SCIENCE

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EVALUATING ENVIRONMENTAL PERFORMANCE: A CASE STUDY IN THE FLAT PANEL DISPLAY INDUSTRY

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ABSTRACT

Evaluating Environmental Performance: A Case Study in the Flat Panel Display Industry develops a four step framework for evaluating environmental performance and explores how a manufacturer of flat panel displays, OIS Optical Imaging Systems, may enhance its competitive position and environmental performance. There are several objectives of this research including: (1) provide a methodology for evaluating the interrelationship between business and the environment; (2) provide environmental metrics to OIS for incorporation into a factory simulation model; and (3) apply the life cycle design, multicriteria analysis. The four step framework for evaluating environmental performance follows a sequential analytical process from (1) industry structural analysis; to (2) corporate-level analysis; to (3) process-level analysis; and then to (4) improvement strategies. A number of recommendations are made to OIS including: Develop a unique set of capabilities that enable the integration of computer electronics and the display; pursue cost reduction projects that minimize environmental burden; prioritize environmental spending based on technical flexibility and relative environmental risks; and develop an environmental management system. Analysis of OIS's manufacturing process indicated that most processes and materials used throughout the manufacture of flat panel displays contribute environmental burdens and seven categories of impacts are described throughout the report including: Energy use; air quality; global climate change; resource depletion; land use development; solid and hazardous waste; water quality; and human health. Environmental improvement strategies are summarized in four multicriteria matrices and a continuum that is based on the business strategy ultimately pursued by OIS.

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EXECUTIVE SUMMARY

The flat-panel display (FPD) industry has enabled the creation of a myriad of products, most importantly the lap top computer, and provided increased benefits to customers that require thin, light-weight, energy efficient, and reliable display units in applications ranging from airplane cockpits to industrial and medical devices. FPDs are ubiquitous. Displays such as Liquid Crystal Displays (LCD), Light Emitting Diodes (LED) and Vacuum Fluorescent Displays (VFD) have been used for decades in products from alarm clocks, to dashboards, to watches. Other technologies such as Active Matrix Liquid Crystal Displays (AMLCD), plasma display panels (PDP), electroluminescent displays (EL), field emissions displays (FED), micro mirror (DMD), among other technologies are also vying for position in the FPD market. The industry is growing at a tremendous pace reminiscent of the growth rate in the semiconductor industry or the television industry. In 2008 conservative predictions forecast a market worth $20 billion dollars and 100 million units sales. As the FPD industry is faced with technological challenges to out perform the venerable cathode ray tube on performance and to do so at a lower cost, the focus of corporate executives has not been on environmental performance specifically pollution prevention, waste minimization, or design for the environment.

Recognizing that flat-panel displays may soon become a major industry in the United States, a team of researchers from the National Pollution Prevention Center including Jonathan Koch, Dr. Gregory Keoleian, and Dr. Jonathan Bulkley initiated a research project with Optical Imaging Systems, Inc. (OIS) a manufacturer of AMLCDs. This case study was funded by Optical Imaging Systems, the Center for Display Technology and Manufacturing, and AT&T Industrial Ecology Fellowship program. Optical Imaging Systems, Inc. (OIS) is one of the world's leading suppliers of custom designed, ruggedized Active Matrix Liquid Crystal Displays (AMLCDs) for military avionics applications. OIS's business strategy has been to complete research and engineering work for military customers as well as develop standard displays that may be sold for use in avionics applications. In the long-run, OIS intends on supplying the computer market with AMLCDs.

Evaluating Environmental Performance: A Case Study in the Flat Panel Display Industry is for managers and academics seeking information on flat panel display industry, the environmental impacts associated with the FPD product system, and the relationship of the environment to an FPD manufacturer's business performance. This report explores several questions including, "How can OIS enhance its competitive position?"; "Does the firm's environmental performance affect its ability to achieve sustainable competitive advantage?"; and "How can OIS improve environmental performance?" There are several objectives of this research including: (1) provide a methodology for evaluating the interelationship between business and the environment; (2) provide environmental metrics to OIS for incorporation into a factory simulation model; and (3) apply the life cycle design, multicriteria analysis.

