toxicity of the substance.

Also like the human health effects methodology, the CDP ecotoxicity LCIA methodology does not consider the fate and transport of a toxic chemical in the environment, nor does it evaluate the potential for actual exposures to occur. In addition, the methodology is limited in that it does not consider toxicity data from all types of aquatic or terrestrial species, but rather focuses on a few selected species for which more toxicity data are available. The limitations and uncertainties in the ecotoxicity scores are discussed further below, following the presentation of results.

3.3.14.1 Aquatic toxicity

Figure 3-21 presents the CRT and LCD LCIA results for the aquatic toxicity impact category, based on the impact assessment methodology presented in Section 3.1.2.13. Complete results for the CRT and LCD are presented in Tables M-37 and M-38 in Appendix M, respectively.

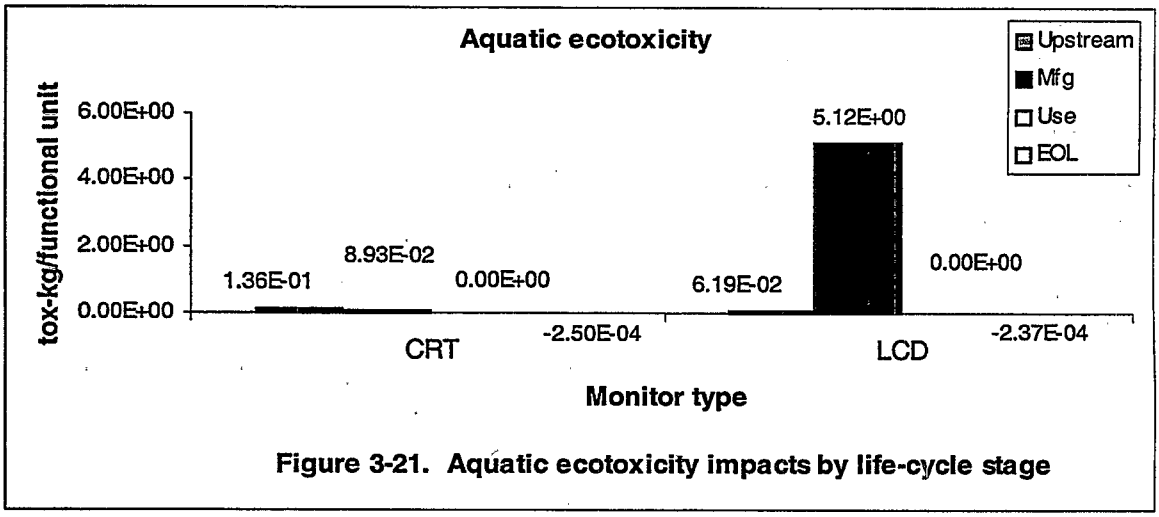


Figure 3-21. Aquatic ecotoxicity impacts by life-cycle stage

The life-cycle aquatic toxicity indicator is 0.22 tox-kg per functional unit for the CRT and 5.19 tox-kg per functional unit for the LCD. As shown in the figure, the CRT aquatic toxicity indicator is driven by water releases in the materials processing stage (64% of total), while the LCD aquatic toxicity indicator is completely dominated by water releases in the manufacturing stage (99% of total). Both monitor types receive zero scores in the use stage and small, negative values at end of life. Negative values are due to the offset of electric power plant emissions from incineration with energy recovery.

Table 3-51 lists the materials that contribute to the top 99% of the CRT aquatic toxicity impact score and the LCI data type. As shown in the table, CRT aquatic toxicity impacts are broadly distributed across a number of different process groups, with most of the top contributors responsible for less than five percent of the impacts. Most of the LCI data from which the scores were calculated are from secondary data sets, although a substantial fraction are from primary data collected to meet the goals and scope of the CDP LCA. Water releases of phosphorus from CRT tube manufacturing represents the single largest contributor to the CRT aquatic toxicity score, accounting for 26% of the total. Aquatic toxicity impacts for phosphorus are driven more by its inherent acute toxicity than the output amount. The phosphorus acute HV is calculated from a fish LC_{50} of 0.020 mg/L, which is significantly more toxic than the geometric mean value of 23.5 mg/L.

The only other specific outputs that contribute more than five percent of the CRT aquatic toxicity score are water discharges of aluminum ions (valence = +3) and copper ions (valence = +1 and +2) from aluminum production. The aluminum HV is calculated from an LC_{50} value of 36 mg/L and a NOAEL value of 3.6 mg/L, which are within an order of magnitude of the geometric mean values of 23.5 mg/L and 3.9 mg/L. Copper, on the other hand, is much more toxic to fish, with an LC_{50} value of 0.014mg/L and a NOAEL value of 0.004 mg/L. The

aluminum aquatic toxicity score exceeds that of copper because it is discharged in much greater quantities.

Table 3-51. Top 99% of the CRT aquatic toxicity impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Manufacturing	CRT tube manufacturing	Phosphorus (yellow or white)	Primary	26%
Materials processing	Aluminum production	Aluminum (+3)	Secondary	12%
Materials processing	Aluminum production	Copper (+1 & +2)	Secondary	9.5%
Materials processing	Invar	Copper (+1 & +2)	Secondary	5.0%
Materials processing	Invar	Aluminum (+3)	Secondary	4.4%
Materials processing	Invar	Zinc (+2)	Secondary	4.0%
Materials processing	Lead	Aluminum (+3)	Secondary	3.6%
Manufacturing	CRT tube manufacturing	Fluoride	Primary	3.1%
Materials processing	Ferrite manufacturing	Zinc (+2)	Secondary	3.0%
Materials processing	Aluminum production	Zinc (+2)	Secondary	2.9%
Materials processing	ABS production	Ammonia	Secondary	2.7%
Materials processing	Lead	Copper (+1 & +2)	Secondary	2.7%
Manufacturing	CRT glass/frit mfg.	Fluorides (F-)	Primary	2.6%
Manufacturing	CRT tube manufacturing	Zinc (elemental)	Primary	2.3%
Manufacturing	CRT tube manufacturing	Copper	Primary	2.1%
Materials processing	Steel production, cold-rolled, semi-finished	Phosphorus (yellow or white)	Secondary	2.0%
Manufacturing	LPG production	Phenol	Secondary	1.9%
Materials processing	Steel production, cold-rolled, semi-finished	Ammonia	Secondary	1.2%
Manufacturing	LPG production	Aluminum (+3)	Secondary	1.1%
Materials processing	Lead	Zinc (+2)	Secondary	0.82%
Materials processing	Polycarbonate production	Copper (+1 & +2)	Secondary	0.54%
Materials processing	Steel production, cold-rolled, semi-finished	Copper (+1 & +2)	Secondary	0.45%
Materials processing	Ferrite manufacturing	Aluminum (+3)	Secondary	0.43%
Materials processing	Aluminum production	Barium sulfate	Secondary	0.40%
Materials processing	ABS production	Aluminum (+3)	Secondary	0.39%
Materials processing	Invar	Ammonia	Secondary	0.36%
Materials processing	Ferrite manufacturing	Copper (+1 & +2)	Secondary	0.31%
Materials processing	ABS production	Copper (+1 & +2)	Secondary	0.25%
Materials processing	Styrene-butadiene copolymer production	Copper (+1 & +2)	Secondary	0.24%
Materials processing	Aluminum production	Titanium tetrachloride	Secondary	0.20%
Materials processing	Polycarbonate production	Mercury compounds	Secondary	0.19%
Materials processing	Aluminum production	Strontium (Sr II)	Secondary	0.14%

Table 3-51. Top 99% of the CRT aquatic toxicity impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Materials processing	Steel production, cold-rolled, semi-finished	Aluminum (+3)	Secondary	0.12%
Materials processing	Ferrite manufacturing	Ammonia	Secondary	0.12%
Materials processing	Lead	Barium sulfate	Secondary	0.10%
Materials processing	Steel production, cold-rolled, semi-finished	Nitrogen dixode	Secondary	0.088%
Materials processing	ABS production	Mercury compounds	Secondary	0.088%
Materials processing	Steel production, cold-rolled, semi-finished	Zinc (+2)	Secondary	0.087%
Materials processing	Styrene-butadiene copolymer production	Mercury compounds	Secondary	0.086%
Materials processing	Steel production, cold-rolled, semi-finished	Fluorides (F-)	Secondary	0.086%
Materials processing	Aluminum production	Lead compounds	Secondary	0.076%
Materials processing	Polycarbonate production	Zinc (+2)	Secondary	0.076%
Materials processing	Invar	Strontium (Sr II)	Secondary	0.074%

*Column may not add to 99% due to rounding.

Table 3-52 lists the materials that contribute to the top 99% of the LCD aquatic toxicity impact score and the LCI data type. Unlike the CRT, LCD impacts in this category are not distributed across a number of different process groups, but dominated by phosphorus emissions from a single process group, LCD monitor/module manufacturing. Phosphorus releases from LCD monitor/module manufacturing are several orders of magnitude higher than phosphorus releases from CRT tube manufacturing (the greatest contributor to the CRT aquatic toxicity impact score). However, the LCD aquatic toxicity score for phosphorus is still driven by the inherent acute toxicity of phosphorus, rather than the release amount.

Other top contributors to LCD impacts in this category include ammonia releases from PMMA sheet production, and phosphorus emissions from LCD panel components manufacturing. No toxicity data were available for ammonia. Consequently, it was assigned a default HV of two, representative of mean acute and chronic fish toxicity values.

Table 3-52. Top 99% of the LCD aquatic toxicity impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score
Manufacturing	LCD monitor/module mfg.	Phosphorus (yellow or white)	Primary	98%
Materials processing	PMMA sheet production	Ammonia	Secondary	0.63%
Manufacturing	LCD panel components	Phosphorus (yellow or white)	Primary	0.56%

3.3.14.2 Terrestrial ecotoxicity

Figure 3-22 presents the CRT and LCD LCIA results for the terrestrial toxicity impact category, based on the impact assessment methodology presented in Section 3.1.2.13. Complete results for the CRT and LCD are presented in Tables M-39 and M-40 in Appendix M, respectively.

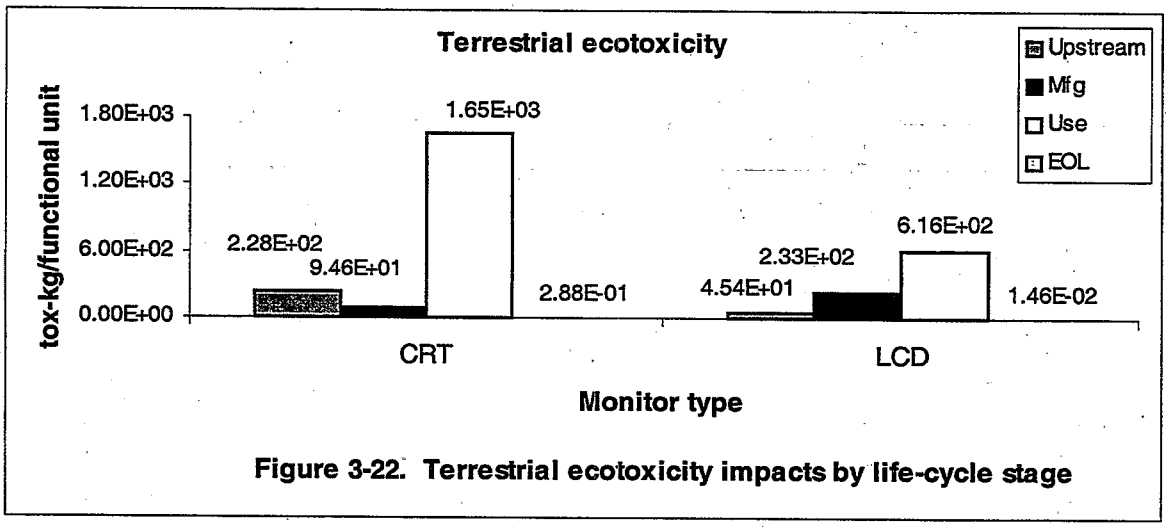


Figure 3-22. Terrestrial ecotoxicity impacts by life-cycle stage

The life-cycle terrestrial toxicity indicator is 1,970 tox-kg per functional unit for the CRT and 894 tox-kg per functional unit for the LCD. As shown in the figure, the CRT result is dominated by toxic chemical outputs from electricity generation in the use stage, which account for almost 84% of CRT impacts in this category. To a lesser degree, LCD terrestrial toxicity impacts are also driven by emissions from electricity generation in the use stage, which account for more than 69% of the total.

The materials processing stage contributes about 12% of CRT terrestrial toxicity impacts and about five percent of LCD impacts. The manufacturing life-cycle stage is responsible for five and 26% of CRT and LCD impacts in this category, respectively. Both monitors receive very small terrestrial toxicity scores at end of life. This is because most terrestrial toxicity impacts from CRT and LCD recycling and disposal processes are offset by a credit on electric grid emissions when the monitors are incinerated with energy recovery.

