APPENDIX D

TECHNICAL MEMORANDUM:
Life-Cycle Inventory Approach for Materials Extraction and Materials Processing Life-Cycle Stages

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1. INTRODUCTION

1.1 Background

The U.S. Environmental Protection Agency's Design for the Environment Program Computer Display Project (CDP) is conducting an environmental life-cycle assessment (LCA) that will evaluate the relative environmental impacts of cathode ray tubes (CRT) and liquid crystal display (LCD) computer monitors. The major life-cycle stages of a product system include materials extraction, materials processing, product manufacturing, product use, and final product disposition (end-of-life). An LCA evaluates the relative environmental impacts of a product system and is defined in greater detail in Chapter 1 of the main report. An LCA generally consists of four phases: goal definition and scoping, life-cycle inventory (LCI), life-cycle impact assessment (LCIA), and life-cycle improvement assessment.

The activity of quantifying the inputs (e.g., materials, utilities) and outputs (e.g., emissions, wastes) of a product system is the LCI phase of an LCA. A product system is made up of the multiple processes that help produce, use, or dispose of the product. Each process typically has an inventory that consists of inputs and outputs for each process. Therefore, an LCI of a product system consists of several inventories for processes throughout the life-cycle of the product. This technical memorandum (TM) addresses the LCIs related to two major life-cycle stages: materials extraction and materials processing, which together will be referred to as the life-cycle stages that are "upstream" of the product manufacturing stage. Ideally, transportation associated with those stages is also included. This TM will describe the approach to choosing the upstream data from secondary sources that will be included in the CDP analysis.

1.2 Purpose and Scope of this Technical Memorandum

The purpose of this TM is to present the approach for obtaining process-specific inventory data related to extraction and processing of the materials needed to produce a CRT and LCD computer monitor. Collecting these upstream inventory data can involve dozens of upstream processes because there are dozens of materials used to produce CRTs and LCDs. Therefore, decision rules are typically used to limit which materials to include in the scope of the LCA, and existing data from secondary sources are generally relied upon. For inventories related to materials extraction and materials processing, various databases with input and output LCI data exist for materials commonly used in industry. The existence of these inventories, and the limited resources available for collecting primary inventory data for the entire life cycle, result in the use of secondary data for upstream processes. In the CDP, more emphasis will be given to collecting primary data for product manufacturing and end-of-life processes. This TM identifies initial materials considered for inclusion in the upstream life-cycle stages. Actual material lists from the inventories collected from the primary data collection efforts were not available until after data collection had to begin for the upstream processes. Therefore, initial materials were identified to help determine which secondary data to obtain. Once actual materials from the manufacturing stage inventory were identified, the selected secondary data source was checked for the appropriate data sets to be included in the study. This TM addresses the initial steps for choosing which upstream data source to use, by identifying and prioritizing several data sources. The remainder of this TM will present a brief summary of results, the methodology for selecting secondary upstream data for the CDP, detailed results in terms of preferred data sources, and the limitations to using the upstream data for the CDP.

2. RESULTS SUMMARY

Based on initial material lists and project decision rules, approximately 40 materials (including some material groups) were initially identified as materials for which upstream data inventories should be included in the CDP LCA. Nine data sources (i.e., studies and/or databases) were evaluated to determine which upstream data would be used for these and other materials that might be identified in the CDP. Two databases were disregarded because the data are not or will not be available to the public. The remaining seven were reviewed for their applicability to the CDP. Complete inventory data for all currently identified CDP materials were not available from any one of the databases/studies alone. Therefore, a hierarchy of preferred data has been chosen for upstream data from secondary sources. The most preferred data is that from the Environmental Information and Management Explorer (EIME) database developed by *Ecobilan* (Ecobalance), a company based in France.

EIME is an LCA software package that specializes in electronics and the electronics industry and currently includes 18, with forthcoming updates expected to bring it to 21 materials specific to the CDP. The database is immediately available, and although it is relatively expensive, it may be attainable at a negotiated price (Glazebrook 1999). The EIME data do not fulfill all the CDP's upstream data requirements and therefore, other databases will be needed. Twelve materials were not found in any of the databases and may require additional research from secondary or primary sources to complete the CDP product system inventories. It appears, however, that EIME, supplemented with Ecobalance's Database for Environmental Analysis and Management (DEAM) will cover most materials needed in the CDP.

3. METHODOLOGY

The method for determining the upstream data that will be used for the CDP depends on which materials need to be included in the upstream evaluation and what existing databases are currently available for those materials. This section consists of three subsections that present the following: (1) how the preliminary list of materials were identified; (2) which data sources were considered for use as CDP upstream inventory data; and (3) the selection criteria for choosing which upstream data to include in the CDP.

3.1 Materials Selection

The first step to selecting upstream data sources is to identify what materials are of interest to the project. Primary data collected from manufacturing facilities will provide a list of upstream materials to consider in the upstream stages. However, the materials inventory from the CDP product manufacturing stage was not yet complete when upstream data collection needed to begin to meet project time and budget constraints. Therefore, a preliminary list of materials used to manufacture the monitors was identified by disassembling a CRT and LCD and by reviewing the literature on manufacturing processes. The list was then slightly reduced based on decision rules to limit the scope of the project. This preliminary list is then used to help choose preferred sources of upstream data for materials of interest in the CDP. The following subsections describe the bills of materials of the LCD and CRT, the decision rules applied to the bills of materials, and the list of selected materials for upstream data collection.

3.1.1 Bills of Materials

A 15" CRT and a 15" LCD desktop monitor were disassembled, to the extent they could be manually separated, into their component parts/materials and each of these parts was weighed using Mettler analytical balances. A 17" CRT (the CDP functional unit) was not available for disassembly and therefore it is assumed that the percent contribution of materials in the 15" CRT and the 17" CRT are equivalent, which is an adequate assumption for the purposes of identifying major product materials.