Evaluating Environmental Performance: A Case Study in the Flat Panel Display Industry follows a sequential analytical process from (1) industry structural analysis; to (2) corporate-level analysis; to (3) process-level analysis; and then to (4) improvement strategies. The report is structured in this way to reflect the importance of a systems approach to environmental management. Environmental decisions are made within the broader context of a competitive business environment; therefore, understanding market segmentation, competitive dynamics, and the basis for future competitive success is critical when making decisions on environmental expenditures. In addition, knowledge of the full life cycle environmental impacts of the product system including each manufacturing process step, burdens associated with use, and burdens associated with product disposition are all necessary for making informed decisions regarding the environment.

STEP 1: INDUSTRY ANALYSIS

The FPD industry is highly concentrated in Japan and rivalry in the market is affected by high entry, high exit costs, and low switching costs among technologies or manufacturers. Joint ventures, alliances, and licensing agreements are growing and further complicating competition in the industry. A multitude of substitute products are commercially produced and new technologies such as FEDs will challenge the LCD as the industry leader. Suppliers play a critical role in advancing equipment and materials technologies used for production. Buyers in the computer segment may exert power in the market now because of an increasingly commonditized product and overcapacity in the industry. The government is committed to spending large sums on developing flat panel technologies; however, these subsidies are not sufficient to support the industry or even the success of a particular company such as OIS.

The FPD market consists of five major segments including computers, business, transportation, consumer, industrial/medical. The market may also be characterized by two broad segments—military and computers. OIS is currently selling custom displays to the military avionics market which is small and not sufficient to sustain long-term economic growth. Other segments of the flat panel market may be attractive to OIS; however, significant over capacity in the industry, competitor's cost advantages derived from economies of scale and learning, and substitute technologies with high price-performance ratios relative to AMLCDs are factors that will challenge OIS while expanding into new markets.

Despite significant competitive challenges, the AMLCD is the fastest growing technology in terms of revenue and the AMLCD is quickly reaching a critical mass and establishing itself as the standard in the industry. The computer segment will be, by far the largest market; however, other markets including transportation and business/commercial segments have strong growth prospects.

Product benchmarking indicates that AMLCDs are the best suited for the computer and avionics markets; however, the commercial availability of FEDs and the large area capability of PDPs are going to challenge AMLCDs dominance. AMLCDs are non-emissive and thus suffer from the use of a backlight unlike emissive displays such as FEDs, which do not require a backlight, therefore offering better power performance. Although, PDPs are power hungry this technology offers full color and large area capability. Moreover, AMLCDs are the most difficult to manufacture requiring many production steps. Competing technologies have simpler production processes and better yields leading to reduced costs.

STEP 2: CORPORATE ANALYSIS

Although a range of business strategy options are presented, this report recommends that OIS develop a unique set of capabilities that enable the integration of computer electronics and the display. This technology known as chip-on-glass technology will enable OIS to capture more value in its products and develop a mechanism to compete against other low cost providers or substitute products that do not have electronics integrated onto the display product. OIS should develop core competencies that lead to a long-term unique advantage in electronics integration onto the display. Competencies in process control should also be developed because advances in efficiency of manufacturing have synergistic effects on environmental performance. Indeed, measures of environmental performance may be good indicators of the success of OIS's core competence acquisition strategy.

Environmental performance will be influenced by OIS's cost reduction strategies to reduce material costs through improved yields and increased material utilization rates. As

part of a cost reduction strategy a framework for prioritizing environmental expenditures is presented based on technical flexibility and relative environmental risks. Revenue generation strategies related to the environment were considered; however, only reduced power consumption of the display throughout use appears to be a viable strategy in this regard.

Strategic environmental issues—factors that may affect core business operations—include the phase out of perflouro carbon gases, supply chain concerns such as DuPont's purchasing policy for PFC gases, and facility closings due to fires or other accidents. Environmental performance may also be of strategic importance if other factors become vulnerabilities to OIS such as future take-back requirements, carbon taxes, ISO 14,000 management systems, raw material input (e.g., water resource), or federal or state financial support.

OIS's environmental performance will be affected by the effectiveness of the firm's management systems. A high performance organizational model revealed that corporate environmental management systems at OIS need significant improvement at three levels: vision, organization, and continuous improvement. OIS does not include the environment in its vision or mission. Organizationally there is not sufficient oversight of environmental issues and in terms of continuous improvement the company does not have formal auditing procedures, metrics for tracking performance, cascading responsibilities, or environmental technology development initiatives.

Measuring environmental performance should occur at both the facility and process level. Corporate measures should account for (1) the total manufacturing water, energy, and materials consumption; (2) waste emissions including solid and hazardous waste, volatile organic compounds, ozone depleting substances, and global warming potentials; and (3) liabilities or penalties incurred due to environmental performance.