The terrestrial toxicity impact results are almost identical to the chronic public health effects results presented previously (see Section 3.3.13). Recall that human health and terrestrial toxicity impacts are calculated using the same noncancer toxicity values (and the same inventory data), with the main difference being that toxicity data on carcinogenic effects are excluded from the terrestrial toxicity impact calculations. However, human health and terrestrial toxicity impacts are almost identical because: (1) impacts in both categories are dominated by emissions of sulfur dioxide from electricity generation (see Tables 3-53 and 3-54 below for top contributors to the CRT and LCD terrestrial toxicity impacts), and (2) sulfur dioxide has a high hazard value for noncancer effects and a hazard value of zero for cancer effects.

Table 3-53 presents the materials that contribute to the top 99% of the CRT terrestrial toxicity impact score. As already noted, SO_2 emissions from a number of different process groups almost completely dominate CRT impacts in this category, accounting for slightly less than 99% of the total. Most of these emissions are from the combustion of fossil fuels to generate electricity. All of the SO_2 LCI data are either from secondary data sets not developed specifically for the CDP or from the electric grid inventories developed from secondary sources for this project. Sulfur dioxide has a relatively high HV, based on an inhalation NOAEL of 0.104 mg/m^3 and the geometric mean inhalation NOAEL of 68.7 mg/m^3. In addition, as noted in the section on human health effects (3.3.13), from a mass loading perspective (i.e., based on the inventory alone), SO_2 emissions were the second largest contributor to CRT life-cycle air pollutant emissions, exceeded only by emissions of carbon dioxide (CO_2). Carbon dioxide is not classified as toxic, and therefore did not contribute to the terrestrial toxicity impact category.

Table 3-53. Top 99% of the CRT terrestrial toxicity impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score*
Use	U.S. electric grid	Sulfur dioxide	Model/secondary	83%
Materials processing	Invar	Sulfur dioxide	Secondary	8.4%
Manufacturing	Japanese electric grid	Sulfur dioxide	Model/secondary	2.9%
Manufacturing	U.S. electric grid	Sulfur dioxide	Model/secondary	1.3%
Materials processing	Steel production, cold-rolled, semi-finished	Sulfur dioxide	Secondary	1.3%
Materials processing	Aluminum production	Sulfur dioxide	Secondary	0.70%
Materials processing	Polycarbonate production	Sulfur dioxide	Secondary	0.40%
Manufacturing	LPG production	Carbon monoxide	Secondary	0.27%

* Column may not add to 99% due to rounding.

Table 3-54 lists the materials that contribute to the top 99% of the LCD terrestrial toxicity impact score and the LCI data type. LCD impacts in this category are also dominated by SO_2 emissions, which are responsible for roughly 92% of impacts. Like the CRT, most of these emissions occur from electricity generation, either during the use stage (68%) or manufacturing (21%). As noted previously, SO_2 has a relatively high HV, due to its low toxicity value (inhalation NOAEL = 0.104 mg/m^3). Similar to the CRT, from a mass loading perspective (i.e., based on the inventory alone), SO_2 emissions were the second largest contributor to LCD life-cycle air pollutant emissions, exceeded only by emissions of CO_2.

Other top contributors to the LCD terrestrial toxicity score include phosphine and phosphorus from LCD monitor/module manufacturing, and carbon monoxide and methane from natural gas production. As noted above in the section on chronic occupational health effects, the phosphine, phosphorus, and benzene scores are driven more by their inherent toxicity than their output amounts.

Table 3-54. Top 99% of the LCD terrestrial toxicity impact score

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score
Use	U.S. electric grid	Sulfur dioxide	Model/secondary	68%
Manufacturing	Japanese electric grid	Sulfur dioxide	Model/secondary	21%
Manufacturing	LCD monitor/module mfg.	Phosphine	Primary	3.2%
Materials processing	Steel production, cold-rolled, semi-finished	Sulfur dioxide	Secondary	1.4%
Materials processing	PMMA sheet production	Sulfur dioxide	Secondary	0.96%
Materials processing	Natural gas production	Benzene	Secondary	0.59%
Materials processing	Aluminum production	Sulfur dioxide	Secondary	0.57%
Materials processing	Natural gas production	Carbon monoxide	Secondary	0.50%
Materials processing	Polycarbonate production	Sulfur dioxide	Secondary	0.50%
Materials processing	Natural gas production	Methane	Secondary	0.39%
Manufacturing	LCD monitor/module mfg.	Phosphorus (yellow or white)	Primary	0.38%

3.3.14.3 Terrestrial toxicity impact scores modified to exclude sulfur dioxide

Because the terrestrial toxicity impact scores for both the CRT and the LCD are dominated by SO_2 emissions, a secondary analysis was run to identify the top contributors to these impacts when SO_2 emissions are excluded from the inventories. Results of this analysis may be more useful to manufacturers seeking to identify problematic toxic chemicals within their own manufacturing processes.

Figure 3-23 presents the CRT and LCD terrestrial toxicity impact scores by life-cycle stage when SO_2 emissions are excluded from the inventories. Under this scenario, the CRT score is reduced almost 99% from 1,970 tox-kg to 21 tox-kg per functional unit, and the LCD score is reduced about 94%, from 894 tox-kg to 54 tox-kg per functional unit. Note that these scores should not be used to evaluate which monitor type has higher overall impacts in this category, but they are useful for identifying life-cycle improvement opportunities that were previously obscured by SO_2 impacts.

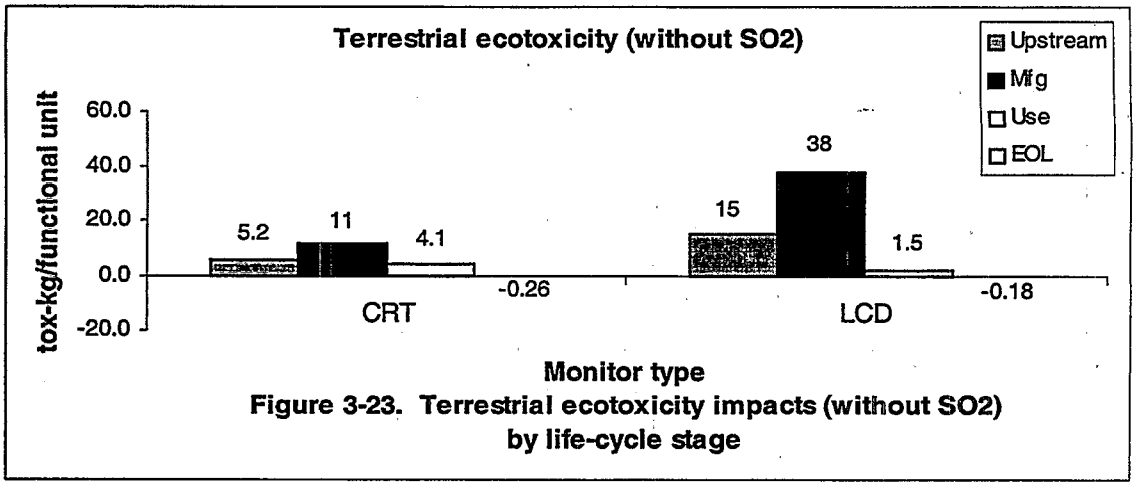


Figure 3-23. Terrestrial ecotoxicity impacts (without SO2) by life-cycle stage

With SO_2 emissions removed from the inventories, terrestrial toxicity impacts are highest in the manufacturing life-cycle stage for both the CRT (56% of impacts) and the LCD (70% of impacts). The materials processing stage is the next largest contributor for both monitor types, contributing 25% of CRT impacts and 27% of LCD impacts, followed by the use stage, which contributes 20% of CRT impacts and almost 3% of LCD impacts. Both monitors have slight negative values at end-of-life, due to the offset of electric grid emissions from incineration with energy recovery.

Table 3-55 presents the materials that contribute greater than one percent of CRT terrestrial toxicity impacts when SO_2 emissions are excluded from the CRT inventory. Like the modified public chronic human health effects results discussed in Section 3.3.13, under this scenario CRT chronic public health impacts are still being driven by emissions of criteria air pollutants, including carbon monoxide, nitrogen oxides, and sulfur oxides (assuming that SO_2 emissions comprise a large part of the sulfur oxide emissions shown in the table). As shown in the table, emissions of these three pollutants or pollutant categories are responsible for some 46% of CRT terrestrial toxicity impacts when pure SO_2 emissions are excluded from the CRT inventory. Note that the majority of these emissions occur from the LPG production process, and most of this LPG is used as a fuel in CRT glass manufacturing. CRT glass manufacturing energy inputs are uncertain and evaluated in a sensitivity analysis (see Section 3.4). Other significant contributors include arsenic from lead production, methane from LPG production and the U.S. electric grid inventory, vanadium and benzene from LPG production, and titanium tetrachloride from aluminum production.

Table 3-55. Materials contributing greater than 1% of the CRT terrestrial toxicity impact score (without SO_2)

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score
Manufacturing	LPG production	Carbon monoxide	Secondary	26%
Materials processing	Lead	Arsenic	Secondary	11%
Use	U.S. electric grid	Nitrogen oxides	Model/secondary	5.7%
Manufacturing	LPG production	Vanadium	Secondary	5.1%
Use	U.S. electric grid	Carbon monoxide	Model/secondary	4.9%
Manufacturing	LPG Production	Benzene	Secondary	4.2%
Manufacturing	LPG production	Methane	Secondary	4.1%
Manufacturing	LPG production	Sulfur oxides	Secondary	3.9%
Materials processing	Aluminum production (all virgin)	Titanium tetrachloride	Secondary	3.5%
Use	U.S. electric grid	Methane	Model/secondary	3.1%
Manufacturing	CRT glass/frit mfg.	Fluorides (F-)	Primary	2.8%
Manufacturing	LPG production	Nitrogen oxides	Secondary	2.8%
Use	U.S. electric grid	Arsenic	Model/secondary	2.7%
Use	U.S. electric grid	Hydrochloric acid	Model/secondary	2.4%
Materials processing	Steel Prod., cold-rolled, semi-finished	Carbon monoxide	Secondary	1.4%
Materials processing	Invar	Titanium tetrachloride	Secondary	1.2%
Manufacturing	CRT tube manufacturing	Carbon monoxide	Primary	1.0%
Materials processing	Lead	Titanium tetrachloride	Secondary	1.0%
Manufacturing	LPG production	Arsenic	Secondary	1.0%

Table 3-56 presents the materials that contribute greater than one percent of LCD terrestrial toxicity impacts when SO_2 emissions are excluded from the LCD inventory. As with the LCD modified chronic human health results discussed in Section 3.3.13, when SO_2 emissions are excluded, phosphine emissions from LCD monitor/module manufacturing are the dominant factor in the LCD terrestrial toxicity score, contributing 53% of the total. Other significant contributors include benzene, carbon monoxide, methane, and nitrogen oxides from natural gas production, and phosphorus, fluorides, tetramethyl ammonium hydroxide, and nitrogen oxides from LCD monitor/module manufacturing. Recall that the LCD monitor/module manufacturing process consumes the majority of the natural gas made in the natural gas production process, where LNG is used as an ancillary material. However, only one of the seven LCD monitor/module manufacturers that provided inventory data to the CDP reported the ancillary use of LNG. Other manufacturers reported using LNG as a fuel.

Table 3-56. Materials contributing greater than 1% of the LCD terrestrial toxicity impact score (without SO_2)

Life-cycle stage	Process group	Material	LCI data type	Contribution to impact score
Manufacturing	LCD module/monitor mfg.	Phosphine	Primary	53%
Materials processing	Natural gas production	Benzene	Secondary	9.8%
Materials processing	Natural gas production	Carbon monoxide	Secondary	8.2%
Materials processing	Natural gas production	Methane	Secondary	6.5%
Manufacturing	LCD module/monitor mfg.	Phosphorus (yellow or white)	Primary	6.3%
Manufacturing	LCD module/monitor mfg.	Fluorides (F-)	Primary	4.7%
Materials processing	Natural gas production	Nitrogen oxides	Secondary	1.2%
Manufacturing	LCD module/monitor mfg.	Tetramethyl ammonium hydroxide	Primary	1.2%
Manufacturing	LCD module/monitor mfg.	Nitrogen oxides	Primary	1.0%

3.3.14.4 Limitations and uncertainties

Most of the limitations and uncertainties in the ecotoxicity results are similar to the limitations and uncertainties in the human health effects scores. The reader is referred to Section 3.3.13 for a full discussion of these limitation and uncertainties. In summary, they can be grouped into three categories:

1. *Structural or modeling limitations and uncertainties* associated with the accuracy of the toxic chemical classification method and the chemical scoring approach used to characterize human health effects.
2. *Toxicity data limitations and uncertainties* associated with the availability and accuracy of toxicity data to represent ecotoxicity.
3. *LCI data limitations and uncertainties* associated with the accuracy and representativeness of the inventory data.