Primary (also referred to as “product”) materials are defined as those that become part of the final assembled monitor. Bills of materials of the CRT and LCD monitors were compiled to quantify the mass contribution of each primary material and component in each monitor. Where individual materials could not be discerned, component parts consisting of multiple materials were identified and weighed. These bills of materials are presented in the CDP’s Industry and Technology Profile Document (MCC 1998). The material makeup of some component parts [e.g., thin-film transistors (TFTs) on LCD glass substrate or phosphors on CRT glass substrate] were identified from published literature (i.e., secondary sources) (O’Mara 1993, DisplaySearch 1998, FCR 1996, MCC 1993, ECT 1980). Simultaneous and subsequent work on the CDP involved obtaining more details on the makeup of certain component parts from manufacturers (i.e., primary sources) through data collection questionnaires.

The next step was to identify common ancillary (also referred to as “process”) materials used in product manufacturing, which were found from secondary sources (O’Mara 1993, DisplaySearch 1998, FCR 1996, MCC 1993, ECT 1980) and reviewed by industry experts. These ancillary materials were added to the primary bills of materials for consideration in the LCA (MCC 1998). Additional ancillary materials were identified from primary sources during concurrent manufacturing data collection activities.

3.1.2 Decision Rules

Due to the complexity of the CRT and LCD monitors, and for any LCA, the boundaries of the analysis must be clearly defined. Thus, the following decision rules for choosing the materials to be evaluated were developed and applied to the primary and ancillary bills of materials. Three major categories of decision criteria were used to select materials for detailed analysis in the LCA: (1) mass contribution; (2) potential environmental and/or energy significance; and (3) technological importance. A priority hierarchy was developed (Figure 1) using a combination of these criteria.

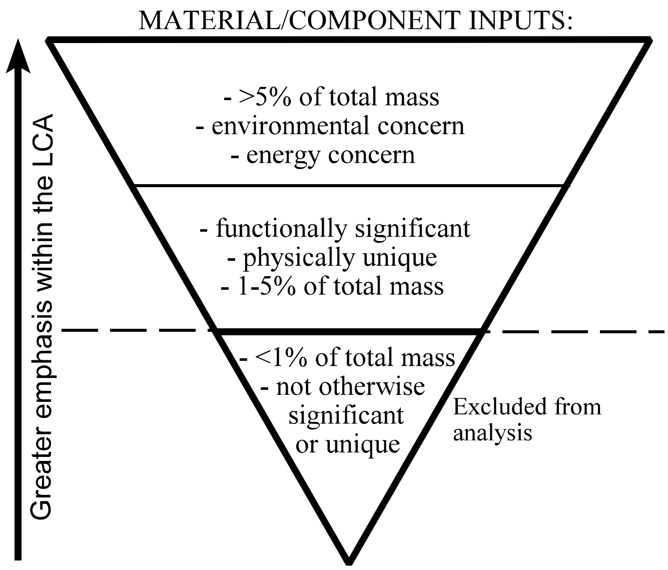

Figure 1. Decision rule hierarchy

The first criterion is applied by including materials that constitute greater than or equal to 1% of the monitor by mass. Materials constituting more than 5% will be given greater emphasis in the LCA. Mass is a simple measure by which to select important materials for consideration in the LCA because in many cases, the larger the material, the greater the impact. This is true for resource consumption impacts which are equivalent to the amount of material used. However, other impact categories may not be equivalent to the amount of material consumed, and simply eliminating materials based on mass alone may exclude important impacts from an environmental life-cycle perspective. Therefore, under the second criterion, materials were also included if they have a potential environmental/health impact (e.g., they may be toxic) or use large amounts of energy to produce. The environmental criterion decision rule refers to materials that may pose risks to the public, occupational workers, or the ecosystem from manufacturing, use, or disposal of the material. The primary and ancillary materials were reviewed by a team of experts at the University of Tennessee and were compared to regulatory lists and other sources (Klaassen et al. 1986, EPA 1998, ChemFinder 1998, SRC 1998) to identify materials with known or potential environmental concerns. When impacts are calculated in the LCIA, a more rigorous review of toxicity data and environmental parameters will be conducted to provide quantitative impact measures.

The third decision rule criterion applies to materials that are critical to the technology (e.g., LCD TFT materials or the CRT phosphors). This is intended to ensure that other materials of potential importance are not overlooked in the LCA. Furthermore, because the LCA will be comparative in nature, greater emphasis will be placed on materials that are physically unique to a display technology.

For the materials meeting the top tier of the decision rule hierarchy (Figure 1) in the CDP, attempts are made to obtain secondary data for those upstream material processes. Materials in the middle segment of the triangular hierarchy scheme are given lower priority, but included, if available. Finally, the last segment of the triangle would contain materials excluded from the analysis.

3.1.3 Material Selection Results

The materials identified here are for selecting which materials require the collection of input and output inventory data from materials extraction, materials processing, and associated transportation, collectively referred to as the "upstream" life-cycle stages. The inventories from each of these life-cycle stages are then used to calculate impacts of the various impact categories considered in the analysis.

The total masses of the CRT and LCD that were disassembled were approximately 12.8 kg and 5.15 kg, respectively. The printed wiring boards (PWBs) and their components were excluded from these weights and from the following materials analysis because they are treated as complex display components not broken down by individual materials. The CRT consists of approximately 17 primary materials and the LCD is comprised of about 23 primary materials (MCC 1998). The major primary materials by weight ($\geq$1%) in the CRT and LCD are listed in Table 1 with their corresponding components. Figures 2 and 3 depict the percent contribution of each of those materials to the overall monitor. For the CRT, eight materials were greater than or equal to 1% and only three [glass, steel, and high impact polystyrene (HIPS)] were greater than 5% of the weight of the monitor. The LCD had seven materials greater than or equal to 1%, five of which were greater than 5% [steel, polycarbonate, acrylonitrile butadiene styrene (ABS), polyester, and glass]. The items in bold in Table 1 represent the materials that are >5% for both the CRT and LCD. Other primary materials to be included in the LCA, based on the environment and technology decision rules, are presented in Table 2. The primary materials that were excluded due to mass are presented in Table 3.

