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.

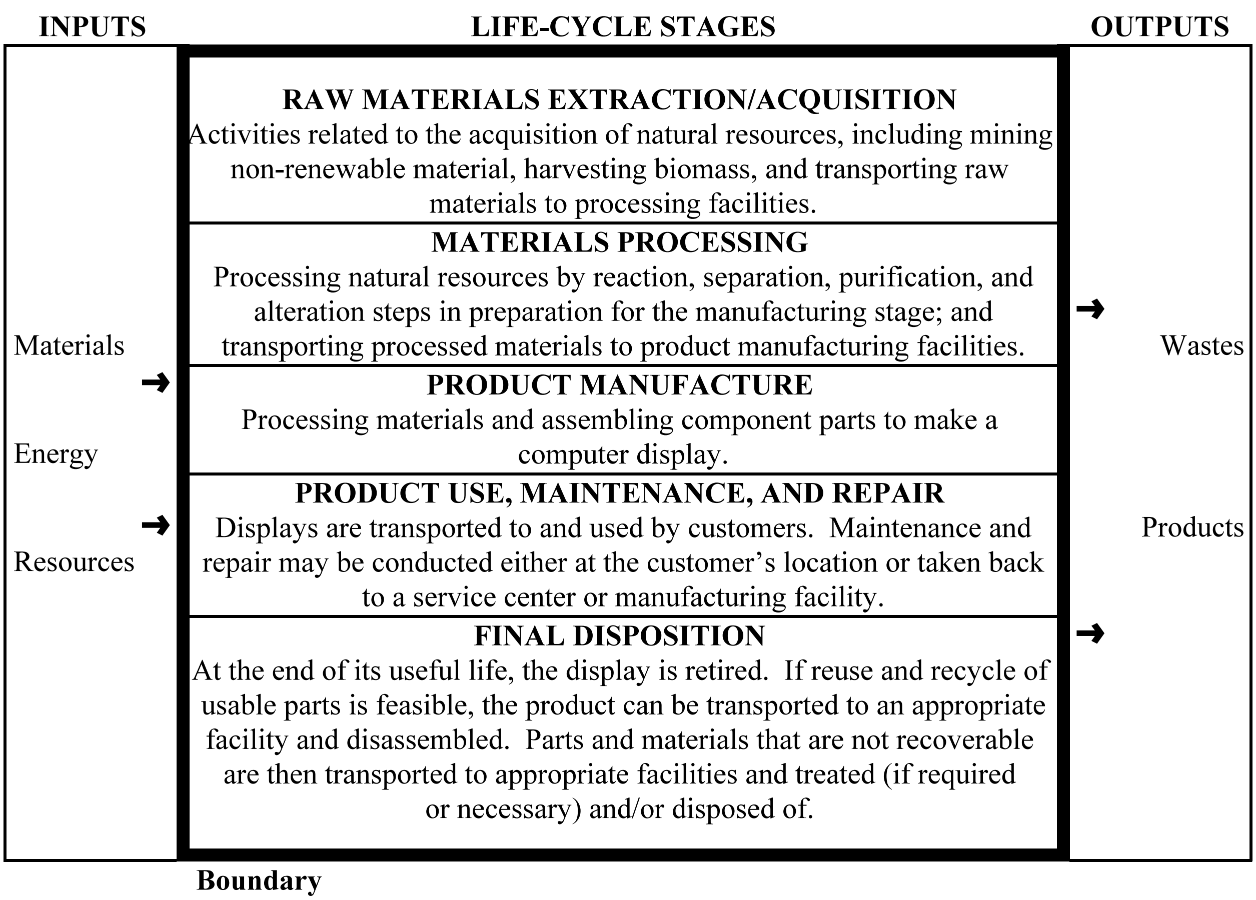


Figure 1-1. Life-cycle stages of a computer display

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, $CaCO_3$)
	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)	------------►	Steel
	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.