With regard to toxicity data, other limitations and uncertainties in the ecotoxicity results are related to the use of surrogates to assess toxicity to all species within an impact category. For example, the aquatic toxicity category uses fish (usually the fathead minnow) as a surrogate to assess toxicity to all aquatic organisms, but it has been well-established in the ecotoxicology literature that fish are not the most sensitive test species to all or most industrial chemicals. In fact, invertebrates (daphnids) or algae (Selenastrum) often are more sensitive to particular chemicals than fish (Smrchek, 1999). Similarly, the terrestrial toxicity category uses mammals, primarily rodents, as a surrogate to assess toxicity to all terrestrial organisms. Terrestrial plants and soil organisms (insects, earthworms, etc.) are not considered, but both of these may be more sensitive than mammals.

Because there are difficulties in comparing test endpoints for different types of organisms, and because there is a very limited toxicity database for some of the other organisms, the LCIA methodology employed in this study uses fish as a surrogate for aquatic toxicity and mammals as a surrogate for terrestrial ecotoxicity. This helps to reduce data gaps and the difficulties in comparing test endpoints for different types of organisms. Furthermore, we

believe this approach to be acceptable for a study, such as the CDP LCA, that gives relative ranking of impacts from different chemicals or process groups instead of absolute values. However, it should be noted that this approach can result in an underestimation of the absolute ecotoxicity and hazards of chemicals.

With regard to LCI data limitations not discussed previously, it should be noted that the CRT and LCD LCAs do not address spills or other accidental releases that could have significant adverse effects on aquatic or terrestrial organisms. This is a common limitation of LCA, which is often too labor-intensive to address different operational scenarios across the product life cycle.

3.3.15 Summary of Top Contributors by Impact Category

Tables 3-57 and 3-58 summarize the top contributors to CRT and LCD life-cycle impacts by impact category. As shown in Table 3-57, CRT impacts are largely driven by two factors: (1) the large amount of LPG fuel used in CRT glass/frit manufacturing, and (2) the relatively large amount of electricity consumed during the use stage. The LPG production process yields the CRT's top contributor in eight of 20 impact categories. Most of this LPG is used as a fuel source in CRT glass manufacturing in the glass/frit process group, which, in turn, produces the top contributor to two of 20 impact categories. Thus, LPG used in the glass/frit process group (primarily CRT glass manufacturing) is ultimately the key driver for CRT impacts in ten categories. Similarly, outputs from electricity generation during the use stage result in the top contributor to seven CRT impact categories. Note that in 14 of the 20 impact categories, the top contributor to CRT impacts is responsible for more than 50% of impacts.

Both the glass manufacturing energy and the use stage lifespan (which determines the amount of electricity generated during the use stage) are evaluated in a sensitivity analysis in Section 3.4. In the modified glass energy sensitivity analysis, LPG inputs are greatly reduced and impacts are therefore reduced, but in the modified lifespan (manufactured life) sensitivity analysis, the number of hours a monitor is in use is increased. Thus, CRT impacts are increased.

LCD impacts are not as dominated by a few data points, but a few processes (LCD monitor/module manufacturing and electricity generation in the use stage) are responsible for a large percent of the impacts. As shown in Table 3-58, both of these processes result in the top contributors to six LCD impact categories each. In addition, the process to produce LNG used as an ancillary material in LCD monitor/module manufacturing is the top contributor to an additional impact category (photochemical smog). Note that in 11 of the 20 impact categories, the top contributor to LCD impacts is responsible for more than 50% of impacts.

Like the CRT, both the glass energy inputs and use stage lifespan of the LCD are evaluated in a sensitivity analysis in Section 3.4. LCD monitor/module manufacturing energy and LCD EOL dispositions are also evaluated. LCD monitor/module manufacturing energy was selected for a sensitivity analysis because of the high degree of variability seen in data provided by manufacturers. The impacts presented in the baseline scenario are calculated with energy outliers removed from the average, but the outliers are included in the sensitivity analysis. This results in higher electricity consumption but lower fuel consumption, which, in turn, causes reduced impacts in some categories and increased impacts in others. Note that the LNG used as an ancillary material in LCD monitor/module manufacturing is not affected by the sensitivity analysis since it only focuses on materials used as an energy source.

Table 3-57. Summary of top contributors to CRT impacts by impact category

Impact category	Top contributors			
	Life-cycle stage	Process group	Material	Contribution to impact score
Renewable resource use	Manufacturing	LPG production	water	79%
Nonrenewable resource use	Manufacturing	LPG production	Petroleum (in ground)	56%
Energy use	Manufacturing	CRT glass/frit mfg.	Liquefied petroleum gas	72%
Solid waste landfill use	Use	U.S. electric grid	Coal waste	38%
Hazardous waste landfill use	End-of-life	CRT landfilling	EOL CRT monitor, landfilled	91%
Radioactive waste landfill use	Use	U.S. electric grid	Low-level radioactive waste	61%
Global warming	Use	U.S. electric grid	Carbon dioxide	64%
Ozone depletion	Use	U.S. electric grid	Bromomethane	49%
Photochemical smog	Manufacturing	LPG production	Hydrocarbons, unspeciated	36%
Acidification	Use	U.S. electric grid	Sulfur dioxide	47%
Air particulates	Manufacturing	LPG production	PM	43%
Water eutrophication	Manufacturing	LPG production	COD	72%
Water quality, BOD	Manufacturing	LPG production	BOD	96%
Water quality, TSS	Manufacturing	LPG production	Suspended solids	97%
Radioactivity	Materials Processing	Steel production, cold-rolled, semi-finished	Plutonium-241 (isotope)	62%
Chronic health effects, occupational	Manufacturing	CRT glass/frit manufacturing	Liquefied petroleum gas	78%
Chronic health effects, public	Use	U.S. electric grid	Sulfur dioxide	83%
Aesthetics (odor)	Manufacturing	LPG production	Hydrogen sulfide	94%
Aquatic toxicity	Manufacturing	CRT tube manufacturing	Phosphorus (yellow or white)	26%
Terrestrial toxicity	Use	U.S. electric grid	Sulfur dioxide	83%

Table 3-58. Summary of top contributors to LCD impacts by impact category

Impact category	Top contributors			
	Life-cycle stage	Process group	Material	Contribution to impact score
Renewable resource use	Manufacturing	LCD monitor/module mfg.	Water	38%
Nonrenewable resource use	Materials processing	Natural gas production	Natural gas (in ground)	65%
Energy use	Use	LCD monitor use	Electricity	30%
Solid waste landfill use	Use	U.S. electric grid	Coal waste	44%
Hazardous waste landfill use	End-of-life	LCD landfilling	EOL LCD monitor, landfilled	97%
Radioactive waste landfill use	Use	U.S. electric grid	Low-level radioactive waste	44%
Global warming	Manufacturing	LCD monitor/module mfg.	Sulfur hexafluoride	29%
Ozone depletion	Manufacturing	LCD panel components manufacturing	HCFC-225cb	34%
Photochemical smog	Materials processing	Natural gas production	Nonmethane hydrocarbons, unspeciated	45%
Acidification	Use	U.S. electric grid	Sulfur dioxide	31%
Air particulates	Materials processing	Steel production, cold-rolled, semi-finished	PM	45%
Water eutrophication	Manufacturing	LCD monitor/module mfg.	Nitrogen	67%
Water quality, BOD	Manufacturing	LCD monitor/module mfg.	BOD	61%
Water quality, TSS	Manufacturing	LPG production	Suspended solids	66%
Radioactivity	Materials processing	Steel production, cold-rolled, semi-finished	Plutonium-241 (isotope)	96%
Chronic health effects, occupational	Manufacturing	LCD monitor/module mfg.	Liquefied natural gas	58%
Chronic health effects, public	Use	U.S. electric grid	Sulfur dioxide	68%
Aesthetics (odor)	Manufacturing	LPG production	Hydrogen sulfide	94%
Aquatic toxicity	Manufacturing	LCD monitor/module mfg.	Phosphorus (yellow or white)	98%
Terrestrial toxicity	Use	U.S. electric grid	Sulfur dioxide	68%

3.4 SENSITIVITY ANALYSES

Due to assumptions and uncertainties in this LCA, as in any LCA, several sensitivity analyses of the baseline results were conducted. Section 2.7.3 described how areas for sensitivity analyses (scenarios) were selected, and the modifications made to the baseline inventory. Sections 3.4.1 through 3.4.4 recap these modifications and present sensitivity analysis results. Section 3.4.5 summarizes the effects of different scenarios on CRT and LCD impacts.

3.4.1 Manufactured Life Scenario

Due to the uncertainty and assumptions associated with the baseline use stage lifespan (effective life) scenario, a "manufactured life" scenario was also considered. Recall that the manufactured life is defined as the length of time a monitor is designed to operate effectively, while the effective life is defined as the actual amount of time a monitor is used, by one or multiple users, before it reaches its final disposition. The manufactured life is the number of hours a monitor would function as manufactured, and is independent of user choices or actions. Section 2.4.1.3 presented a detailed discussion of how the manufactured life was determined, and is summarized below.

The manufactured life of both monitor types was estimated using the mean-time-before-failure (MTBF) specifications of the monitor and its components. From review of MTBF information obtained on CRT-based monitors (see Appendix H, Attachment A, Table A2), it appears that the CRT tube itself is the component that 99% of the time determines whether the entire monitor has reached its end-of-life. Thus, an average of the two ranges obtained on the estimated lifetime of CRT tubes (10,000 and 15,000 hours) was used as the CRT manufactured lifetime (12,500 hours).

For active matrix LCDs, the components that have the greatest potential to fail first are the display panel itself (including the liquid crystals and thin-film transistors), backlights, driver integrated circuit (IC) tabs, and other smaller components. The backlights and driver IC tabs can be field-replaced, thus their failure does not necessarily represent the end of the monitor's life. However, failure of the liquid crystals or transistors, which would require replacement of the display panel itself, would most likely mean that the monitor cannot be cost-effectively repaired. Thus, in this study, the amount of time an LCD monitor would operate during its manufactured life is assumed to be the average of the non field-replaceable values, or 45,000 hours. In order for a monitor to operate for 45,000 hours, any major field-replaceable parts that have MTBFs less than 45,000 hours are accounted for in the inventory. For example, assuming the backlights last on average 32,500 hours (the average of the values obtained for backlights), approximately 1.4 backlights on average would be needed for every panel during its 45,000 hour lifetime.

To calculate the manufactured life electricity consumption (kWh/life), the energy use rate (kW) was multiplied by the lifespan (hours/life) for each monitor in each power mode (see Table 2-20 in Section 2.4.1.3). The LCD manufactured life (45,000 hours) is 3.6 times greater than the CRT manufactured life (12,500 hours). In an LCA, comparisons are made based on functional equivalency. Therefore, if one monitor will operate for a longer period of time than another, impacts should be based on an equivalent use. Thus, based on equivalent use periods, 3.6 CRTs would need to be manufactured for every LCD. This was incorporated into the profile analysis for the manufactured life LCA. To apply the manufactured life scenario to the CRT and LCD

life-cycle profiles, the following modifications were made to the baseline (effective life) scenario:

- change the CRT electricity input in the use stage from 635 kWh (2,286 MJ) to 788 kWh (2,837 MJ); [3]
- change the LCD electricity input in the use stage from 237 kWh (853 MJ) to 1,035 kWh (3,726 MJ);
- increase the manufacturing of CRTs by a factor of 3.6 to account for the functional equivalency of CRTs and LCDs. This was done by increasing the functional unit by a factor of 3.6, which equates to manufacturing, using, and recycling or disposing of 3.6 times more CRTs than in the baseline case; and
- increase the manufacturing of the LCD backlight lamp by a factor of 1.4 to account for the functional equivalency of LCDs and CRTs. This was done by increasing the backlight lamp mass (0.0023 kg) by a factor of 1.4, which in turn results in an increase in inputs and outputs associated with manufacturing the backlilght.

Table 3-59 presents the CRT and LCD life-cycle results by impact category for the baseline and manufactured life scenarios. It also presents the percent change from the baseline to the manufactured life scenario for both monitor types. Note that the manufactured life results are most useful for evaluating the CRT and LCD together, not for comparing the CRT or LCD baseline (effective life) results to its manufactured life results. This is because the CRT and LCD manufactured life results are functionally equivalent, but the CRT to CRT and LCD to LCD effective life and manufactured life scenarios are not. The baseline for both monitor types represents impacts from manufacture and final disposition of one monitor. The CRT manufactured life scenario represents impacts from 3.6 CRT monitors and the LCD manufactured life scenario represents impacts from one LCD monitor and 1.4 backlights. However, the percent change figures are presented to better understand how the manufactured life scenario affects overall results.