Process level metrics, which were derived from analysis conducted in Step 3, should include (1) measures of product materials efficiency; (2) process chemicals usage rates per display or substrate; and (3) product stewardship measures such as power consumption during use and asset recovery rates. Metrics presented in this report indicate that the AMLCD is energy, resource, and material intensive.

STEP 3: ENVIRONMENTAL PROFILE

An evaluation of OIS's manufacturing process indicated that most processes and materials used throughout the manufacture of FPDs contribute environmental burdens including: Process chemicals throughout photolithography steps; dopant and process gasses for deposition; wet and dry etchants; cleaning substances/techniques; metalization processes. Seven categories of impacts are described below including: Energy use; Air Quality; Global Climate Change; Resource Depletion; Land Use Development; Solid and Hazardous Waste ; Water Quality; and Human Health.

Energy use may be the most important environmental issue facing AMLCD manufacturers and other semiconductor and electronics producers world-wide. Energy consumption at OIS's Northville facility will be substantial in order to power process equipment, clean room machinery, waste disposal equipment, and the facility's daily requirements for computers and lights. Clean room design and chiller configuration as well as display driver requirements throughout the use of the product are critical determinants of the level of energy demand across the product system.

Air quality issues associated with AMLCD manufacturing include the release of particulate emissions, volatile organic compounds (VOC), acid fumes, and inorganic gases. The VOC emissions consist of 1-methyl-2-pyrolidinone (NMP), acetone, isopropyl alcohol (IPA), propylene glycol monomethyl ether acetate (PGMEA), toloune, and polyurethane

methylacrylate (or acrylic acid). The highest emissions rate is acetone at .4453 lbs/hour—a small amount because of the scale of the facility.

All the acid gas emissions will be produced by the thin-film metal etching solutions. The maximum controlled acid fume emissions rates from the combined etching processes will be .04 pounds per hour or .14 TpY including hydroflouric acid (HF), phosphoric acid (H_3PO_4), Nitric Acid (HNO_3), Acetic Acid (CH_3COOH), and Hydrochloric Acid (HCL). The highest controlled emission rate is .0324 pounds per hour of HCL.

Inorganic gas emissions will be produced in the photolithography and PECVD processes including emission of silane, ammonia, chlorine, tetraflouromethane (CF_4), sulfur hexaflouride (SF_6), phosphine (PH_3), diborane (B_2H_6), nitrogen triflouride (NF_3). The highest controlled emission rate is 1.56E-04 pounds per hour of SF_6.

Global warming gases such and carbon tetraflouride (or tetraflouromethane, CF_4), hexaflorethane (C_2F_6), nitrogen triflouride (NF_3), sulfur hexaflouride (SF_6), methane (CH_4), C_3F_8 (Freon 38) and nitrous oxide (N_2O) will be used in OIS' Northville facility for a variety of purposes including chemical vapor deposition, etching, and cleaning chambers.

Ozone depletion results from the use of CFCs and HCFCs. OIS has changed a number of its cleaning operations to DI rinses, UV ozone cleans, and ultrasonic cleans to avoid using CFCs; however, the chillers used to produce air conditioning and process cool water uses HCFCs. HCFCs are currently acceptable substitutes for air conditioning under SNAP, EPA's official list of substitutes for CFCs, as of March 18, 1994.

Resources depletion including **water use** and **non-renewable** energy use are significant impacts. OIS's Northville facility will consume roughly 460 gallons per minute of water for air conditioning and process cool water and 100 gallons per minute for DI water production. OIS's AMLCD production will consume a tremendous load of energy produced from non-renewable resource supplied from Detroit Edison.

Land use impacts include an increase the number of industrial buildings in a particular zone and increase traffic of cars commuting to the area, maintenance vehicles, and delivery/disposal trucks. Community safety/protection from accidents are also critical issues to be addressed in case of emergencies.

Solid waste streams from the plant are minimal in terms of volume; however, the reuse of display components is an end-of-life management issue not currently addressed by OIS or the flat panel industry. **Hazardous waste** resulting from the manufacture of AMLCDs include organic compounds waste streams from developing and photoetching processes. OIS is responsible for storing the wastes from the photoresist processes in a tank (10,000 gallon on-site) and transporting them to a RCRA registered facility. The fate of the solvent is arranged by the company that transports the chemicals, Federal Environmental. Currently these chemicals are refined by a chemical company in Georgia and sold as a waste fuel to a cement kiln operator. Pump oil, Fromblin™ or Crytox™, must be properly recycled or disposed of as a hazardous waste.