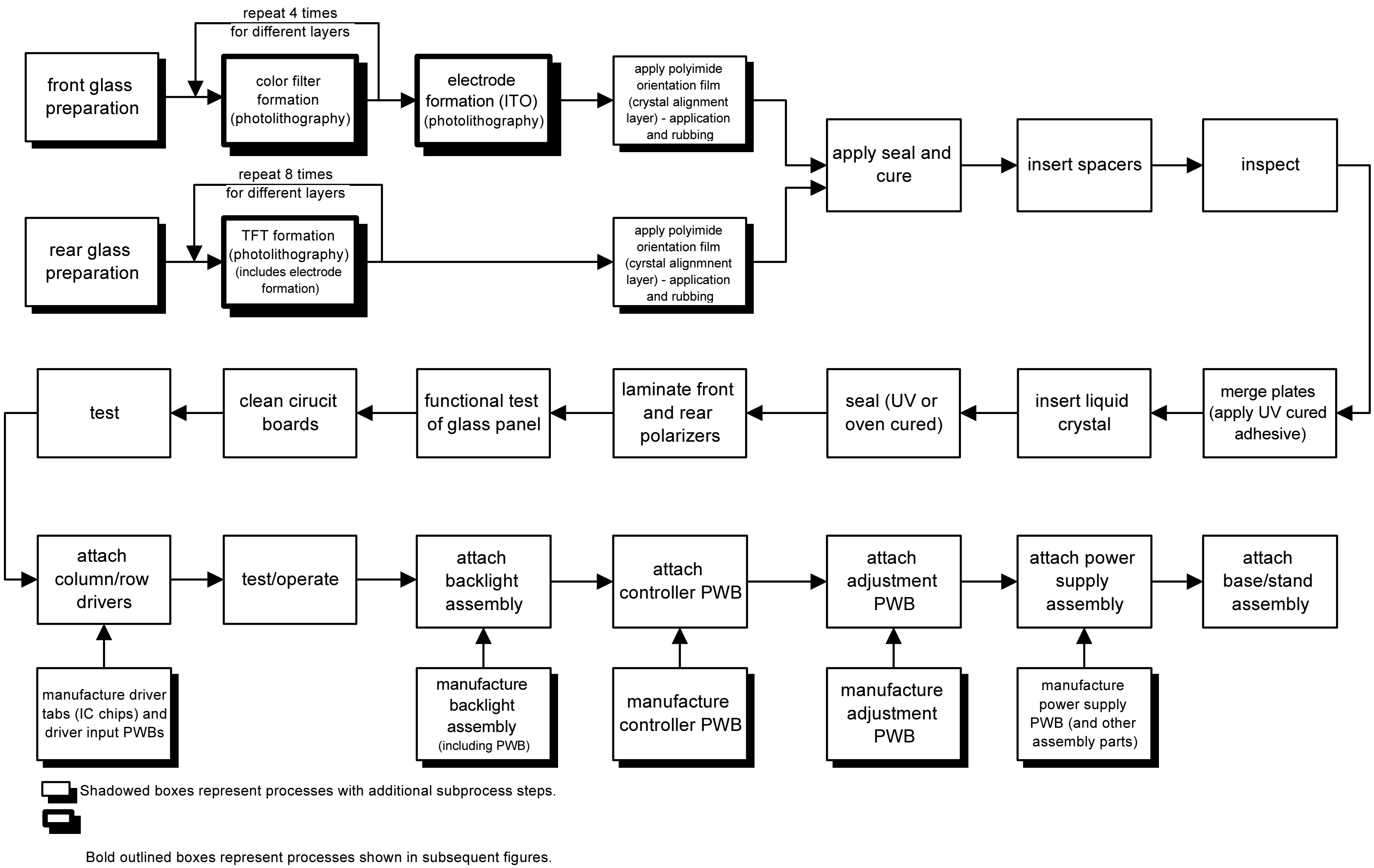


Figure 1-2. Traditional twisted nematic AMLCD manufacturing process

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

<table>
<tr><th colspan="3">LCD component parts</th><th>Materials</th></tr>
<tr><td rowspan="22">Backlight assembly</td><td>Metal plate</td><td></td><td rowspan="2">Steel (Fe)</td></tr>
<tr><td>Screws</td><td></td></tr>
<tr><td>Brass threaded stand off</td><td></td><td>Brass</td></tr>
<tr><td>Gasket</td><td></td><td>Foam rubber</td></tr>
<tr><td>Nylon strain relief</td><td></td><td rowspan="2">Nylon</td></tr>
<tr><td>Nylon clamp</td><td></td></tr>
<tr><td>Clear protector</td><td></td><td>Plexiglas</td></tr>
<tr><td>Opaque diffuser</td><td></td><td rowspan="2">Polyester</td></tr>
<tr><td>White reflector</td><td></td></tr>
<tr><td>Light pipe</td><td></td><td>Polycarbonate</td></tr>
<tr><td>Corner tape</td><td></td><td>Aluminized mylar</td></tr>
<tr><td rowspan="3">Light assembly</td><td>Cold cathode tube</td><td>Glass, phosphor, Hg</td></tr>
<tr><td>Shock cushion</td><td>Silicone rubber</td></tr>
<tr><td>Cable assembly</td><td>Insulated Cu</td></tr>
<tr><td rowspan="7">Rear plate assembly</td><td>Rear plate</td><td rowspan="3">Steel (Fe)</td></tr>
<tr><td>Screws</td></tr>
<tr><td>Hold-down plate</td></tr>
<tr><td>Cable clamp</td><td>Nylon</td></tr>
<tr><td>Plastic tube</td><td>Polycarbonate</td></tr>
<tr><td>Flat cable toroid</td><td>Hi-mu ferric</td></tr>
<tr><td>Caution label</td><td>Paper</td></tr>
<tr><td>Backlight PWB</td><td></td><td>Misc. (Si, Cu, etc.)</td></tr>
</table>

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).