[3] This represents the electricity use for a 12,500 hour life span. This figure is then multiplied by a factor of 3.6 in the functional equivalency calculations (see third bullet, below).

Table 3-59. Baseline and sensitivity analysis results—manufactured life

		CRT			LCD		
Impact category	Units/ Monitor	Baseline	Manu-factured	% change	Baseline	Manu-factured	% change
Renewable resource use	kg	1.31e+04	4.83e+04	268%	2.80e+03	4.30e+03	53.5%
Nonrenewable resource use	kg	6.68e+02	2.58e+03	286%	3.64e+02	6.12e+02	68.0%
Energy use	MJ	2.08e+04	7.70e+04	270%	2.84e+03	5.71e+03	101%
Solid waste landfill use	m3	1.67e-01	6.86e-01	312%	5.43e-02	1.79e-01	230%
Hazardous waste landfill use	m3	1.68e-02	6.05e-02	260%	3.60e-03	3.60e-03	0.00%
Radioactive waste landfill use	m3	2.00e-04	8.00e-04	328%	1.00e-04	3.00e-04	194%
Global warming	kg-CO2 eq.s	6.95e+02	2.90e+03	317%	5.93e+02	1.17e+03	97.3%
Ozone depletion	kg-CFC-11 eq.s	2.05e-05	8.27e-05	304%	1.37e-05	2.66e-05	94.1%
Photochemical smog	kg-ethene eq.s	1.71e-01	6.20e-01	262%	1.41e-01	1.47e-01	4.22%
Acidification	kg-SO2 eq.s	5.25e+00	2.19e+01	317%	2.96e+00	7.29e+00	146%
Air particulates	kg	3.01e-01	1.13e+00	277%	1.15e-01	1.87e-01	63.4%
Water eutrophication	kg-phosphate eq.s	4.82e-02	**1.74e-01**[a]	260%	4.96e-02	4.96e-02	0.02%
BOD	kg	1.95e-01	7.02e-01	260%	2.83e-02	2.83e-02	0.02%
TSS	kg	8.75e-01	3.15e+00	260%	6.15e-02	6.15e-02	0.02%
Radioactivity	Bq	3.85e+07	1.14e+08	197%	1.22e+07	1.28e+07	4.49%
Chronic health effects, occupational	tox-kg	9.34e+02	3.39e+03	263%	6.96e+02	7.41e+02	6.47%
Chronic health effects, public	tox-kg	1.98e+03	8.56e+03	333%	9.02e+02	2.98e+03	230%
Aesthetics (odor)	m3	7.58e+06	2.74e+07	262%	5.04e+06	5.30e+06	5.00%
Aquatic toxicity	tox-kg	2.25e-01	8.10e-01	260%	5.19e+00	5.19e+00	0.02%
Terrestrial toxicity	tox-kg	1.97e+03	8.54e+03	333%	8.94e+02	2.97e+03	232%

[a] Bold indicates impact category indicator that reversed direction from the baseline scenario such that the CRT indicator is now greater than the LCD.

As shown in Table 3-59, under the manufactured life scenario CRT impacts exceed those of the LCD in every impact category except aquatic toxicity. CRT impacts were expected to be greater than those of the LCD in most impact categories for the following reasons:

- Under the baseline scenario CRT impacts exceeded those of the LCD in every category but water eutrophication and aquatic toxicity.
- The manufactured life scenario assumes more CRTs are manufactured than LCDs during the manufactured life lifespan, which results in greater impacts.
- The manufactured life use stage is longer than the baseline, effective life use stage, and the CRT consumes more electricity during use than the LCD.

By looking at the percent change in impact scores from the baseline to manufactured life for a monitor type we can better understand which aspect of the life-cycle is driving impacts. For example, CRT impacts increased by roughly 260% in several impact categories, which is the increase from manufacturing or disposing of an additional 2.6 monitors. Energy impacts increased by more than 260% due to the additional increase in electricity consumption during use. The CRT chronic public human health effects category increased by some 330%. This is explained by the increase in SO_2 emissions in the use stage and the high HV for SO_2, which has a

proportionately greater effect on overall impacts than increased outputs of other pollutants with lower HVs in other life-cycle stages.

LCD impacts increased only slightly from the baseline to the manufactured life scenario in some impact categories, but increased up to 230% in others. Most of the LCD impact categories with less than one percent increase are for impacts related to water discharges (e.g., water eutrophication, aquatic toxicity, etc.). This is because the most significant change to the LCD inventory from the baseline to the manufactured life scenario was in the use stage, and few water discharges are reported in the U.S. electric grid inventory. On the other hand, the chronic public health effects and terrestrial toxicity impact categories show the greatest increase. These results are driven by air emissions of SO_2 from U.S. power production, which increased significantly with the longer lifespan.

To further illustrate how the longer lifespan (and additional manufacturing requirements, mainly for the CRT) in the manufactured life scenario is affecting impacts, Figures 3-24 and 3-25 compare the energy impacts and public chronic health effects, respectively, of both monitor types under the baseline and manufactured life scenarios. As shown in Figure 3-24, CRT energy impacts are still dominated by the manufacturing stage in the manufactured life scenario. This is mainly due to the large amount of LPG used to manufacture 3.6 sets of CRT glass. On the other hand, LCD energy impacts during the use stage exceeded those in manufacturing by a factor of about 2.6 in the baseline scenario, but are ten times greater in the manufactured life scenario. This is due to the longer lifespan for a single LCD in the manufactured life scenario.

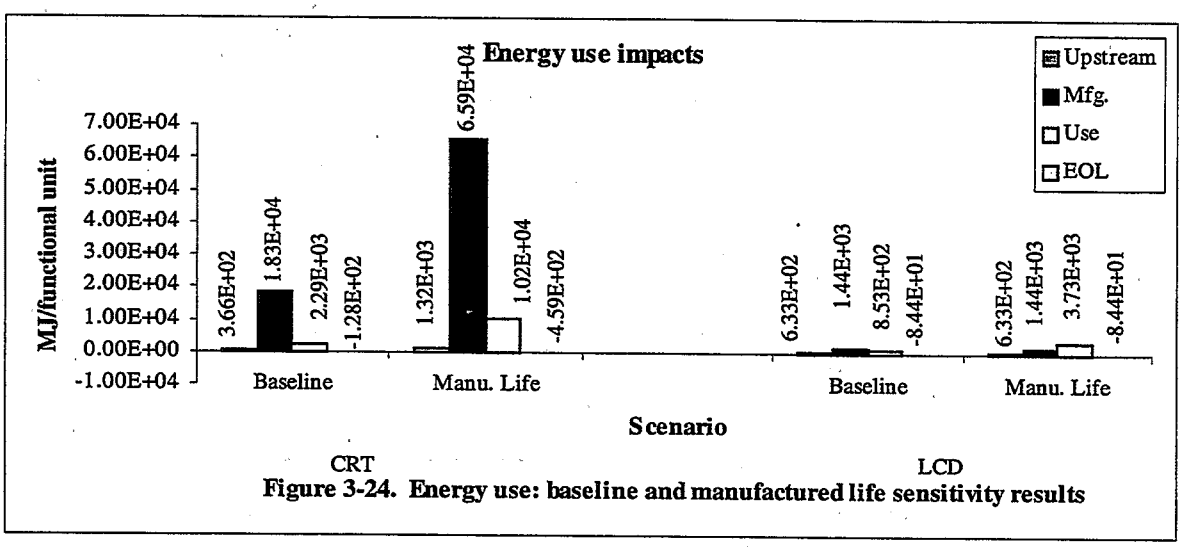


Figure 3-24. Energy use: baseline and manufactured life sensitivity results

Figure 3-25 shows that CRT chronic public health impacts are similarly distributed in the baseline and manufactured life scenarios. However, a greater percentage of LCD chronic health impacts are in the use stage under the manufactured life scenario than the baseline due to the longer use stage.

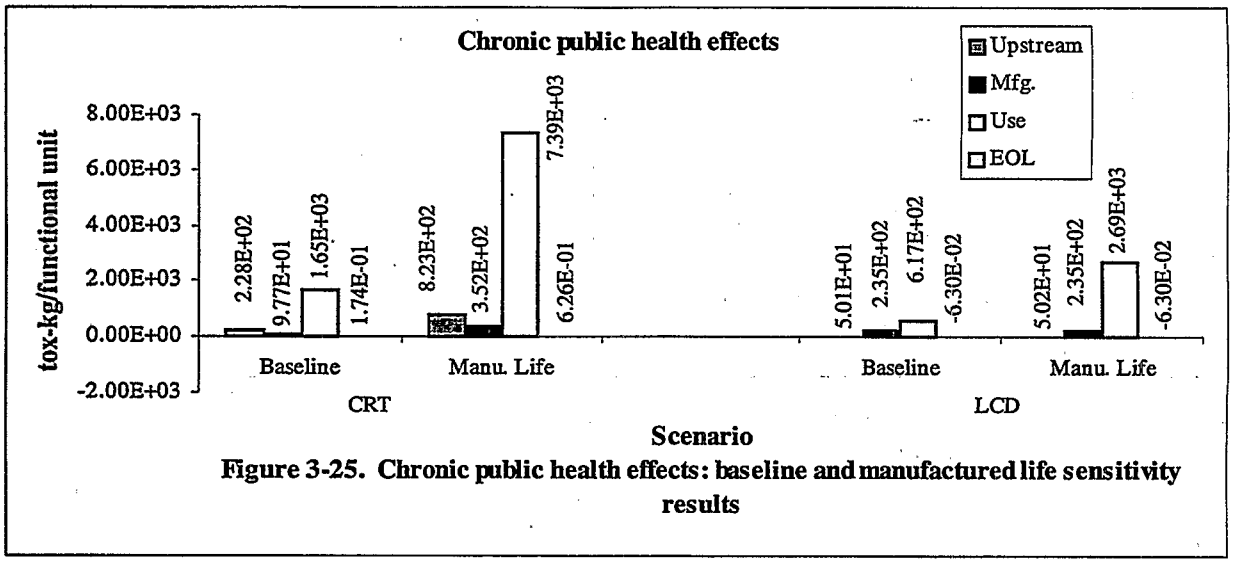


Figure 3-25. Chronic public health effects: baseline and manufactured life sensitivity results

3.4.2 Modified Glass Energy Scenario

One area of relatively large uncertainty and variability in the primary data supplied for the project was the glass manufacturing data. Both the CRT and LCD glass data were based on data supplied by CRT lead oxide (PbO) glass manufacturers, since no LCD glass manufacturers were willing to provide data to the project. To represent an LCD glass inventory, lead (Pb) materials in the CRT glass inventory were removed. Based on conversations with industry members, it was assumed that the same amount of energy per kilogram of glass produced is used to generate LCD and CRT glass. In addition, large variability among the three data sets collected resulted in a large degree of uncertainty in the glass inventory. Finally, a number of the CRT impact category results are being driven by the glass energy data or by the production process for producing the large amount of LPG used as a fuel in glass manufacturing. Consequently, the glass manufacturing inventories for both LCD and CRT glass were modified and life-cycle impacts were recalculated.

To conduct the sensitivity analysis, the energy input data for glass manufacturing were modified by removing, from the average, data that appeared unusually large, and that might be inconsistent with general industry statistics. However, industry statistics are greatly lacking when specifically considering specialty glasses such as CRT and LCD glass. Modifying the energy inputs greatly reduced the fuel energy amounts reported for the glass production process.

The baseline scenario, based on averaged primary data from manufacturers, assumed that the total energy to produce a kilogram of CRT or LCD glass was 1,560 MJ (433 kWh) of energy, with only 0.3% of that as electrical energy. The sensitivity analysis scenario assumes 16.3 MJ (4.5 kWh) per kilogram of glass produced, with approximately 30% as electrical energy. The majority of the fuel energy in the baseline scenario was from LPG. The actual input amounts are not presented here to protect the confidentiality of data provided by glass manufacturers.

Under the sensitivity (modified glass energy) scenario, only the manufacturing stage is affected, since the production of the fuels used during manufacturing is included in the manufacturing life-cycle stage. All impact categories, not only energy, are also affected because

the inputs and outputs from fuel production and electricity generation processes affect each of the impact categories evaluated in this study.

Table 3-60 shows the baseline impact results and the revised impact results based on the modified glass energy inputs. The overall life-cycle impact results are highly sensitive to the energy consumption values from glass manufacturing. Under the modified glass energy scenario, the nonrenewable resource use, global warming, photochemical smog, BOD, TSS, chronic occupational health effects, and odor impact categories reversed direction such that the LCD had greater impacts within each impact category than the CRT in the overall life cycle. Note that the percent change in CRT results in most impact categories is much greater than that of the corresponding LCD results. This is because the CRT uses approximately ten times more glass than the LCD and therefore, the CRT results are much more sensitive to the glass manufacturing data than are the LCD results.