Ancillary materials, such as those required for photolithography, are used in greater quantities for LCDs than CRTs. Preliminary literature searches (O'Mara 1993, DisplaySearch 1998, FCR 1996, MCC 1993, ECT 1980) found four ancillary materials for CRTs and 12 for LCDs (MCC 1998). The latter portion of Table 2 presents the ancillary materials that are included for either technological or environmental importance. The mass criterion for ancillary materials will be identified through responses to data collection questionnaires distributed to manufacturers participating in the project. Table 3 shows the ancillary materials that were preliminarily excluded based on environmental and technical criteria because mass data for ancillary materials are not yet available.

Table 1. Primary materials comprising $\geq$1% by mass of a CRT or LCD monitor and associated components [a]

Material	Associated component(s)	
	CRT	LCD
ABS	-----	Base/stand
Aluminum (Al)	Aluminum shielding, power board heat sink, connectors	Power supply heat sink, TFT metal
Copper (Cu)	Deflection yoke	-----
Ferrite-magnet	Deflection yoke	-----

Table 1. Primary materials comprising ≥1% by mass of a CRT or LCD monitor and associated components [a]

Material	Associated component(s)	
	CRT	LCD
Glass (e.g., borosilicate) [b]	-----	LCP panel
Glass (lead oxide)	Panel, funnel, neck, frit	-----
Lead (Pb) [c]	Funnel & neck glass, frit	-----
Plexiglas	-----	Backlight clear protector
Polycarbonate	-----	Backlight light pipe
Polyester	-----	Power supply & rear cover insulators
Polystyrene, high-impact (HIPS)	Casing	-----
Silicone	Potting material in flyback transformer	-----
Steel	Base, right, left & back shields; shadow mask	Base/stand weight & brackets, backlight plates, rear cover metal plate, power supply housing

[a] See Figures 2 and 3 for material percent contributions to total mass of monitor, excluding PWBs.
[b] Includes materials that could not be easily separated from the glass (e.g., frit, phosphors, transistors) and subtracts the estimated lead content of the glass for the CRT.
[c] The mass of lead was estimated from the total mass of the different glass components and approximate lead levels in the CRT glass components (MCC 1994). On average, approximately 10% of the total mass of CRT glass was assumed to be lead.
NOTE: Materials in bold are >5% of the monitor by weight.

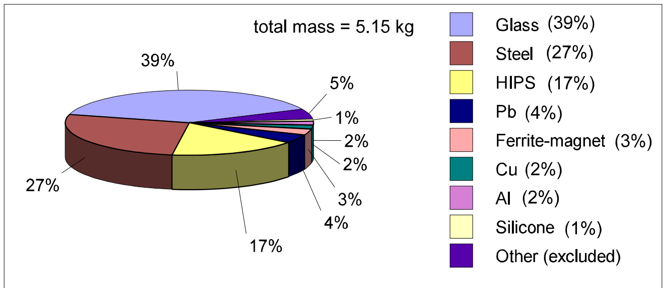

Fig. 2. CRT product materials meeting mass decision rule

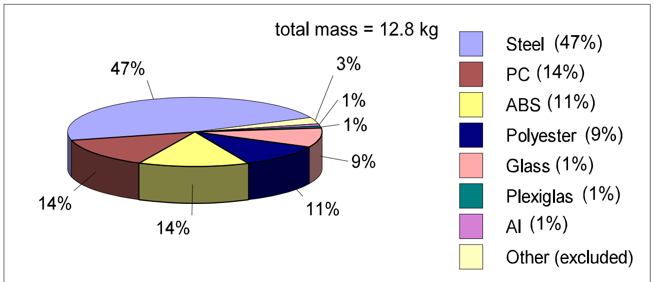

Fig. 3. LCD product materials meeting mass decision rule

Table 2. Primary and ancillary materials or components meeting technology (T), environment (Env), or energy (E) criteria

Materials	Associated components or process		Decision criteria	
	CRT	LCD	CRT	LCD
Primary materials				
Aluminum oxide (Al_2O_3)	Electron gun wire heater	-----	Env	-----
Aquadag	Faceplate black matrix coating	-----	T	-----
Beryllium (Be)	-----	Be-Cu metal clips	-----	Env
Bismuth oxide	Shadow mask back coating	-----	Env	-----
Color filters (acryl epoxy resins)	-----	Front panel glass color filters	-----	T
Divinylbenzene resin	-----	Spacers in AMLCD cell	-----	Env
Frit (lead solder glass)	Glass solder joints	-----	Env, E	-----
Indium-tin oxide (ITO)	-----	Electrode	------	T
Liquid crystals (e.g., polycyclic aromatic halogenated hydrocarbons, cyanobiphenyl, phenylcyclohexane compounds)	-----	Light-modulating material	-----	T, Env
Mercury	-----	Cold cathode fluorescent tube in backlight	-----	Env
Nickel	Electron gun cathodes	-----	T, Env	-----
Phosphors (e.g., ZnS, Y_2O_2)	Illuminating material	-----	T, Env	-----
Polyimide	-----	AMLCD cell alignment layer	-----	T
TFT metals (e.g., Al, Cr, Mo, W)	-----	Transistor	-----	T, Env
TFT silicon materials (e.g., SiO_2, SiNx, doped Si)	-----	Transistor	-----	T
Tungsten (W)	Electron gun wire heater	Transistor	T, Env	T, Env
Ancillary materials				
Boron trichloride (BCl_3)	-----	Photolithographic etchant	-----	Env
Carbon tetrafluoride (CF_4)	-----	Photolithographic etchant	-----	Env
Carbon trifluoride (CHF_3)	-----	Photolithographic etchant	-----	Env
Chloride (Cl_2)	-----	Photolithographic etchant	-----	Env
Ferric chloride ($FeCl_3$)	Photolithographic etchant (shadow mask)	-----	Env	-----
Hydrochloric acid (HCl)	-----	Photolithographic etchant	-----	Env
Isopropyl alcohol (IPA)	-----	Glass cleaner	-----	Env
N-methyl pyrrolidone (NMP)	-----	Photolithographic developer	-----	Env
Polyvinyl alcohol	Photolithographic application of phosphors	-----	Env	-----
Sulfur hexafluoride (SF_6)	-----	Photolithographic etchant	-----	Env