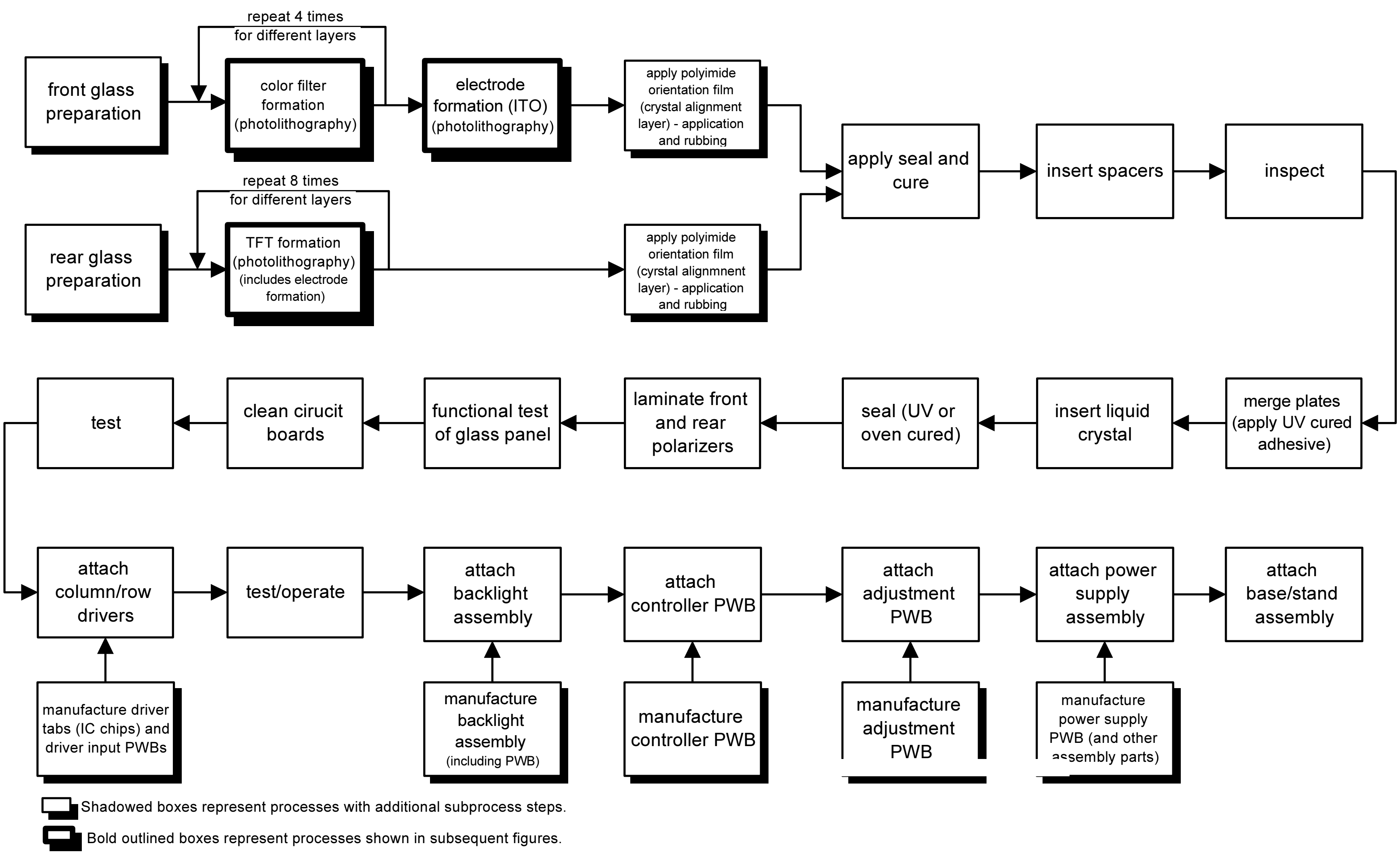


Figure 1-3. Traditional twisted nematic AMLCD manufacturing process