Table 3-60. Baseline and sensitivity analysis results—modified glass energy

		CRT			LCD		
Impact category	**Units/Monitor**	**Baseline**	**Glass energy**	**% change**	**Baseline**	**Glass energy[a]**	**% change**
Renewable resource use	kg	1.31e+04	2.67e+03	-79.6%	2.80e+03	2.43e+03	-13.4%
Nonrenewable resource use	kg	6.68e+02	2.35e+02	-64.8%	3.64e+02	**3.49e+02**	-4.14%
Energy use	MJ	2.08e+04	3.02e+03	-85.5%	2.84e+03	2.04e+03	-28.0%
Solid waste landfill use	m3	1.67e-01	1.23e-01	-26.0%	5.43e-02	5.27e-02	-2.82%
Hazardous waste landfill use	m3	1.68e-02	1.54e-02	-8.13%	3.60e-03	3.60e-03	-1.35%
Radioactive waste landfill use	m3	2.00e-04	2.00e-04	0.12%	1.00e-04	1.00e-04	0.01%
Global warming	kg-CO2 eq.s	6.95e+02	5.23e+02	-24.8%	5.93e+02	**5.87e+02**	-1.01%
Ozone depletion[b]	kg-CFC-11 eq.s	2.05e-05	1.97e-05	-3.75%	1.37e-05	1.37e-05	-0.18%
Photochemical smog	kg-ethene eq.s	1.71e-01	5.59e-02	-67.3%	1.41e-01	**1.37e-01**	-2.84%
Acidification	kg-SO2 eq.s	5.25e+00	4.02e+00	-23.4%	2.96e+00	2.92e+00	-1.45%
Air particulates	kg	3.01e-01	1.72e-01	-42.9%	1.15e-01	1.10e-01	-3.97%
Water eutrophication	kg-phosphate eq.s	4.82e-02	4.10e-03	-91.5%	4.96e-02	4.80e-02	-3.17%
BOD	kg	1.95e-01	7.00e-03	-96.4%	2.83e-02	**2.16e-02**	-23.8%
TSS	kg	8.75e-01	2.06e-02	-97.6%	6.15e-02	**3.09e-02**	-49.7%
Radioactivity	Bq	3.85e+07	3.16e+07	-17.9%	1.22e+07	1.22e+07	0.00%
Chronic health effects, public	tox-kg	1.98e+03	1.97e+03	-0.56%	9.02e+02	9.01e+02	-0.02%
Chronic health effects, occupational	tox-kg	9.34e+02	2.30e+02	-75.4%	6.96e+02	**6.63e+02**	-4.74%
Aesthetics (odor)	m3	7.58e+06	1.09e+04	-99.9%	5.04e+06	**4.79e+06**	-4.99%
Aquatic toxicity	tox-kg	2.25e-01	2.18e-01	-3.07%	5.19e+00	5.19e+00	0.01%
Terrestrial toxicity	tox-kg	1.97e+03	1.97e+03	-0.42%	8.94e+02	8.94e+02	-0.01%

[a] Bold indicates impact category indicator that reversed direction from the baseline scenario such that the LCD indicator is now greater than the CRT.

[b] LCD impacts in this category are greater than CRT impacts when phased out substances are removed from the inventories (see Section 3.3.6).

The energy impacts for the baseline and modified glass energy scenarios are presented in Figure 3-26. In the baseline scenario, over 18,000 MJ of energy were consumed per CRT monitor during manufacturing. Almost 83% of this was from the glass/frit process group, mainly from glass manufacturing energy alone. When the glass energy inputs are reduced under the modified scenario, total energy use in the CRT manufacturing stage decreases some 97% to just

under 500 MJ, and the use stage dominates the overall life-cycle energy impacts at approximately 2,300 MJ per functional unit (i.e., per monitor). The 97% decrease in manufacturing stage energy use is due to the reduced glass manufacturing fuel inputs and the consequent reduction in energy inputs to the fuel production process.

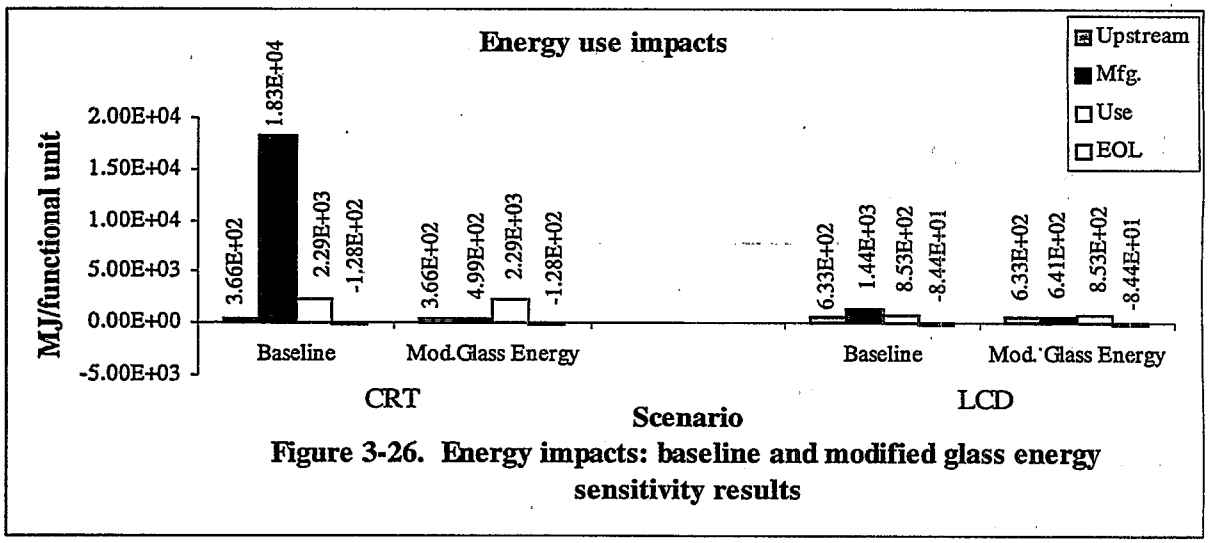


Figure 3-26. Energy impacts: baseline and modified glass energy sensitivity results

The modified glass energy scenario has a lesser, but still significant, effect on the distribution of LCD energy impacts across life-cycle stages. Under the sensitivity scenario, the LCD manufacturing stage energy consumption is reduced 55% from 1,440 MJ per monitor to about 640 MJ per monitor, and the use stage becomes the biggest energy consumer at about 850 MJ per monitor.

Global warming is one of the impact categories in which the CRT has the greater impacts than the LCD under the baseline scenario, but the LCD has the greater impacts under the sensitivity analysis. Figure 3-27 shows the global warming impacts for both monitor types under the baseline and modified glass energy scenarios. Under the latter scenario, CRT global warming impacts in the manufacturing stage are reduced some 85%, but LCD impacts are only reduced 2.5%. Again, this illustrates the greater sensitivity of CRT impact results to glass energy inputs. Also, as discussed in Section 3.3.5, a large part of LCD global warming impacts are driven by sulfur hexafluoride emissions from LCD monitor/module manufacturing, which are unaffected by the revised glass energy scenario.

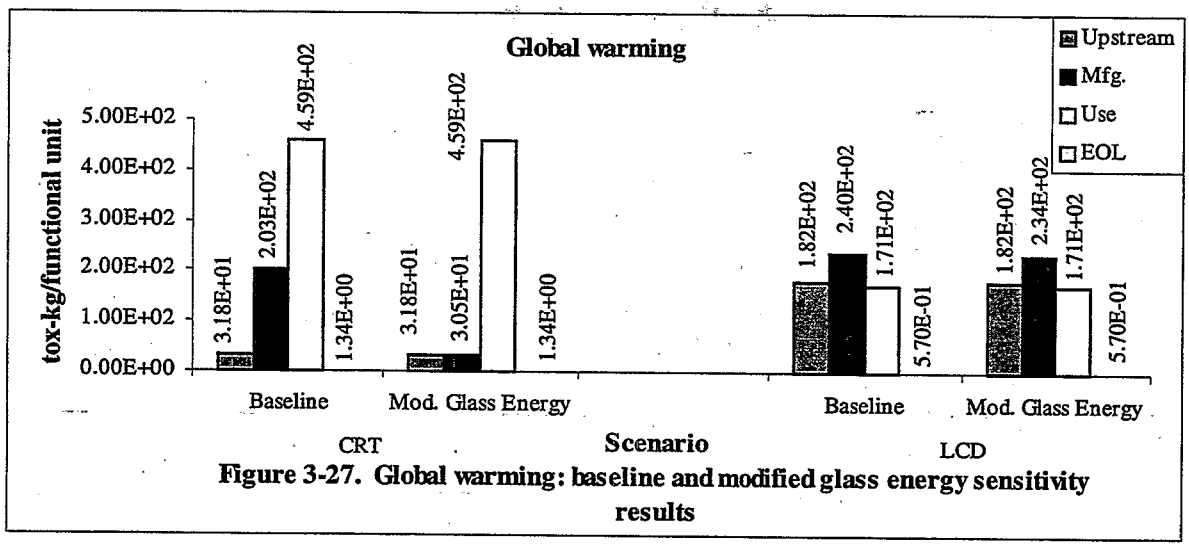


Figure 3-27. Global warming: baseline and modified glass energy sensitivity results

3.4.3 Modified LCD Module Energy Scenario

LCD monitor/module manufacturing energy was another area of relatively large uncertainty and variability in the inventory data. As discussed in Section 2.7.3.3, total energy inputs reported in six data sets received from LCD monitor/module manufacturers in Japan and Korea ranged from 330 MJ to 7,310 MJ, with a mean and standard deviation of 2,269 MJ and 2,906 MJ, respectively. The manufacturing energy data reported in two of the data sets were found to be outliers and removed from the averages used in the baseline inventory. However, for this sensitivity analysis, the outliers were added back in to the averages. Thus, to apply the modified LCD manufacturing energy scenario to the LCD profile, the following modifications were made to electricity and fuels:

- changed the electric energy inputs to the LCD monitor/module manufacturing process group from 82.1 kWh (253 MJ) per monitor to 70.1 kWh (217 MJ) per monitor,
- changed the fuel oil # 4 inputs from 0.25 kg to 0.30 kg per monitor,
- changed the kerosene inputs from 0.35 kg to 0.23 kg per monitor,
- changed the LPG inputs from 0.68 kg to 0.45 kg per monitor,
- changed the LNG inputs from 3.8 kg to 45 kg per monitor, and
- changed the natural gas inputs from 0.99 to 0.70 kg per monitor.

Note that one LCD monitor/module manufacturer also reported using a large amount of LNG as an ancillary material. However, this input amount is not affected by the sensitivity analysis, which only deals with inputs used as an energy source.

Table 3-61 presents the baseline impact results and the revised LCD impact results based on the modified LCD module energy scenario. It also shows the baseline CRT results. Under the modified LCD energy scenario, LCD impacts in ten categories actually decrease slightly, due to the slight decrease in average electrical energy consumed during LCD monitor/module manufacturing. However, impacts in six categories increase slightly, and impacts in four categories (nonrenewable resource use, energy use, photochemical smog and chronic

occupational health effects) increase by more than 10%. As expected, life-cycle energy impacts are the most affected by this sensitivity analysis, due to the increased fuel consumption during manufacturing. However, under this scenario, none of the impact category results reversed direction from the baseline such that the LCD now has greater impacts than the CRT or vice versa, where the baseline LCD impacts were greater than the CRT.

Table 3-61. Baseline and sensitivity analysis results—LCD modified module energy

Impact category	Units/Monitor	CRT	LCD		
		Baseline	Baseline	Mod. energy	% change
Renewable resource use	kg	1.31e+04	2.80e+03	2.78e+03	-0.69%
Nonrenewable resource use	kg	6.68e+02	3.64e+02	4.06e+02	11.4%
Energy use	MJ	2.08e+04	2.84e+03	4.68e+03	64.9%
Solid waste landfill use	m3	1.67e-01	5.43e-02	5.47e-02	0.74%
Hazardous waste landfill use	m3	1.68e-02	3.60e-03	3.60e-03	-0.01%
Radioactive waste landfill use	m3	2.00e-04	1.00e-04	1.00e-04	-3.88%
Global warming	kg-CO2 eq.s	6.95e+02	5.93e+02	6.17e+02	4.05%
Ozone depletion[a]	kg-CFC-11 eq.s	2.05e-05	1.37e-05	1.37e-05	-0.26%
Photochemical smog	kg-ethene eq.s	1.71e-01	1.41e-01	1.61e-01	13.7%
Acidification	kg-SO2 eq.s	5.25e+00	2.96e+00	3.00e+00	1.48%
Air particulates	kg	3.01e-01	1.15e-01	1.19e-01	3.85%
Water eutrophication	kg-phosphate eq.s	4.82e-02	4.96e-02	4.96e-02	0.00%
BOD	kg	1.95e-01	2.83e-02	2.83e-02	-0.12%
TSS	kg	8.75e-01	6.15e-02	6.13e-02	-0.30%
Radioactivity	Bq	3.85e+07	1.22e+07	1.22e+07	-0.09%
Chronic health effects, occupational	tox-kg	9.34e+02	6.96e+02	7.66e+02	10.1%
Chronic health effects, public	tox-kg	1.98e+03	9.02e+02	8.82e+02	-2.14%
Aesthetics (odor)	m3	7.58e+06	5.04e+06	5.04e+06	0.01%
Aquatic toxicity	tox-kg	2.25e-01	5.19e+00	5.19e+00	0.02%
Terrestrial toxicity	tox-kg	1.97e+03	8.94e+02	8.74e+02	-2.25%

[a] LCD impacts in this category are greater than CRT impacts when phased out substances are removed from the inventories (see Section 3.3.6).