Table 2. Primary and ancillary materials or components meeting technology (T), environment (Env), or energy (E) criteria

Materials	Associated components or process		Decision criteria	
	CRT	LCD	CRT	LCD
Tetramethyl ammonium hydroxide (TMAH)	-----	Photolithographic developer	-----	Env

The materials identified for inclusion in the CDP (Tables 1 and 2) are then prioritized based on the decision rule hierarchy triangle. Those materials that are either: (1) >5% by mass; or (2) of environmental/energy concern, fit into the top priority of the upstream data collection effort. Those materials that are either: (1) between 1-5% by mass; or (2) functionally important and/or physically unique, fit into a lower priority of upstream data collection, but are still included in the project. Those materials that are less than 1% by mass and do not meet the other criteria listed above are excluded from the analysis. Currently, the materials falling into each segment of the decision rule hierarchy are listed in Table 4.

Table 3. Materials excluded from analysis

Material	Associated component/application	
	CRT	LCD
Primary materials		
Aluminized mylar		Corner tape on backlight assembly
Brass	Brass ring on neck assembly	Brass threaded standoff in backlight assembly
Foam rubber		Foam gasket in backlight assembly
Nylon		Cable clamp, strain relief in backlight assembly, clamp in backlight, bushing in base/stand assembly
Paper		Caution label on rear plate assembly
Polysulphone	Insulating rings on neck assembly	
Silicone rubber		Gaskets in LCD panel assembly, shock cushion in light assembly, rubber feet in base/stand assembly
Ancillary materials		
Nitrocellulose binder	For frit application	
Amyl acetate	For frit application	
O_2		Metal etchant
N_2		Metal etchant
Iodine		Polarizer coating

For the top priority materials, we obtained upstream inventory data from secondary sources where available. If no secondary sources were available, we attempted to collect primary data or conduct further research from the literature. For materials in the middle tier, we attempted to collect secondary data but gave less emphasis on including them if too many resources were required. The top tier consists of materials greater than 5% by mass and all the materials in Table 2. Each material in Table 2 was added to the list of materials for either environmental or technological reasons and all except tungsten (W) were unique to a technology. However, tungsten is also included in the top tier for potential environmental concern. As a result, all the materials in Table 2 are of potential environmental concern and/or are both functionally important and physically unique (see Figure 1).

Table 4. Summary table of preliminary CDP materials in priority hierarchy

Top tier	Middle tier	Lowest tier (excluded)
Steel, CRT glass, HIPS, Polycarbonate, ABS, Polyester, LCD glass, lead, Al_2O_3, Aquadag, Be, Bismuth oxide, Acryl epoxy resins (color filters), Divinylbenzene resin, Frit, ITO, Liquid crystals, Hg, Ni, Phosphors, Polyimide, TFT metals, TFT silicon materials, W, BCl_3, CF_4, CHF_3, Cl_2, $FeCl_3$, HCI, IPA, NMP, Polyvinyl alcohol, SF_6, TMAH	Ferrite-magnet, Silicone, Plexiglas, Al, Cu	Aluminized mylar, Brass, Foam rubber, Nylon, Paper, Polysulphone, Silicone rubber, Nitrocellulose binder, Amyl acetate, N_2, O_2, Iodine

3.2 Data Sources Evaluated

In order to identify upstream inventory data to be used for the CDP, nine different data sources (databases or studies) were evaluated. The following nine were chosen based on UT's experience in LCA, which included a comprehensive review of LCA databases (Menke et al. 1996), and from the scoping process for this project:

- American Plastics Council (APC)
  The APC is a major trade association for the U.S. plastics industry. APC is comprised of 24 of the leading plastics manufacturers in the United States with many members having a strong global market presence. APC's membership represents 80% of the U.S. resin production capacity (APC 1999). APC has collected LCI data that are expected to be released in 1999 for polyethylene (PE), polypropylene (PP), high impact polystyrene (HIPS), polyethylene terephthalate (PET), and polyvinyl chloride (PVC) resins and polyurethane precursors (Hentges 1999). Data are mostly vintage 1991 or 1993 and cover production in North America (Hentges 1999). Additional inventories from APC have not yet been identified, although they are presumed to exist.

- Association of Plastics Manufacturers in Europe (APME)
  APME is an industry body that has published inventory data on olefins, polystyrene (PS), PE, PP, PVC, PET and polymethanes (APME 1999), as well as ABS, Plexiglas, polycarbonate, polyester, and polyimide (Karlsson 1999).
- Boustead
  Dr. Ian Boustead is a well known LCA practitioner who developed the Boustead model and database that allows users to produce LCIs of complete systems. Boustead's focus areas are aerosols, automotive products, beverage containers, building materials, and the plastics industry. The organization is based in the United Kingdom (Boustead 1999).
- BUWAL
  BUWAL is the Swiss Agency for the Environment, Forests and Landscape (BUWAL 1999). They have several published reports on LCA. BUWAL 250 is an English version of their LCI database of several common industrial materials.
- Environmental Information and Management Explorer (EIME)
  This software design tool was developed by the *Ecobilan* group in conjunction with IBM, Alcatel, Legrand, Schneider, and Thompson. *Ecobilan* was founded in 1990 and has offices in Europe and in the United States (*Ecobilan* 1999). Version 1.4 of EIME has been released and the embedded database contains 170 modules on the most commonly used materials and subcomponents of the electronic and electric industry (EIME 1999).
- Industrial DEsign MATerials (IDEMAT)
  Dr. J.A.M. Remmerswaal and J. Rombouts of the Delft University of Technology's Section for Environmental Product Development produced this software with a database of LCI data for various industrial materials. There is a student version that was released in 1995 that is available to the public at no cost, but the availability and cost of the complete version is yet undetermined by UT. This evaluation focuses on the student version that was available to UT.
- New Jersey Institute of Technology (NJIT) Report
  NJIT's "Lifecycle Assessment of Television CRTs," (Caudill 1998) report is not a database of upstream inventory data *per se*, however, it is a preliminary LCA that includes LCI data for a CRT and therefore it was considered for use in the CDP as an upstream data source.
- Personal Computer (PC) Ecolabel Report
  This study was developed by Atlantic Consulting and IPU (Institute for Product Development of the Technical University of Denmark) for the Ecolabel Unit of the European Commission (AC and IPU 1998). The purpose of the report was to study personal computers so that an ecolabel could possibly be established. Similar to the NJIT report, this is an LCA with inventory data applicable to the CDP, but it is not a traditional database of upstream inventory data. Analysis of the inventory in the PC Ecolabel Report for the purposes of the CDP was based on Version 1.11 of the report downloaded from their website in January of 1998.
- United States Automotive Materials Partnership (USAMP)
  Formed in June 1993, this partnership set out to conduct vehicle-oriented research and development in materials and materials processing to improve the competitiveness of the U.S. auto industry (USAMP 1999). The USAMP is conducting joint research to further the development of lightweight materials for improved automotive fuel economy. The major technology groups being studied are polymer composites, light metals (including