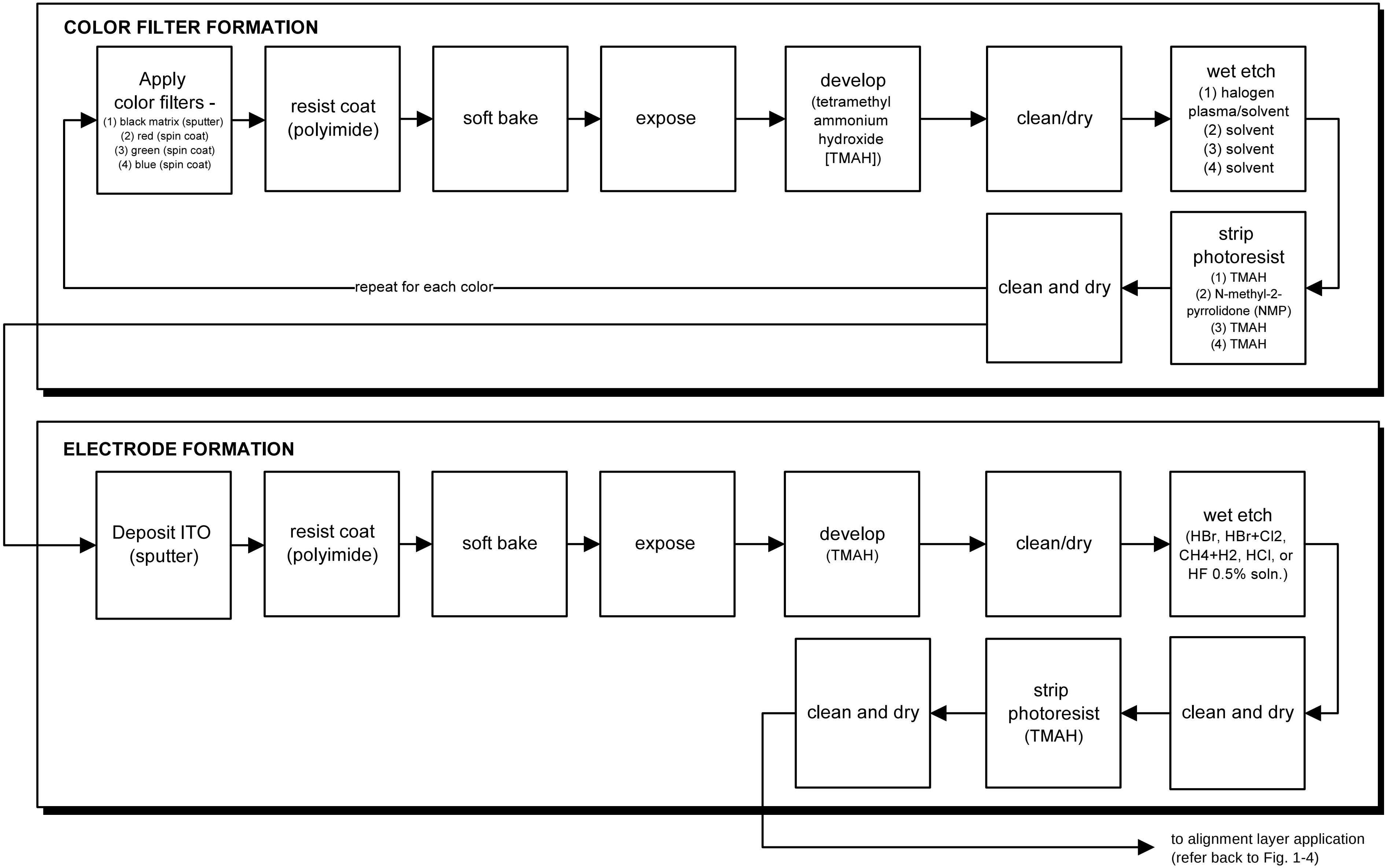


Figure 1-4. Front glass AMLCD manufacturing (photolithography)