Figure 3-28 presents the LCD baseline and sensitivity analysis results for the energy use impact category, the category with the greatest percent change from the baseline to the modified LCD module energy scenario. Under this scenario, LCD energy use impacts in the manufacturing stage increased almost 230% from 1,440 MJ per functional unit to 3,280 MJ per functional unit. However, total life-cycle energy use impacts increased only 65%. This sensitivity analysis did not affect consumption rates outside of the manufacturing stage.

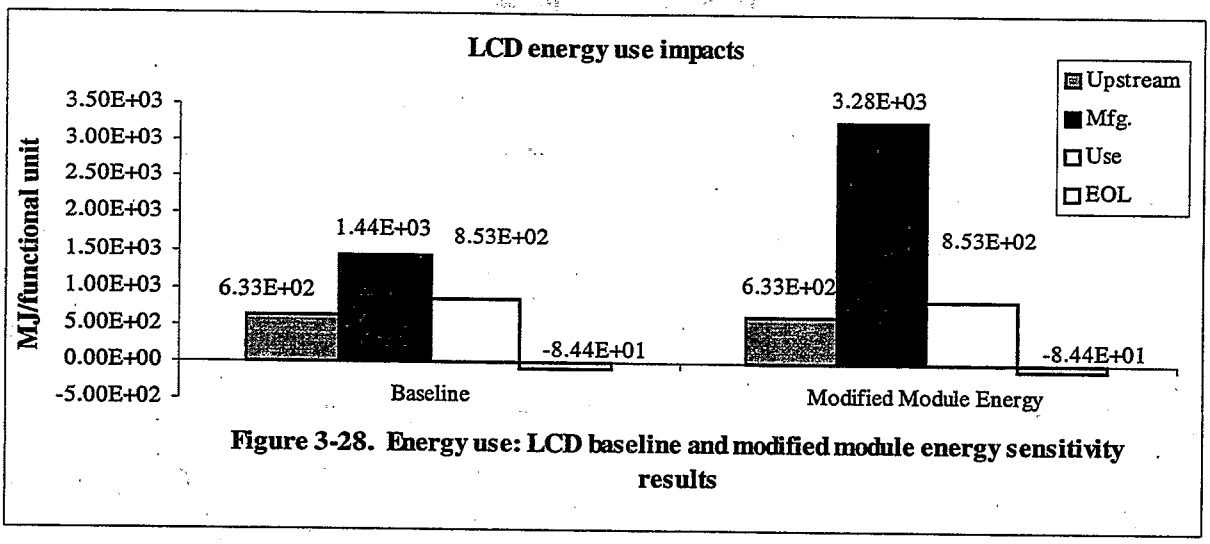


Figure 3-28. Energy use: LCD baseline and modified module energy sensitivity results

Figure 3-29 shows the effects of the sensitivity analysis on LCD chronic occupational health effects, another impact category with a relatively large percentage change. As shown in the figure, the manufacturing stage impact score in this category increased about ten percent, from 684 tox-kg per monitor to 755 tox-kg per monitor, due to the increase in fuel inputs. The chronic occupational health effect impacts were less sensitive than energy impacts because health effects results are calculated using a scoring approach that considers the inherent toxicity of a chemical instead of a simple loading approach (as is used for energy impacts). No toxicity data were available for LNG, the input with the greatest change in quantity. Therefore, the LNG HV is representative of a mean toxicity value.

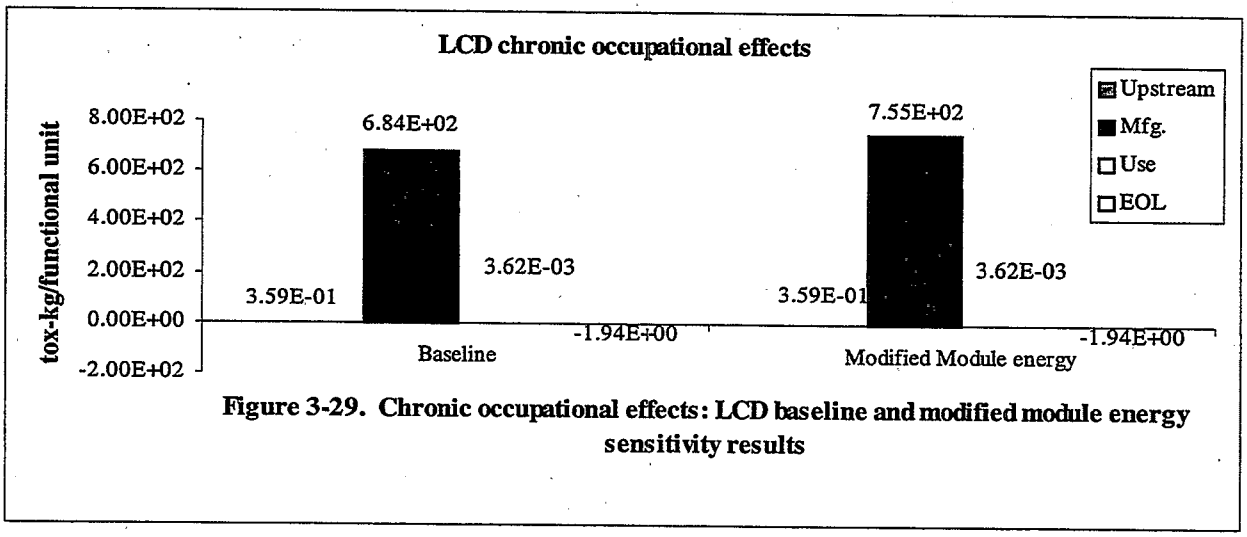


Figure 3-29. Chronic occupational effects: LCD baseline and modified module energy sensitivity results

3.4.4 Modified LCD EOL Dispositions Scenario

Finally, because very few desktop LCDs have reached their end of life, and usually only if they have been damaged in some way, very little is known about the EOL disposition of LCDs. In the baseline scenario it was assumed that a certain percent of EOL LCDs are incinerated, recycled, remanufactured, landfilled as solid waste, and landfilled as hazardous waste. (See Section 2.7.3 and Appendix I for an explanation of how EOL disposition percentages were determined.) To address uncertainties in the allocation of disposition percentages, this sensitivity analysis qualitatively evaluates a different set of final disposition numbers, as follows:

- change percent recycled from 15% to 0%,
- change percent remanufactured from 15% to 40%,
- change percent landfilled (solid waste) from 50% to 40%.
- do not change fraction incinerated (15%) or fraction sent to a hazardous waste landfill (5%).

Thus, under the modified EOL disposition scenario, recycling and solid waste landfilling impacts would decrease, remanufacturing impacts would increase, and incineration and hazardous waste landfilling impacts would not change. However, in attempts made to obtain remanufacturing data, it was found that remanufacturing processes spanned a wide range of activities, from as little as replacing button tops to as extensive as testing and replacing PWBs or transformers. Given the broad range of possibilities, and because few desktop LCDs have reached their end of life, no single set of operations could be identified to adequately represent remanufacturing activities that could be incorporated in our model. Remanufacturing data were, therefore, excluded from the assessment.

As shown in the baseline LCIA results (Section 3.3), LCD EOL dispositions have little effect on overall life-cycle impacts under the baseline scenario. In fact, the only impact categories in which an EOL process was a top contributor to overall impacts were the hazardous waste landfill use impact category, where the portion of a monitor landfilled contributed 97% of impacts, and the solid waste landfill use category, where the portion of a monitor landfilled contributed 3.5% of impacts. As noted above, hazardous waste landfill use impacts would not change under the modified LCD EOL dispositions scenario, but solid waste landfill impacts would be expected to decrease slightly. In a preliminary quantitative analysis of this scenario, LCD life-cycle solid waste landfill impacts were found to decrease less than one percent, and life-cycle impacts in other impact categories decreased less than 0.1%. Thus, the modified LCD EOL dispositions scenario would have only a minor effect on LCD life-cycle impacts and would not change comparative CRT and LCD results.

3.4.5 Summary of CRT and LCD Sensitivity Analysis Results

The results of the sensitivity analyses are useful to manufacturers who want to understand how uncertainty in the inventory affects impacts. This information can be used to identify areas for additional study or potential improvement opportunities. As discussed in Sections 3.4.1 through 3.4.2, it appears that CRT life-cycle impacts are highly sensitive to the glass energy data, and less sensitive to the lifespan assumptions (lifespan assumptions greatly affect the magnitude of CRT life-cycle impacts, but they do not greatly affect the distribution of impacts among life-

cycle stage). LCD impacts are less sensitive to the glass energy data and in fact are not greatly affected by any of the sensitivity analysis scenarios, except the longer lifespan under the manufactured life scenario.

Sensitivity results are also useful to interested members of the public who may be evaluating the relative impacts of different monitor types and are interested in whether the CRT or LCD has greater life-cycle impacts in any given impact category. Table 3-62 presents the monitor type with greatest impacts by impact category and by scenario. This information helps us determine whether major assumptions (e.g., the monitor lifespan and LCD EOL distribution assumptions) or uncertain data (e.g., glass energy data and LCD monitor manufacturing energy) are driving results. As shown in the table, the modified glass energy scenario is the only scenario that significantly changes the results from the baseline CRT and LCD comparative results. Under this scenario, life-cycle impact results in seven categories reverse direction from the baseline assessment, such that the LCD has greater impacts than the CRT. Therefore, under this scenario, a total of nine out of 20 categories are greater for the LCD than the CRT, compared to two out of 20 categories under the baseline scenario. The only other scenario that affects these results is the manufactured life scenario, when impacts in the water eutrophication category are greater for the CRT than the LCD.

Table 3-62. Summary of CRT and LCD LCIA results

Impact category	Monitor type with greatest impacts by scenario				
	Baseline	Manu-factured life	Modified glass energy	Modified LCD module energy	Modifed LCD EOL distribution[a]
Renewable resource use	CRT	CRT	CRT	CRT	CRT
Nonrenewable resource use	CRT	CRT	LCD	CRT	CRT
Energy use	CRT	CRT	CRT	CRT	CRT
SW landfill use	CRT	CRT	CRT	CRT	CRT
HW landfill use	CRT	CRT	CRT	CRT	CRT
RW landfill use	CRT	CRT	CRT	CRT	CRT
Global warming	CRT	CRT	LCD	CRT	CRT
Ozone depletion	b	b	b	b	b
Photochemical smog	CRT	CRT	LCD	CRT	CRT
Acidification	CRT	CRT	CRT	CRT	CRT
Air particulates	CRT	CRT	CRT	CRT	CRT
Water eutrophication	LCD	CRT	LCD	LCD	LCD
Water quality, BOD	CRT	CRT	LCD	CRT	CRT
Water quality, TSS	CRT	CRT	LCD	CRT	CRT
Radioactivity	CRT	CRT	CRT	CRT	CRT
Chronic health effects, occupational	CRT	CRT	LCD	CRT	CRT
Chronic health effects, public	CRT	CRT	CRT	CRT	CRT
Aesthetics (odor)	CRT	CRT	LCD	CRT	CRT

Table 3-62. Summary of CRT and LCD LCIA results

Impact category	Monitor type with greatest impacts by scenario				
	Baseline	Manu-factured life	Modified glass energy	Modified LCD module energy	Modifed LCD EOL distribution[a]
Aquatic toxicity	LCD	LCD	LCD	LCD	LCD
Terrestrial toxicity	CRT	CRT	CRT	CRT	CRT

[a] Based on a qualitative evaluation, not quantitative results.

[b] CRT impacts are greater than LCD impacts in this category when all data are included in the inventories, including data for substances that have been phased out. However, LCD impacts are greater than CRT impacts when phased out substances are removed from the inventories (see Section 3.3.6).

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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 450°C (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

[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 450°C, 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 350°C. 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 $\mu g/L$.

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 than 2,000 mg/kg of body weight (classified as exhibiting harmful effects to humans by the

[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.

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.