Water quality issues include effluent discharges. The AMLCD manufacturing process demands a large flow of water. This water is used on site and is ultimately discharged into the publicly owned treatment works of the Detroit metropolitan region. Waste water from the plant will be acidic in nature and pretreated through neutralization and metals precipitation processes prior to being discharged into the local sewer connection.

Numerous studies have been prepared on **human health** effects and hazard control technology in the semiconductor industry. There are a number of significant health issues including: Exposure to solvents such as glycol ethers and acetone; pyrophoric gas use (e.g., silane); toxic gas use/exposure (e.g., phosphine, diborane); exposure to metals; and catastrophic releases. Exposure to solvents, particularly glycol ethers, has been studied

extensively by industry groups, corporations, and academia. The results of these studies have demonstrated that work in semiconductor fabrication facilities is associated with an increased rate of spontaneous abortion as a result of exposure to glycol ethers.

The environmental burdens described above are a function of how efficiently and effectively OIS uses materials and resources to deliver product. Because there is a direct relationship between consumption rates and the ability to enhance shareholder value, OIS is continuously striving to improve its operations. Thus, synergistic improvements in the overall environmental performance of the product system will result from process advancements. Several technological advances are explored in this report including new color filter applications processes, photoresist usage, and yield improvement. Results from a spreadsheet model indicate that yield improvements can lead to significant environmental gains. The yield analysis also indicates where in the production process it is most efficient and effective to make process improvements. For example, reductions in the water usage rates in early stages of the active device wet process will yield significant water savings. Sensitivity analysis revealed that improving yields of the later stages of production are almost as effective as improving the entire production process.

Environmental burdens are assoicated with the use and end-of-life phase of the FPD product system. A comparison of manufacturing to use energy requirements indicates that the cummulative environmental burden associated with using 40,000 displays throughout their useful life can require at least twice the energy as production of the display. End-of-life burden is primarily the solid waste stream.

STEP 4: ENVIRONMENTAL IMPROVEMENT STRATEGIES

Environmental improvement strategies are summarized in four multicriteria matrices that describe the life cycle stages (i.e., manufacturing, use, and end-of-life) and three product system components (i.e., product, process, and distribution). The matrices define high level requirements that OIS should use as guides for developing specific improvement strategies. The environmental matrix provides a list of a number of improvement strategies related to specific production processes.

Environmental improvement strategies targeted by OIS will depend on the business strategy that OIS decides to pursue. For example, if OIS stays the course in the avionics military sector incremental changes in environmental performance could include the increased material use efficiencies, reduction of water consumption, energy use, or increased solvent recycling. If more aggressive attempts are made to cut costs, then reengineering of the production process may be necessary. Adoption of new deposition technologies or reduction in the number of photolithography steps or the elimination of pyrophoric or toxic hydride gases may result from reengineering the production processes. However, if a new game strategy such as one targeted at developing capabilities in chip-on-glass technology are pursued, OIS may by able to offer significant improvement in its own production process and offer life cycle environmental improvements by avoiding the use of other electronic components.

INTRODUCTION

I. OVERVIEW AND GOALS OF RESEARCH

II. ORGANIZATION OF REPORT

III. INTRODUCTION TO OIS OPTICAL IMAGING SYSTEMS, INC.

I. OVERVIEW AND GOALS OF RESEARCH

This work is the result of a project initiated in May 1994 in which OIS Optical Imaging Systems, Inc. and the Center for Display Technology and Manufacturing (DTM) jointly sponsored an intern at the National Pollution Prevention Center -- me -- to conduct an environmental performance and improvement assessment. Using the research conducted over the summer of 1994 and additional work in the Winter of 1996, I completed this report in fulfillment of my Master's Practicum requirement.

This report has three broad goals that fulfill personal, business, and academic interests. My "personal" goal is to apply the skills and concepts studied in the School of Natural Resources and the Business School as part of the Corporate Environmental Management Program and provide an example to managers within the flat panel industry of how to integrate business strategy with environmental management.

The question I continually asked myself is, "Does the environment matter to the display industry?" A partial answer is that executives in the industry are cognizant of environmental issues associated with flat panel production; however, executives are not thinking of the environment as source of competitive advantage. My goal was to determine if, in fact, there are good reasons why the environment should be seen as an opportunity and how the environment may be a driving force behind achieving a sustainable competitive advantage.