aluminum, magnesium, etc.), engineered plastics, cast iron, steel and ceramics (USAMP 1999). The aluminum, plastics, steel and automotive industries are participating in a collaborative LCI project to produce a quantitative database of information regarding all the resources used to make, operate and dispose of a generic 3200-pound vehicle (USAMP 1999).

3.3 Selection Criteria

For choosing which upstream data to use for the CDP, the following 11 criteria were considered. Descriptions of each criterion and what is preferred for that category are presented below:

1. Geographic boundaries – Describes whether the data are representative of Europe and/or the United States. In general, U.S. data are preferred for this project, assuming most of the materials for the monitors are extracted and processed in the U.S. However, because some of the CDP manufacturing is in Asia, materials may originate from non-U.S. locations/countries.

2. Origin of data – Describes whether or not the data originate from primary or secondary sources. Primary sources that are clearly identified are preferred.

3. Currency of data – This refers to the dates that represent the actual inventory data. More recent data are preferred. If the date of the inventory data is not known, the date the database was released is considered.

4. Public availability – Data are categorized as either public or private. Publicly available data can be considered for the CDP.

5. When available – This describes whether or not the data are currently available and if not, when they are expected to be available. Immediately available means the data are available from the appropriate company or individual; however, more time may be required for UT to obtain the data. Also provided under this criterion will be whether UT currently has some of the data applicable to the CDP. Immediately available is preferred and further consideration is given to data that UT already has in house.

6. Cost – Due to limited resources, cost is an important factor for determining which upstream data should be obtained for the CDP. However, if possible, negotiations for or donations of data can be pursued as this is a collaborative project with industry and other stakeholders. Least costly data are preferred.

7. Upstream life-cycle stages – Which upstream life-cycle stages are included from each data source are identified, if possible. In some cases, the databases or reports address more than only upstream stages and other stages included will also be noted under this criterion. In the results of this analysis, we will present the names of the life-cycle stages as they are labeled in each respective data source. However, such labels may not be consistent with the specific terminology used in this report. For use in the CDP, we prefer data sources that include materials extraction, materials processing, and associated transportation.

8. Aggregation of data – This describes whether or not the data from the various life-cycle stages are aggregated into one set of inventory numbers or how the data are aggregated. With less aggregation, the CDP will better be able to predict impacts particular to a specific life-cycle stage. Therefore, less aggregation is preferred. For some of the reports considered in this analysis, processes may also be aggregated for an entire product or component and therefore it is difficult to separate out the inventory for one particular material. The advantage of material-specific LCI databases is that the data are not aggregated into a larger component or product.

9. Input/output categories – This lists which categories of inputs and outputs are included in the database or report (e.g., non-renewable resources, fuel and energy inputs, water use, air emissions, water effluents, solid/hazardous wastes). Ideally, the input and output categories would match those defined for the CDP that will be used to calculate the impacts. The LCIA TM (Socolof 1999) describes the impact categories and how the inventory data will be used to calculate impacts. Also of interest is whether the outputs within each category are chemical specific. The more speciated the chemicals, the more desirable the data. In some cases, chemical groups or categories of chemicals are provided. The CDP LCIA methodology requires chemical-speciated data to calculate most impacts.

10. Data quality indicators – If the data source provides an indication of its data quality, this will help determine the data quality of the CDP. In several cases, we were not able to discern whether there were data quality indicators for a particular data set. If the data source provides some indication of data quality, this can then be incorporated into the CDP's data quality indicators for the upstream data.

11. CDP materials included – These are the materials that have been identified in Set. 3.1.3, which constitute the initial list of materials of interest in the CDP. They were cross-referenced with each data source under consideration. Preferred data sources are those with the greatest number of materials of interest to the CDP.

Each database or report was reviewed based on available information, and in some cases, limited information was available. This exercise was not intended to be a comprehensive review of each database, because we were not able to purchase each source. It was intended to be a cursory review of available data sources to assist in the decision of which inventory data to obtain and include in the CDP for the upstream life-cycle stages. When we could not obtain a database, our review was based on information available on company websites, other available literature on the database, personal contacts with company representatives, or third parties who have had experience with using a particular database.

Based on all this information, preferred data sources were identified. All factors were considered, including expected data quality and cost. The first most important criterion was whether the data source included many of the materials of interest to the CDP. Although additional materials may be identified during the concurrent CDP data collection efforts, we expect that the majority of materials of interest have already been identified.

4. RESULTS

Using the CDP decision rules, we initially identified approximately 40 materials (including some material groups) for which upstream data inventories should be included in the CDP LCA (Sect. 3.1.3). Nine data sources were evaluated to determine which upstream data would be used for these and other materials that might be identified. Tables 5 and 6 present a comparison of the data sources evaluated. Table 5 lists the first ten criteria presented in Sect. 3.3, which are related to the type of data provided, availability of the data, and cost. Table 6 cross-references the materials of interest in the CDP to the materials found in the various data sources (the 11^{th} criterion in Sect. 3.3). Together this information was used to identify which data are preferred for use in the CDP as upstream inventory data. Brief discussions of each data source and a final conclusion are presented below.