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Chapter 5

SUMMARY AND CONCLUSIONS

The purpose of the CDP, as stated in Chapter 1, is to provide a scientific baseline of life-cycle environmental impacts of CRTs and LCDs, help manufacturers identify areas to focus improvement assessment activities, and to develop a life-cycle model for future analyses. The primary targeted audience is the electronics industry, for whom results may provide insight into improvement opportunities in the life cycle of CRTs and/or LCDs. In addition, the general public may also find results useful when considering environmental impacts of each display type. This chapter briefly summarizes the results and draws conclusions based on those results. This report, however, does not include direct comparative assertions or improvement assessments based on the results. Alternatively, results and conclusions are described in terms of the overall LCI versus the LCIA, and details of the impact assessment, including the additional assessments of lead, mercury and liquid crystals, and the sensitivity analyses. Major uncertainties, cost and performance considerations, suggestions for improvement opportunities, and suggestions for further research are also provided.

5.1 LCI vs. LCIA

In this LCA, a life-cycle inventory (LCI) was compiled from many data sources, including both primary and secondary data sources. The primary data were obtained from component and monitor manufacturers of CRTs and LCDs. In an LCA, inventory data provide information on how much material is being consumed in the life cycle (i.e., inputs) and how much material is generated/released (i.e., outputs). The LCI results of this report are detailed in Chapter 2. The LCI provides inventory data grouped by inventory type (e.g., primary material, energy, air emission, solid waste).

The LCI alone, however, does not always translate directly into impact categories that may be of interest. That is, a given amount of one material may have different impacts (for a certain impact category) than the same amount of another material. Furthermore, some materials may affect more than one impact category. For example, an air emission could affect air acidification as well as being toxic to humans breathing it. Therefore, a life-cycle impact assessment (LCIA) is conducted to reveal potential impacts in several impact categories. In this CDP LCIA, described in detail in Chapter 3, impacts are sometimes driven by materials other than the top inventory contributors. For example, the top air emission for LCDs is carbon dioxide (Table 2-49), however the greatest global warming impact score is from SF_6 in the LCD monitor/module manufacturing process (Table 3-25).

To illustrate that the inventory results may not directly translate into impact results, the first two columns in Table 5-1 show which monitor has greater inventory amounts for each inventory type in the LCI, and the last two columns show which monitor has greater impact scores for each impact category in the LCIA. The impact categories that are affected by each inventory type are in the same rows as the associated inventory type. As seen in Table 5-1, some impact categories associated with ancillary material and water pollutant inventory types had opposing outcomes in the LCI versus the LCIA. For example, the three impact categories affected by the ancillary material inventory had greater impacts for the CRT, although the

ancillary material inventory had greater amounts of inputs for the LCD. In this case, both primary and ancillary materials contribute to the impact categories, causing differing results.

Considering the wastewater outputs, which are greater for the LCD than the CRT, the impacts related to water releases are in some cases greater for the CRT than the LCD. Note that although the wastewater volume is greater for the LCD, the total mass of water pollutants in the LCI is greater for the CRT (see Table 2-24). In the LCIA, the LCD has greater impacts for water eutrophication and aquatic toxicity, but not for the two water quality categories (BOD and TSS), chronic health effects to the public, nor terrestrial toxicity, all of which include water emissions in calculating the impact score.

Table 5-1. Baseline LCI vs. LCIA: monitor with greater inventory amount and impact

Baseline life-cycle inventory (LCI)		Baseline life-cycle impact assessment (LCIA)	
Inventory type	**Monitor with greater inventory results**	**Potential impact category(ies) associated with inventory type**	**Monitor with greater impact results**
Primary materials	CRT	Renewable resource use	CRT
		Nonrenewable resource use	CRT
		Chronic health effects, occupational	CRT
Ancillary materials	LCD	Renewable resource use	CRT
		Nonrenewable resource use	CRT
		Chronic health effects, occupational	CRT
Water inputs	CRT	Renewable resource use	CRT
Fuel inputs	CRT	Energy use	CRT
		Chronic health effects, occupational	CRT
Electricity inputs	CRT	Energy use	CRT
Total energy inputs	CRT	Energy use	CRT
Air pollutant outputs	CRT	Global warming	CRT
		Ozone depletion	*a*
		Photochemical smog	CRT
		Acidification	CRT
		Air particulates	CRT
		Chronic health effects, public	CRT
		Aesthetics (odor)	CRT
		Terrestrial toxicity	CRT

Table 5-1. Baseline LCI vs. LCIA: monitor with greater inventory amount and impact

Baseline life-cycle inventory (LCI)		Baseline life-cycle impact assessment (LCIA)	
Inventory type	**Monitor with greater inventory results**	**Potential impact category(ies) associated with inventory type**	**Monitor with greater impact results**
Wastewater outputs	LCD	*none*	NA
Water pollutant outputs	CRT	Water eutrophication	LCD
		Water quality, BOD	CRT
		Water quality, TSS	CRT
		Chronic health effects, public	CRT
		Aquatic toxicity	LCD
		Terrestrial toxicity	CRT
Hazardous waste outputs	CRT	Hazardous waste landfill use	CRT
Solid waste outputs	CRT	Solid waste landfill use	CRT
Radioactive waste outputs	CRT	Radioactive waste landfill use	CRT
Radioactivity outputs	CRT	Radioactivity	CRT

[a] The LCIs for both the CRT and LCD contain data for substances that were phased out of production by 1996 due to their ozone depletion potential. Whether these emissions still occur in countries that were signatories to the Montreal Protocol and its Amendments and Adjustments (such as the United States and Japan) is not known, but considered to be unlikely. When phased-out substances are included in the inventory, the CRT has greater ozone depletion impacts than the LCD. However, if phased-out substances are removed from the inventories, the results are switched, with the LCD having greater impacts.

5.2 LCIA RESULTS

5.2.1 CRT and LCD Baseline Results

The LCIA results, presented in detail in Chapter 3, showed that the CRT has greater total life-cycle impact indicators in most of the impact categories (see Table 3-10). In the baseline scenario, the CRT has greater impacts than the LCD in all but two impact categories (eutrophication and aquatic toxicity). However, note that for the ozone depletion category, the LCIs for both the CRT and LCD contain data for substances that were phased out of production by 1996 due to their ozone depletion potential. Whether these emissions still occur in countries that were signatories to the Montreal Protocol and its Amendments and Adjustments (such as the United States and Japan) is not known, but considered to be unlikely. When phased-out substances are included in the inventory, the CRT has greater ozone depletion impacts than the LCD. However, if phased-out substances are removed from the inventories, the results are switched, with the LCD having greater 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 (refer to Section 3.3). Table 5-2 summarizes which life-cycle stages have the greatest impacts for each impact category for the CRT and LCD. As shown in Table 5-2, the CRT has nine and the LCD has 11 impact categories with greatest impacts from the manufacturing life-cycle stage. Only six categories (solid waste landfill use, global warming, ozone depletion, acidification, air particulates, and chronic public health) have greatest impacts from the CRT use stage, and four categories (solid waste landfill use, acidification, air particulates, and chronic public health) have greatest impacts from the LCD use stage. The CRT has three categories with greatest impacts from the upstream life-cycle stage and the LCD has three. The end-of-life (EOL) life-cycle stage is greatest for the same two impact categories for both the CRT and LCD (hazardous waste landfill use and radioactive waste landfill use). Note that the EOL stage impacts are generally very small contributors to the overall impacts. This is likely because of the small inventories associated with the EOL processes, but also may be a function of the incomplete and/or secondary data for the EOL (i.e., no remanufacturing data, and secondary data not completely specific to the monitors evaluated in this study).

A more detailed evaluation of lead, mercury, and liquid crystals was completed in Chapter 4. As expected, the CRT, which has lead in the glass, frit, and printed wiring boards (PWBs), has greater impacts from lead than did the LCD, which only has lead in the PWBs. Regarding mercury, there were greater inventories of mercury in the CRT life cycle than in the LCD life cycle, despite the fact that only the LCD has mercury directly in the product. The greater amount of mercury is from the release of mercury and mercury compounds from the generation of electricity. And as the CRT life cycle uses more electricity than the LCD, there was a greater quantity of mercury releases reported for the CRT than the LCD. Liquid crystals are only found in LCDs, and therefore, there are no associated impacts for the CRT. Little conclusive information was available on the liquid crystal materials. A detailed literature search was conducted, however very little data were available on the toxicity of these materials. Based on the limited toxicity data obtained, liquid crystals currently do not appear to be a significant human health or environmental hazard in the LCD life cycle. However, there were insufficient toxicity data available to make a definitive conclusion about liquid crystal toxicity.

Table 5-2. Monitor type with greatest impacts for each life-cycle stage and impact category (baseline scenario)

Impact category	Monitor type 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

5.2.2 CRT Results

For the CRT, many of the impacts were driven by a single material in the inventory. As stated in Section 3.3.15 and shown in Table 3-57, in 14 of the 20 impact categories, the top individual contributor to the impacts was responsible for greater than 50% of the impacts. This shows that the CRT data are highly sensitive to a few data points. Major conclusions from the CRT LCIA are as follows:

- Energy used in glass manufacturing and associated production of LPG are driving the baseline CRT results (they dominate ten impact categories, including overall life-cycle energy use).

- The large amounts of fuel used as energy sources are driving occupational health effects. Occupational impacts are calculated from inventory input amounts, and therefore there may or may not actually be exposure to these fuels (e.g., they may be contained); however, the results illustrate the potential for health effects, especially under spill or upset conditions.
- The generation of electricity for the use stage dominates seven impact categories.
- Air emissions of sulfur dioxide from electricity generation (for the use life-cycle stage) drive chronic public health effects, acidification, and terrestrial toxicity impacts. This may be a concern, for example, in areas in nonattainment of regulated levels of sulfur dioxide in the United States.

The use of LPG fuel in glass manufacturing dominated ten impact categories: two directly from the LPG used in glass/frit manufacturing (energy use impacts and chronic occupational health effects) and eight from LPG production (renewable resource use, nonrenewable resource use, photochemical smog, air particulates, water eutrophication, BOD water quality, TSS water quality, and aesthetics). In addition, impacts from the generation of electricity during the use stage dominated seven impact categories: solid waste landfill use, radioactive waste landfill use, global warming, ozone depletion, acidification, chronic public health, and terrestrial toxicity. The CRT tube manufacturing process, which represents the most functionally and physically (by mass) significant component of the CRT monitor, only dominated one impact category (aquatic toxicity). Twenty-six percent of the aquatic toxicity score was from phosphorus outputs from tube manufacturing, while most of the rest were from the materials processing life-cycle stage. The remaining two impact categories (hazardous waste landfill use and radioactivity) had greatest impacts from the landfilling of the assumed hazardous proportion of CRT monitors, and the release of Plutonium-241 in steel production, respectively (Table 3-57). The radioactivity impacts are driven by the radionuclide Pu-241, due to the electric grid inventory included in the steel production secondary data set, which includes nuclear fuel reprocessing.

The large amount of LPG reported for glass manufacturing was originally questioned during the data collection and verification stage of this project. While no compelling reason could justify removing the LPG data in the baseline case, a sensitivity analysis was conducted in which the glass energy data were modified. Other sensitivity analyses were also conducted (i.e., manufactured life, modified LCD monitor manufacturing energy, and modified LCD EOL distributions). However, the only scenario that substantially altered the comparative results was the modified glass energy scenario (see Table 3-62 and Section 3.4.5).

The overall energy in the baseline scenario was nearly seven times greater than that in the modified scenario (from 20,800 MJ to 3,020 MJ), and the amount of LPG dropped to zero, while other energy sources increased. The basis for the modified data was removing the energy inputs from one suspect data set. As a result, the CRT modified glass energy scenario had greater energy use impacts in the *use* stage than in the *manufacturing* stage for the CRT. The amount of LPG used in glass manufacturing in the baseline scenario is 351 kg/monitor of LPG, which alone

costs about $71.[1] This is a significant amount of the cost of a complete CRT monitor (the range of a few currently selling 17" CRTs is $158-316, and the average cost from primary data collected in the CDP was $541, which are presented in Section 5.4). Therefore, it is likely that the actual energy inputs to the glass manufacturing process is somewhere between the baseline and modified glass scenarios. In conclusion, more information is needed on energy used in glass manufacturing, which is driving CRT baseline results.

The additional analyses for the CRT of lead and mercury also revealed that the use of lead could present health risks, but the method of using only inputs to evaluate occupational impacts (see Section 3.1.2.13) may not adequately represent occupational exposures and risks. Further refinement of the occupational impact analysis may be warranted.

Although there is no mercury in the CRT monitor, mercury emissions from electricity generation in the CRT life cycle were greater (in mass) than the mercury used in the LCD. Therefore, to reduce mercury emissions from the CRT life cycle, efforts to reduce electricity consumption could be taken. Additionally, changes to the electric grid could also reduce mercury emissions from the CRT life-cycle.