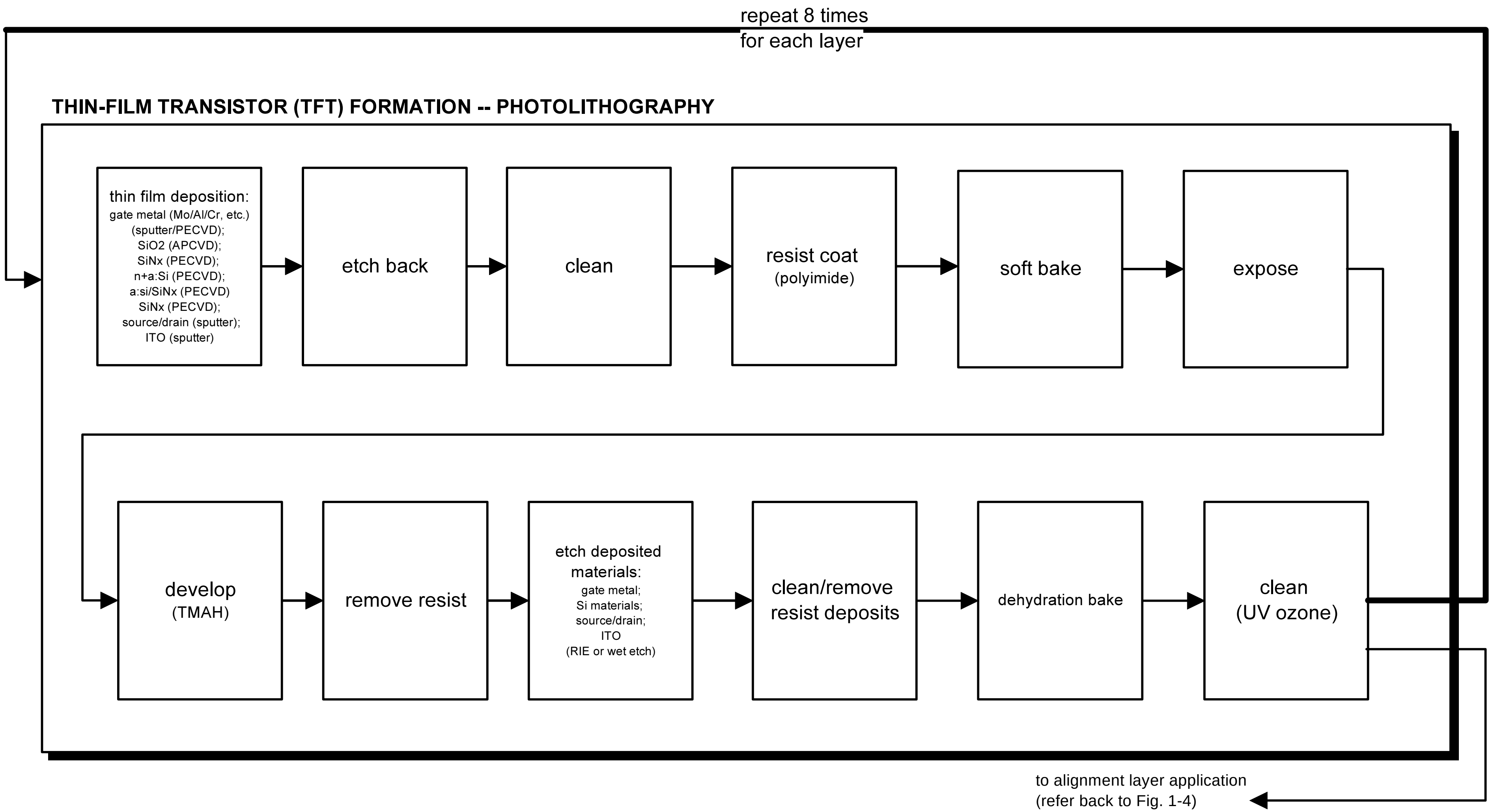


Figure 1-5. Rear glass AMLCD manufacturing (photolithography)