Referring to Table 5, APC data are not yet available and it is uncertain if they will be available as scheduled, as they were expected to be released in previous years but were not. Therefore, APC is not considered further in this analysis. USAMP inventory data, which were intended only for participating organizations is not a publicly available data set. Therefore, USAMP as a source of upstream data for the CDP is also excluded from further analysis. The remaining seven data sources are evaluated by analyzing Tables 5 and 6.

The eleven criteria described above (Sect. 3.3) can be condensed into three major areas:

- Cost;
- Data quality; and
- Applicability to CDP.

Each source will be described in terms of these criteria, without giving a particular weight to any one over another. Note that the “data quality” criterion is a combination of the origin of the data, the currency of the data, the upstream life-cycle stages included, data quality indicators, and to some extent, the geographic boundaries of the data (see Table 5). The “applicability to the CDP” criterion depends on which upstream life-cycle stages are included, how the data are aggregated, what input and output categories are included (including whether or not the output data are speciated), whether data quality indicators are provided, and which materials of interest to the CDP are included.

Table 5. Selected criteria of upstream data sources

	APC	APME	Boustead	BUWAL 250	EIME	IDEMAT	NJIT LCA	PC Ecolabel	UPAMP
Geographic boundaries	U.S.	Europe	Europe	Europe	U.S. & Europe	Netherlands & Europe	U.S.	Europe	U.S.
Origin of data	Unknown	Primary	Primary	Secondary	Majority is primary, some secondary	Unknown	Secondary	Secondary	Unknown
Currency of data	1990s	1990s (varies per material)	Unknown	1996	1990s (varies)	Second Student version, released in 1995	1970s - 1990s	Not completely determined, but most appear to be 1990s	1990s
Public availability	Public	Public	Public	Public	Public	Public (student version); unknown for complete version	Public	Public	Public
When available	Expected to be released in 1999	Immediate (UT has 2 applicable materials)	Immediate	Immediate (UT has 6 applicable materials)	Immediate	Immediate (UT has 9 applicable materials; unknown if complete version can be obtained)	Interim report immediately available (UT has copy)	Version 1.11 immediately available (UT has copy)	Not available to public
Cost	No cost	No cost	~ $10,000	~ $250	~ $7,500; > $5,700 for universities (Negotiable)	No cost, unknown for complete version	No cost	Version 1.11 no cost; ~ $75 for final report	Not available to public
Upstream life-cycle stages	Unknown	Raw material extraction, material processing, transport	Process operations (including fuel production) and transport operations	Pre-combustion, combustion + processes, transports	Extraction, processing, transportation	Production, which includes transportation when noted, and not clear if extraction included	Material extraction and material synthesis	Material production, manufacturing, transport, use, EOL	Unknown

Table 5. Selected criteria of upstream data sources

	APC	APME	Boustead	BUWAL 250	EIME	IDEMAT	NJIT LCA	PC Ecolabel	UPAMP
Aggregation of data	Unknown	Some data presented as process-specific e.g., fuel production, transport, process)	Often classified into several processes: fuel production, fuel use, transport operations, process operations	Aggregated as "LCI" or "energy consumption," latter subclassified (e.g., final energy source, energy supply, final process energy, transport)	Aggregated over all upstream life-cycle stages for each module (material) into impact categories, system administration can access LCI data separately	Each material aggregated for all life-cycle stages for the following categories: processes, thermal energy, electrical energy, and transports	Process specific; sometimes a few subprocesses are aggregated	Aggregated by major computer components (e.g., monitor) for each life-cycle stage, not process or material specific	Unknown
Input/ Output categories	Unknown	Energy, primary fuels, and raw material inputs; air, water, and solid waste emissions; outputs mostly unspecified	Gross energy, primary fuels & feedstocks: raw materials; water use; air, water solid waste emissions; outputs provided as chemical categories and several speciated chemicals	Commercial fuels resources, feedstock resources, materials used in final stage, main product, co-products, usable wastes, waste treatment; outputs provided as chemical categories and as some speciated chemicals	Natural resources, energy, water inputs; air, water, hazardous waste outputs; outputs relatively well speciated	Material inputs (including water), energy inputs; air, water, and solid outputs; mostly unspeciated outputs	Raw material and energy inputs; solid, air, and waterborne waste outputs; outputs as chemical categories and some speciation	Resource consumption (raw materials), air emissions, water emissions, and waste; includes chemical categories, but also very well speciated	Unknown

Table 5. Selected criteria of upstream data sources

	APC	APME	Boustead	BUWAL 250	EIME	IDEMAT	NJIT LCA	PC Ecolabel	UPAMP
Data quality indicators	Unknown	All calculations were referred back to participating companies before being used	Not provided, but data quality believed to be moderately good (above average as compared to other available sources)	Unknown	Provides high, medium, and low measures of reliability of the data	Unknown	Data were gathered on each material, carefully citing notes and references which document the original sources	Unknown	Unknown

Key:
APC = American Plastics Council
APME = Association of Plastics Manufacturers in Europe
EIME = Environmental Information and Management Explorer
IDEMAT = Industrial DEsign MATerials
NJIT = New Jersey Institute of Technology
USAMP = U.S. Automotive Materials Partnership

4.1 Data Source Reviews

APME data are European-based, of moderate quality, and available for free. However, the data are mostly limited to materials of interest to the plastics industry and therefore only apply to 7 materials of interest to the CDP. The materials covered by APME constitute 17% of the product weight of the CRT described in Figure 2 and 49% of weight of the LCD in Figure 3.