The near-term goal of OIS was to develop a set of environmental metrics that could be used within factory simulation model under development with DTM. A number of metrics were recommended to OIS to be used at the facility level and at the tool or process level. Metrics pertaining to the facility or corporate level are presented in Step 2 described below, whereas metrics pertaining to processes are presented in Step 3.

This study does not provide process or material substitutions strategies to OIS that can be implemented after reviewing this report. Rather the report provides guidance on the how OIS should be managing environmental risks from both a business and an operations perspective and assists OIS in prioritizing which environmental improvement strategies to pursue in the future. There are two reasons why this report does not provide specific technological recommendations to OIS concerning environmental improvement strategies. First, the manufacture of flat panel displays is an extremely complicated undertaking and not one that I am experienced enough with to provide specific advice to experts in the field. Second, the engineers at OIS that are qualified to make design changes have not worked on this project for a number of reasons, most importantly, the timing of this study coincided with the construction and roll out of product from OIS's new Northville facility.

From an academic perspective, this project provides another opportunity to apply life cycle design. The goals of life cycle design are to integrate environmental requirements into the design of products expressly considering the different phases of the product system (i.e., raw materials, manufacture, use/service, end-of-life management). This study applies the principles of life cycle design and uses design matrices in Step 4 to organize product and process design requirements of flat panel displays.

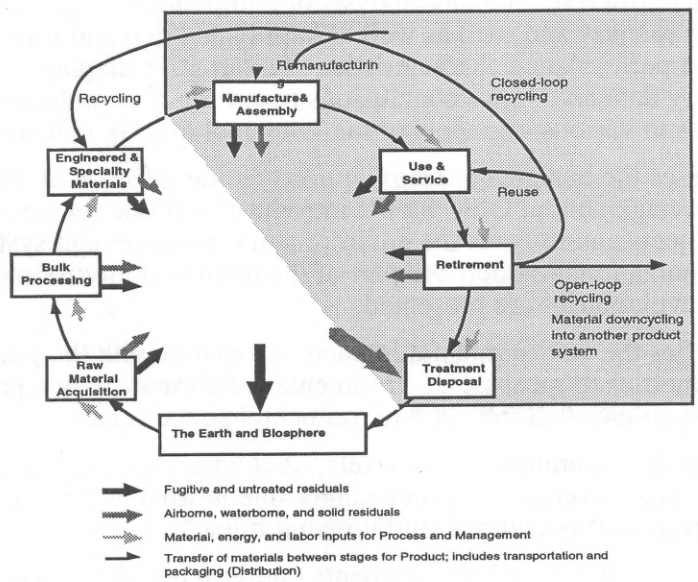
A. RESEARCH TEAM AND ROLES

The Research Team for this project includes Dr. Jonathan Bulkley, Director NPPC, Dr. Greg Keoleian, Manager NPPC, and Jonathan Koch, Researcher NPPC. Dr. Bulkley is a joint professor of Civil and Environmental Engineering and of Water Resource Policy in the School of Natural Resources & Environment (SNR&E). Dr. Keoleian is an assistant Research Scientist in SNR&E working to develop Design for Environment approaches to pollution prevention. Mr. Koch is a candidate for a dual Masters of Business Administration and Master of Science in Resource Policy. This research project and manuscript is the basis for fulfillment of Mr. Koch's practicum requirement for his Master of Science. Grant support for Dr. Bulkley's and Dr. Keoleian's participation in this project was provided by an AT&T Industrial Ecology Faculty Fellowship.

B. SCOPE OF ANALYSIS

The environmental performance and improvement assessment is defined by spatial and temporal boundaries as well as the intended use or application of the results of the project. The scope and boundaries of NPPC's research is limited by life cycle stage and process steps during product fabrication Fig. 1-1 illustrates the product system and indicates the boundaries of NPPC's research efforts. The scope of the research is as follows:

- Spatial boundaries: OIS northville facility and local, regional, and global impacts
- Temporal boundaries: OIS Northville pilot demonstration plant and future plants
- Life cycle stages: manufacture, use/service, and end-of-life management
- Manufacturing processes: color filter formation and active device formation



Shaded Area Indicates Research Boundaries

Fig. 1: The Product System and Boundaries for OIS Study

II. ORGANIZATION OF REPORT

Fig. 1-2 depicts a four-step process to evaluate environmental performance at OIS that reflects a systems approach including analysis of industry and corporate levels, the product system, and manufacturing unit processes. In practice, each step of the research is not sequential; however, for purposes of organizing the results (and gaps) of the study this framework is a useful guide. In addition, feedback or information exchange between the steps is necessary to complete the analysis.