5.2.3 LCD Results

The LCD impact results were less sensitive to an individual input or output than the CRT results, although in 11 of the 20 impact categories an individual input was still responsible for greater than 50% of the total impacts (Table 3-58). In general, the LCD results are less uncertain than the CRT results. This is because most of the CRT results are being driven by either glass input data or data from secondary sources, while LCD impacts are being driven more by data from primary sources. Some results to note are as follows:

- The LCD monitor/module manufacturing process group had greatest impacts in six impact categories (Table 3-58).
- Although the top contributor to the energy impact category was electricity consumed in the use stage (30%), the overall energy impacts were greater from the manufacturing stage than the use stage.
- In the glass energy sensitivity scenario, the use stage had greatest energy impacts, although only by a small margin over the manufacturing stage (see Figure 3-26).
- Sulfur dioxide [emitted from electricity generation for the use stage, and constituting only 0.37% of the air emission inventory (see Table 2-49)] dominates the acidification, chronic public health, and terrestrial toxicity impact categories (Table 3-58). The high public health and terrestrial toxicity scores are due to its low non-cancer toxicity value and resulting high hazard value (HV).
- Sulfur hexafluoride (SF_6) from LCD monitor/module manufacturing was the single greatest contributor to the global warming impact score; however, carbon dioxide from the use stage and the materials processing stage also contributed significantly to the global warming impacts (Table 3-25).

[1] Based on a "daily market price" on August 29, 2001, of $0.4160/gallon of LPG (http://www.americanpowernet.com/pub_energy/futures.html). For 351 kg/functional unit in the CRT manufacturing life-cycle stage, the cost is about $71 per functional unit (i.e., one monitor), assuming a density of LPG of 2.053 kg/gallon. For the LCD, the 16.8 kg/functional unit of LPG would cost about $3.40 per monitor.

- The glass energy inputs did not directly dominate any impact categories, as they did for the CRT (due to the smaller mass of glass in the LCD); however, LPG production (required for the glass energy fuel) dominated two categories: TSS water quality and aesthetics (Table 3-58).
- LNG as an ancillary inventory material was questionably very large and had greatest impacts in two categories: nonrenewable resource use and photochemical smog (Table 3-58; shown there as "Natural Gas Production" due to that process being used as a surrogate for LNG production).

The additional analyses of lead, mercury, and liquid crystals showed that the LCIA alone is not adequate enough to determine all the potential impacts within the life-cycle of the LCD monitors. Similar to the conclusion for the CRT, lead-based occupational impacts would require further refinement of the LCIA methodology. The LCIA method in this LCA used inputs as surrogates for occupational exposure. There are outputs, within the occupational setting, that should also be considered.

For mercury, which is found in the backlights of the LCD monitors, there is nearly the same amount of mercury by mass emitted to the air during electricity generation as there is mercury used to make the backlight unit. The mass of mercury input for backlights is only about 20% greater than the mercury air emissions from electricity generation (across all life-cycle stages).

Liquid crystals were also identified by the CDP Core Group as a material for which additional information would be reviewed. The LCIA did not find the liquid crystals to be significant contributors to any impact categories; however, this could partially be due to the lack of information on them. The additional analysis also revealed limited information, but qualitatively, did not show significant potential risk.

5.2.4 CRT vs. LCD Sensitivity Analysis Results

The only sensitivity analysis to show significant difference in the results was the modified glass energy scenario. In comparing the CRT and LCD, the CRT *baseline* scenario had greater impacts than the LCD in all but two impact categories (eutrophication and aquatic toxicity) and possibly three (ozone depletion). In the *modified glass energy scenario*, nine of the 20 categories had greater impacts from the LCD life-cycle than the CRT. Energy use remained greater for the CRT; however, nonrenewable resource use, global warming, photochemical smog, eutrophication, BOD and TSS water quality, chronic occupational health effects, and aesthetics all reversed such that the LCD had greater impacts than the CRT (Table 3-62). As stated above, it is believed that a more true representation of the monitor life cycles lies somewhere between the baseline and modified glass energy scenario. Further work is recommended in clarifying and refining glass energy input information.

5.3 UNCERTAINTIES

As with any LCA, it is not uncommon for there to be uncertainty associated with such a large data collection effort. Two of the largest sources of uncertainty in this LCA that have a significant effect on the results are as follows:

- *CRT and LCD glass manufacturing energy inputs (from primary data)*: The larger amount of glass used in CRTs than LCDs results in the CRT having greater associated uncertainty than the LCD results.
- *Secondary data for upstream and fuel production processes*: When any one material is used in the life-cycle of either monitor in large quantities, the impacts associated with the inputs and outputs from the production of that material may become significant. For example, LPG and LNG production were both used in significant enough amounts to influence some impact categories. Therefore, the uncertainty in the secondary data becomes important. This highlights the need for a consistent, national (or international) LCI database that is updated regularly.

Other uncertainties associated with individual data points collected from primary data sources may be found in the data for this analysis. However, they had less effect on the overall results than the uncertainties mentioned above. For manufacturers interested in conducting improvement assessments, closer review of such uncertainties may be warranted.

Other uncertainties in the LCA pertain to uncertainties inherent in LCIA methodology. The purpose of an LCIA is to evaluate the *relative potential* impacts of a product system for various impact categories. There is no intent to measure the *actual* impacts or provide spatial or temporal relationships linking the inventory to specific impacts. Uncertainties are inherent in each impact category, and the reader is referred to the baseline LCIA results in Section 3.3 for a detailed discussion of uncertainties by impact category.

Another point that should be recognized in the overall comparison of CRTs and LCDs is that CRTs are a more mature technology than LCDs. Changes in LCD manufacturing processes have likely occurred during the development and publication of this report. Therefore, comparisons must be carefully drawn when evaluating the mature CRT to the newer LCD technology.

5.4 COST AND PERFORMANCE CONSIDERATIONS

The focus of this study has been on the environmental effects associated with CRTs and LCDs. The environmental attributes or burdens of a product are not expected to be considered alone when evaluating the marketability and commercial success of a product. The cost and performance of each monitor type are obviously critical components to a company's or consumer's decisions of whether to produce or purchase a product. This section briefly addresses a few direct costs associated with the monitors. A complete cost analysis, including all direct costs (e.g., material costs) and indirect costs (e.g., environmental costs to society) are beyond the scope of this report. Direct retail costs of the monitors and electricity costs are presented herein.

The average retail price of 1997-2000 model year monitors, collected from the manufacturers who supplied data for this project, as well as the performance information, are presented in Table 5-3. Costs collected from current monitors on the market are presented in Table 5-4. From Table 5-3, which represents primary data collected on the actual monitors included in this study, the LCD is approximately 2.7 times more costly. More recent data show that prices have come down, and the difference in prices between the CRT and LCD has also been reduced.

Table 5-3. Primary cost and performance data collected from manufacturers for the CDP

Monitor	Display Size	Resolution	Brightness range	Contrast ratio range	Number of Colors	Average cost from primary data
	(inches)	(pixels)	(cd/m^2)			(US$)
CRT monitor (functional unit aggregate)	17	1024x768	86-154	---	"Full color"	$541
LCD monitor (functional unit aggregate)	15	1024x768	200-300	200:1 - 300:1	"Full color"	$1,450

--- Not reported or not applicable.

A complete cost analysis would require assessing the costs from each life-cycle stage. The costs presented above are retail costs that presumably represent the manufacturing costs, but probably not external environmental costs, for example. The costs from the use stage can be represented by the electricity costs during the use stage. The average cost of residential and commercial electricity in the United States is approximately $0.021/MJ,[2] and the CRT and LCD monitors use about 2,290 and 853 MJ/functional unit, respectively, in the use stage baseline scenario, which assumes a total of 13,547 hours per life over a period of 6.5 years (see Section 2.4.1.2). Therefore, the electricity costs to consumers during the use stages are $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 in the baseline scenario are presented in Table 5-5.

[2] This number was calculated from a value found at the following Web address: www.eia.doe.gov/cneaf/electricity/ esr/t11.txt.

Table 5-4. Cost and performance data for some currently selling CRTs and LCDs[a]

Monitor	Display Size	Resolution	Brightness	Contrast ratio	Number of Colors	2001 Cost
	(inches)	(pixels)	(cd/m^2)			($US)
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 the manufacturer's Web site except for prices, which where obtained from http://www.cdw.com on 8/29/01.
[c] Data are from the manufacturer's Web site.
---- Not reported or not applicable.

Table 5-5. Life-cycle electricity costs (baseline scenario)

	CRT			LCD		
Life-cycle stage	**Electricity use (MJ/functional unit) (see Table J-3)**	**unit cost ($/MJ)**	**Cost ($US)**	**Electricity use (MJ/functional unit) (see Table J-12)**	**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
EOL	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. Note that the use of the *U.S.* average cost is simply to compare costs among life-cycle stages, although the actual costs would be mostly from *Asia*.
[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.

can weigh energy more heavily in concluding which monitor may have lower environmental impacts, while keeping in mind the data limitations and uncertainties, as well as cost and performance considerations.

The LCA is defined such that the monitor assessments are performed on a functionally equivalent basis. To the extent possible, data were collected on functionally equivalent monitors. The data presented in Table 5-3 are the range of specifications provided by the monitor assemblers, but not necessarily from the manufacturers of all of the component parts. Therefore, we are unsure if the specifications provided by the monitor assemblers also represent those of the component parts, since the component parts manufacturers did not consistently supply performance data as requested in the data collection questionnaire used in this study. However, when companies were approached to participate in the study, they were informed of the performance specification parameters within which the study boundaries were defined. Therefore, it is assumed that they meet the specifications as presented in Chapter 1 (Table 1-2) and in Table 5-3 and they perform relatively equivalently. In the primary data, the reported brightness of the CRT was less than the LCD, otherwise, they are functionally similar.

5.6 SUGGESTIONS FOR FUTURE RESEARCH

Areas where future research could be conducted to refine and/or continue the use of the results in this study are as follows:

- gather more information on energy use in glass manufacturing;
- develop consistent materials and fuel processing data in a national (or international) LCI database that is updated regularly;
- refine and/or update some of the LCD manufacturing data (e.g., LNG data);
- collect more complete EOL data (e.g., remanufacturing data, and primary data for incineration and landfilling) to determine better representation of the EOL impacts;
- conduct more research on EOL options for LCDs;
- collect more detailed data on landfilling and other treatment processes, such as water treatment where no impacts were calculated;
- update manufacturing data to meet more recent monitor model years;
- conduct a more focused analysis on selected areas for detailed improvement assessments; and
- evaluate process changes or other alternatives against an "average 1997-2000 model year" to evaluate impacts of changes or improvements over time.

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5.5 IMPROVEMENT ASSESSMENT OPPORTUNITIES AND TARGETED AUDIENCE USES OF REPORT

To meet the primary objective of providing the display industry with data to perform improvement assessments, the industry should look at the manufacturing life-cycle stage, while recognizing the influences of the other stages. CRT improvement opportunities could include improved energy efficiency during glass manufacturing and display use, as well as reductions in lead content. LCD improvement opportunities could also include improved energy efficiency, especially during manufacturing. Certain materials, such as SF_6 and its contribution to global warming, may also be of concern and an area to focus on in future improvement assessments.

In addition, any improvement assessment should consider how changes in one life-cycle stage will affect impacts in other stages. For example, in Chapter 4 we saw that the mercury inputs and outputs from the intentional use of mercury in an LCD backlight are less than (by mass) the mercury emissions from the CRT use stage, due to the relatively high energy usage by the CRT and the emissions of mercury from electricity generation. In this example, we can see that on a pure mass basis, a product's energy efficiency is a key consideration and any changes in manufacturing should consider if it will affect changes in use. However, this project did not conduct a quantitative risk assessment to determine where the greatest potential for mercury exposure (and therefore risk) might occur. Consequently, we cannot definitively say whether it is better to have a potentially less energy-efficient backlight that does not contain mercury or a more energy-efficient backlight that does. Nonetheless, this analysis highlights the life-cycle trade-offs that must be considered in an improvement assessment.

Another objective of this study was to provide an LCA model for future analyses. Companies or individuals who have more current data for the CRT or LCD can apply them to the model presented here. For example, changes in an individual process can be identified and incorporated into the model. The other processes that are not expected to change significantly can be left unchanged, and only limited data would need to be altered. This would reduce the time and resources that would normally be required for a complete analysis.

Finally, those interested in comparing the results of the two monitors can apply their own set of importance weights to each impact category to determine their individual decision. For example, if energy impacts are much more important than aesthetics to a particular person, they can weigh energy more heavily in concluding which monitor may have fewer environmental impacts, while keeping in mind the data limitations and uncertainties, as well as cost and performance considerations.

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- collect more detailed data on landfilling and other treatment processes, such as water treatment where no impacts were calculated;
- update manufacturing data to meet more recent monitor model years;
- conduct a more focused analysis on selected areas for detailed improvement assessments; and
- evaluate process changes or other alternatives against an "average 1997-2000 model year" to evaluate impacts of changes or improvements over time.