The Boustead data are very expensive, of moderate quality, and include several materials of interest for the CDP, including most of the major product materials by weight of the CRTs and LCDs (55% and 85%, respectively, see Table 6). The significant material missing for the CRT is the leaded glass, which is approximately 39% of the mass of the monitor. The Boustead data include two of the ancillary materials that have been identified for the CDP, but do not include several of the other materials identified for potential environmental concern. The Boustead data are moderately equipped with speciated chemical data as required for the CDP. Data are aggregated for all upstream stages, but are also available as some individual upstream inventories (e.g., transport operations, process operations). Although data quality indicators are not provided by Boustead for the data, the Center for Clean Products and Clean Technologies assesses it as above average based on comparisons with other databases reviewed.

Table 6. Cross-reference of preliminary CDP materials and potential upstream data sources

		APME	Boustead	BUWAL 250	EIME [4]	IDEMAT [8]	NJIT	PC Ecolabel
Primary Materials								
1	ABS	Y	Y		Y (APME)	Y	Y	Y
2	Aluminum		Y	Y	Y	Y	Y	Y
3	Aluminum oxide		Y	Y	Y (BUWAL)			
4	Aquadag							
5	Beryllium					Y		
6	Bismuth oxide					Y (C) [9]		
7	Color filters (acryl epoxy resins)				Y [5]			
8	Copper		Y		Y	Y	Y	Y
9	Chromium (TFT metal)		mining chromite ore		(Y)	Y		
10	Divinylbenzene resin							
11	Ferrite-magnet		Y [2]		Y [6]			Y
12	Frit							Y
13	Glass, borosilicate (LCD)	Y	Y	Y	(Y)	Y		
14	Glass, lead oxide (CRT)						Y	Y
15	Indium-tin oxide - ITO							
16	Lead		Y		Y	Y	Y	Y
17	Liquid crystals				Y			
18	Mercury					Y (C)		
19	Molybdenum (TFT metal)				(Y)	Y		
20	Nickel				Y	Y		Y

Table 6. Cross-reference of preliminary CDP materials and potential upstream data sources

		APME	Boustead	BUWAL 250	EIME [4]	IDEMAT [8]	NJIT	PC Ecolabel
21	Phosphors: e.g., ZnS, Y_2O_2							
22	Plexiglas [polymerization of methyl ester (methyl methacrylate)]	Y			Y (APME)			
23	Polyimide	Y			Y (APME)			
24	Polycarbonate	Y	Y		Y (APME)	Y	Y	Y
25	Polyester	Y			Y (APME)	Y (C)		
26	Polystyrene-HIPS	Y	Y	Y	Y (APME)	Y	Y	Y [11]
27	Silicon TFT materials: e.g., SiNx, SiO2				Y	Y (C)		
28	Silicone				Y			
29	Steel		Y	Y	Y(BUWAL)	Y (C)	Y	Y
30	Tungsten (TFT metal)					Y		Y
Ancillary Materials								
31	Boron trichloride							
32	Carbon tetrafluoride							
33	Chlorine		Y	Y				
34	Ferric chloride							
35	Hydrochloric acid		Y		Y			
36	Isopropyl alcohol							
37	N-methyl pyrrolidone							
38	Polyvinyl alcohol							
39	Surfur hexafluoride							
40	Tetramethyl ammonium hydroxide							
Totals		7	12 [3]	6	18 (21) [7]	12 (17) [10]	8	12
% contribution of CRT primary materials >= 1% by mass [1]		17	55	46	56	25 (52) [10]	91	94
% contribution of LCD primary materials >= by mass [1]		49	85	57	88 (97) [7]	38 (96) [10]	76	76

1. The percent mass contribution of the primary materials were summed to identify the total percent of the monitor by mass that is covered by each data source.
2. Inventory data are available for iron, which is assumed to represent ferrite-magnet.
3. The tally of chemicals for Boustead excludes mining chromite ore for chromium.
4. Cells with a Y and the name of a data source [e.g., "Y (APME)"] indicate the data source that EIME obtained that particular inventory from, if that source is included elsewhere in this table. "(Y)" represents materials that are expected in EIME's forthcoming update.
5. "Epoxy resins" assumed to be for color filters (acryl epoxy resins).
6. The EIME database does not have ferrite-magnet listed, but it does have ferrites MnZn as a mateiral inventory.
7. The first value represents the current EIME dataset and the value in parenthesis indicates materials expected in the forthcoming update.
8. The student version of IDEMAT was the source investigated. "C" (for "complete") indicates cases where IDEMAT has the inventory on a given material only in the complete version.
9. Bismuth
10. The first value is for the student version and the value in parthenthesis is for the complete version.
11. The study only listed polystyrene (PS) and did not indicate if it was high-impact polystyrene (HIPS).

BUWAL 250 is a relatively inexpensive database that is also European data and believed to be from secondary sources. Therefore, the data quality is marginal and its applicability to the CDP is also relatively low as it only appears to cover the least number of materials of interest. Some chemical speciation is provided as output data and the inventories are aggregated over the upstream processes.

EIME appears to be the best candidate for the purposes of the CDP as it is targeted specifically for the electronics industry and includes many of the materials of interest to the CDP (Table 6). The current version includes 18 materials and, with forthcoming updates to the database, there are expected to be 21 materials covered (Karlsson 1999), representing 56% of the materials by mass of the CRT and 97% of the LCD. The low CRT percent is again due to the lack of leaded glass, which is 39% of the CRT. These data also include important materials not included in the weight criterion such as liquid crystals, lead, silicon materials, and color filters. Each of these, with the exception of lead are not found in any other data sources reviewed. The EIME inventory output data appear to be relatively well speciated, but the inventory data in general cannot be separated into each upstream life-cycle stage. The data quality is adequate as some data are from the U.S. and from primary sources. The data specific to the electronics components are from the five industrial partners and their suppliers, while some of the other common industrial materials were obtained from other LCI databases (EIME 1999). The cost is relatively high; however it covers the cost of the entire life-cycle software tool. Discussions with *Ecobilan* representatives have revealed their willingness to negotiate for the use of some material inventory data, provided we supply our results to them in a desirable format. Alternatively, we would be required to purchase the entire software package to obtain the desired inventory data.