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

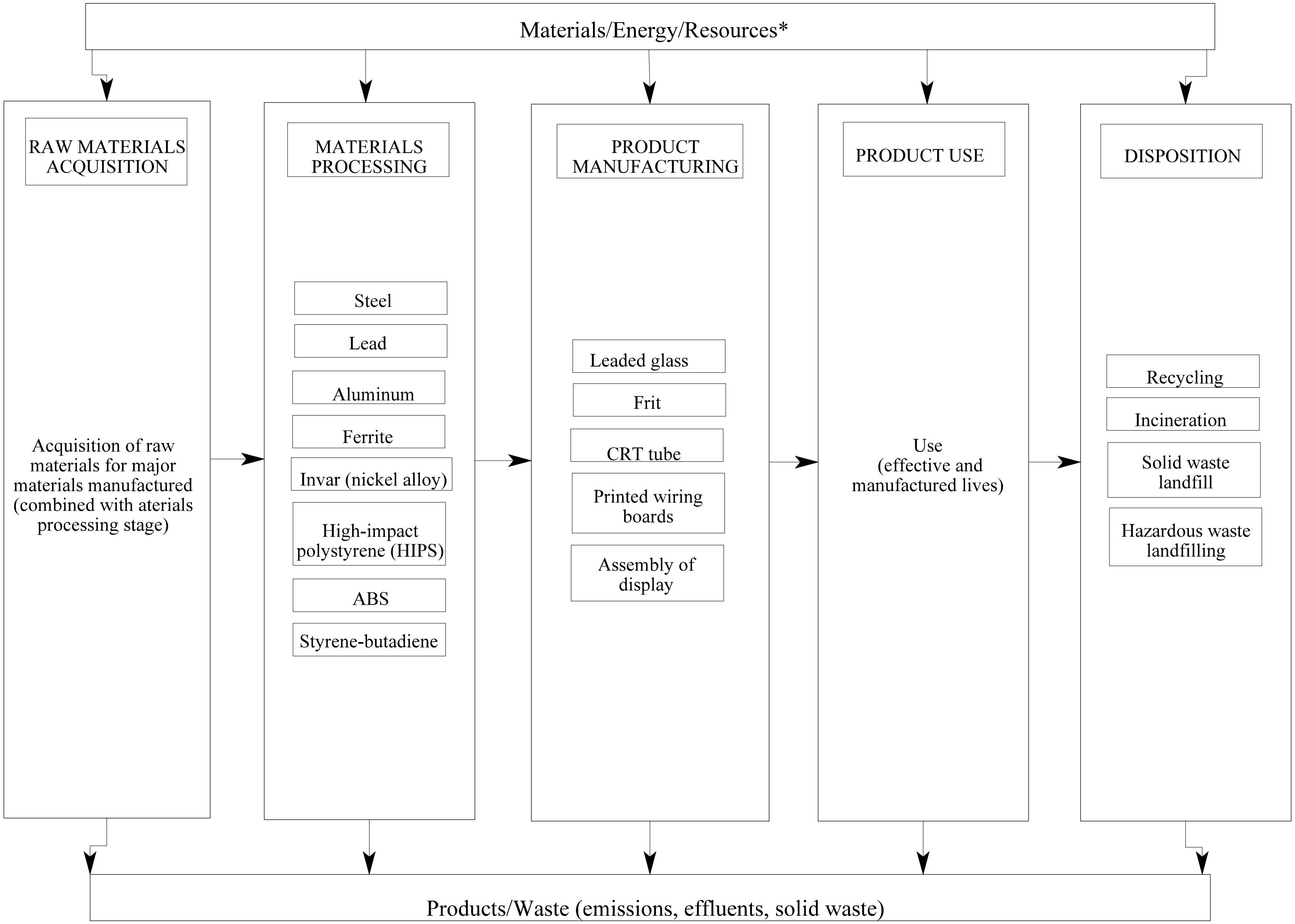
The geographic boundaries of this assessment are shown in Table 1-5. This LCA will focus on the U.S. display market; therefore, the geographic boundary for the use and disposition stages of displays is limited to the United States. Raw materials acquisition and material processing for materials used 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