The student version of IDEMAT is another free set of data that is European-based. The true quality of the data is not yet well determined by UT. Several (12) CDP materials are included in the student version, and it is believed that 17 would be covered with the complete version. IDEMAT has a few materials, metals in particular, that are not found in any of the other data sources reviewed.

The NJIT LCA report provides only eight material inventories relevant to the CDP; however, because it is an LCA of a television with a CRT, it includes leaded glass, which is not commonly found in existing databases. Some of the inventory data, which are U.S.-based, are from relatively old secondary sources (*circa* 1970). Furthermore, not all outputs are quantified. The report includes two upstream life-cycle stages: materials extraction and "materials synthesis" (referred to as "materials processing" in the CDP). Transportation within these upstream stages is not included. Data are easily identified per material, and some chemical speciation is included. This report does not provide sufficient amount of upstream data to be used exclusively, but given that it is available at no cost, it may supplement missing data (e.g., leaded glass).

The PC Ecolabel LCA is a report that includes 12 of the materials of interest in the CDP in its study and has very well speciated output data. UT has obtained a copy of Version 1.11 at no charge. It is based on European data and of undetermined quality. This was a study that was intended to present results of the life-cycle impacts of a PC and is not intended to be a database of material inventories. UT chose to evaluate this as a potential source for upstream data because of the relevant subject matter of the LCA. And although it covers several materials of interest, the inventory data cannot be separated into individual material inventories. Data are presented for different life-cycle stages, but not provided on a material basis. Therefore, this report could be helpful for checking our final results of the LCA, but not for providing upstream inventories of specific materials.

4.2 Conclusion

To identify the priorities for using upstream data, we would prefer to use as much data from one source as possible to help ensure consistency and thus improve the data quality of the results of the CDP. We have selected to target EIME as the primary source of upstream data. However, what is seen from the information in Table 6 is that no one data source will completely encompass the product materials of the CDP. Twelve of the 40 materials were not covered by any data source. EIME includes the greatest number, yet even including the expected updates to EIME, ten primary materials and nine ancillary materials are not covered by EIME. Four of the ten primary materials and eight of the nine ancillary materials were not covered by any other data sources. Six materials that are not in EIME are believed to be in other data sources. These include the following: beryllium, bismuth oxide, frit, leaded glass, mercury, and tungsten. Beryllium and tungsten are in the student version of IDEMAT and bismuth and mercury are in the complete version of IDEMAT. The NJIT and PC Ecolabel studies include leaded glass and the PC Ecolabel study also includes frit. The NJIT report, however, does not quantify the outputs from leaded glass production. Furthermore, because the PC Ecolabel study's inventory is aggregated over the whole monitor, individual inventory data cannot be produced for the specific materials. Therefore, IDEMAT data and the quantified inputs from the NJIT report may help supplement the EIME data.

Subsequent work for the CDP revealed that Ecobalance also had DEAM data available that supplemented the EIME data, both of which were listed as upstream data sources for this project. Procuring EIME requires negotiations with *Ecobilan* for a reduced price. This will begin subsequent to the final approval of this TM by EPA and the CDP Core and Technical Work Groups. In the event we cannot procure the EIME data for a reduced price, we will try to rely on the no cost options of APME, IDEMAT and NJIT data. Together, these three data sources cover 17 materials with the IDEMAT student version or 20 with the complete version. Relying on several material inventories from each of the three sources will reduce consistency in our upstream data and thus reduce the data quality in the CDP. For materials not included in the data sources obtained, UT will attempt to find the data from primary or secondary sources.

5. LIMITATIONS AND UNCERTAINTIES

Information on the different databases were from personal communications, websites, and in some cases, review of selected inventories obtained for a database. Copies of the NJIT and Ecolabel reports were available for review. This evaluation of upstream sources was not intended to be a comprehensive assessment of each data source, but instead a cursory review to evaluate which data to pursue. Therefore, there remain uncertainties to the information presented in this TM, but it is believed that adequate information was available to make recommendations in this report.

Using secondary data will also have an effect on the limitations of the CDP results. Using secondary data that are not tailored to the specific goals and boundaries of a project limits the quality of the data. However, due to the large data collection efforts in the LCA, priorities are given to collecting data. Thus, secondary sources have been chosen for upstream inventories and primary sources will be approached for monitor and component manufacturing data, as well as some end-of-life processes.

Once the upstream data are incorporated into the CDP, limitations in those databases will be transferred to limitations in the CDP. Furthermore, the use of more than one database (e.g., EIME supplemented by NJIT and IDEMAT) will reduce consistency in our upstream data and thus somewhat reduce the data quality in the CDP. However, it should be noted that the upstream data are only one portion of the overall inventory of the product systems being evaluated.

ACRONYMS/ABBREVIATIONS

ABS	=	Acrylonitrile butadiene styrene
APC	=	American Plastics Council
APME	=	Association of Plastics Manufacturers in Europe
BUWAL	=	The Swiss Agency for the Environment, Forests and Landscape
CDP	=	Computer Display Project
CRT	=	Cathode ray tube
DEAM	=	Database for environmental Analysis and Management
EIME	=	Environmental Information and Management Explorer
IDEMAT	=	Industrial DEsign MATerials
IPA	=	Isopropyl alcohol
IPU	=	Institute for Product Development of the Technical University of Denmark
HIPS	=	High impact polystyrene
LCA	=	Life-cycle assessment
LCD	=	Liquid crystal display
LCI	=	Life-cycle inventory
LCIA	=	Life-cycle impact assessment
LDPE	=	Low density polyethylene
NJIT	=	New Jersey Institute of Technology
NMP	=	N-methyl pyrrolidone
PC	=	Personal computer
PS	=	Polystyrene
PE	=	Polyethylene
PET	=	Polyethylene terephthalate
PP	=	Polypropylene
PVC	=	Polyvinyl chloride
PWB	=	Printed wiring board
TFT	=	Thin-film transistor
TM	=	Technical memorandum
TMAH	=	Tetramethyl ammonium hydroxide
USAMP	=	United States Automotive Materials Partnership

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