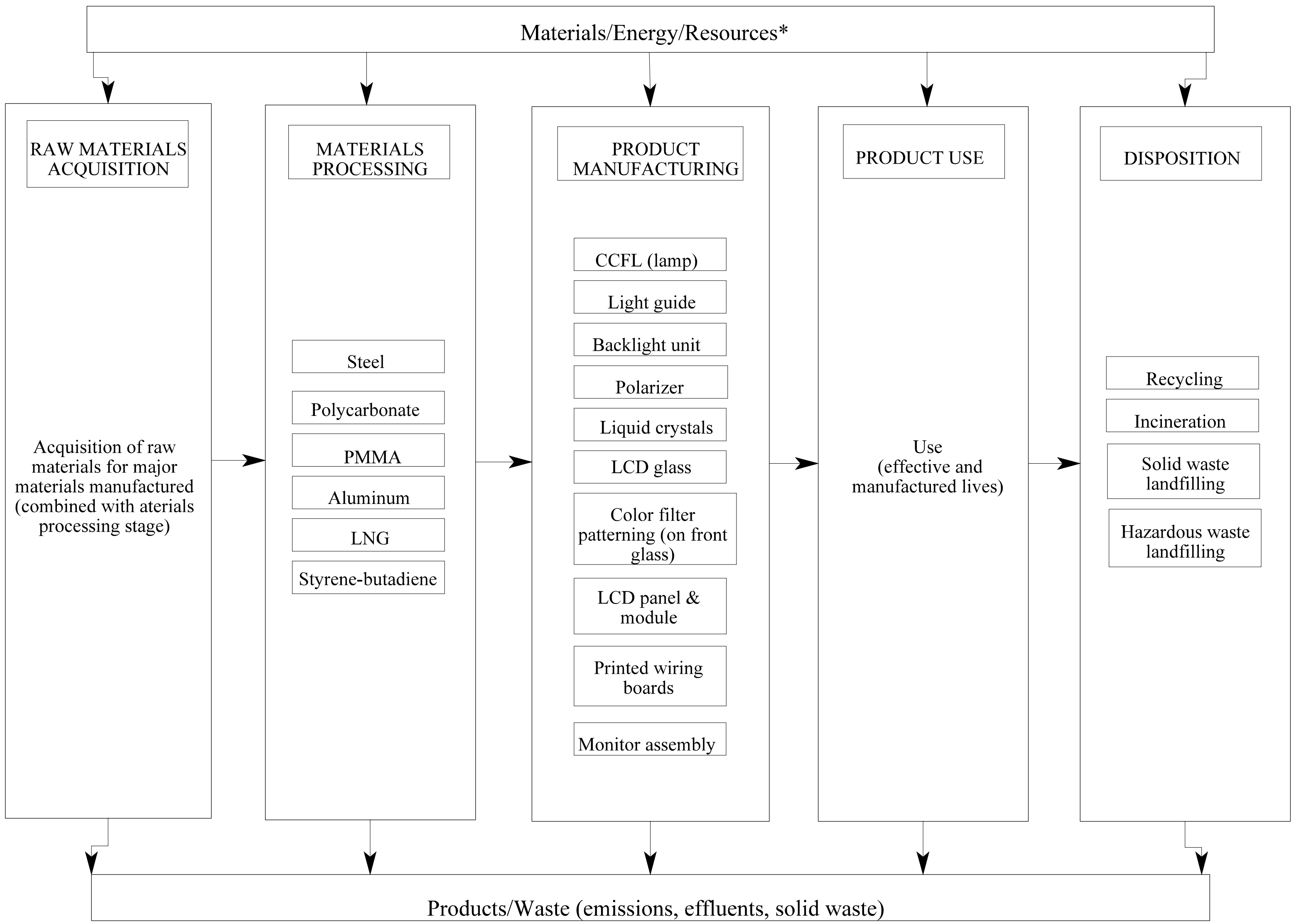
[a] In this study, worldwide boundaries were considered; however, the actual geographic locations for LC1 data are presented in Chapter 2 (Sections 2.2 and 2.3).

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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