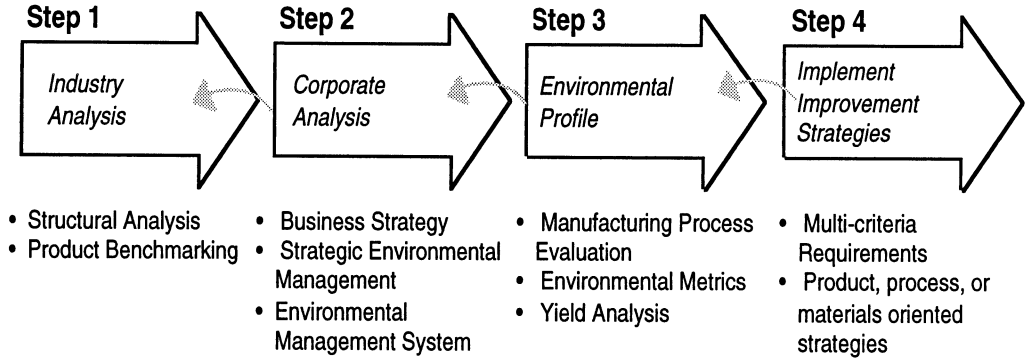


Fig. 2 Four-Step Process to Evaluate Environmental Performance

Step 1 evaluates the flat panel display industry structure and benchmarks display products. Industry structure includes analysis of competition, suppliers, buyers, substitute products, barriers to entry and exit, as well as supply and demand forecasts. Benchmarking compares product performance characteristics of alternative display technologies. Step 1 highlights industry data and draws conclusions regarding the competitive factors that determine success in various segments of the flat panel display industry.

Step 2 discusses the business strategy options facing OIS and evaluates strategic environmental management at OIS. Step 2 introduces a frame for prioritizing environmental improvement projects and reviews the environmental management systems using a high performance organizational model. As part of the review of environmental management system, facility level metrics are presented.

Step 3 identifies the environmental impacts associated with the product across life cycle stages; presents metrics to measure environmental performance on a process basis; and reviews operations issues that impact environmental performance.

Step 3 consisted of literature reviews, telephone interviews, and database queries of existing books, reports, conference proceedings, and journal articles related to the production of flat panel displays and potential environmental impacts.

Step 4 presents multi-criteria requirements matrices and summarizes strategies for environmental improvement and discusses how these strategies may be implemented.

III. INTRODUCTION TO OIS OPTICAL IMAGING SYSTEMS, INC.

OIS specializes in developing flat panel displays for severe environments. Presently, OIS produces active-matrix liquid crystal displays (AMLCDs) that are capable of performing

under shock, humidity, salt and fog, and explosive decompression. Displays have been developed in OIS's Troy, Michigan facility for development programs including the F-22 Advanced Tactical Fighter, the Space Shuttle Multi-Function Electronic Display retrofit, and the Boeing & Peripheral Vision Display System along with nine other programs.

"It is the near-term goal of management to establish OIS as a premier supplier of special application high performance AMLCDs to the world military and commercial avionics markets." [1] OIS has made significant progress toward establishing itself a premier supplier of displays to military and avionics markets. To address its current customer demand and develop more efficient operations, OIS competed for and won $48 million from ARPA towards the construction of a $100 million demonstration facility in Northville, Michigan. In addition, OIS intends to continue leveraging internal research and development with external relationships. To accomplish this, OIS has become a founding member of both the US Display Consortium (USDC) and the Center for Display Technology and Manufacturing at the University of Michigan.

OIS has developed a program of building "stock" or "catalog" displays making them available on an "off-the-shelf" basis. The company's four stock products include 4" square high-resolution color display, a 3.4" by 2.8" color display, a 6" x 8" color display, and a 5" square color display. Fig. 1-3, OIS Product, is a photo of the 4' by 4' AMLCDs produced by OIS. These products offer sunlight readability, low power consumption, light weight, wide viewing angles, extensive temperature ranges, and high reliability (measured as mean time between failure, MTBF).

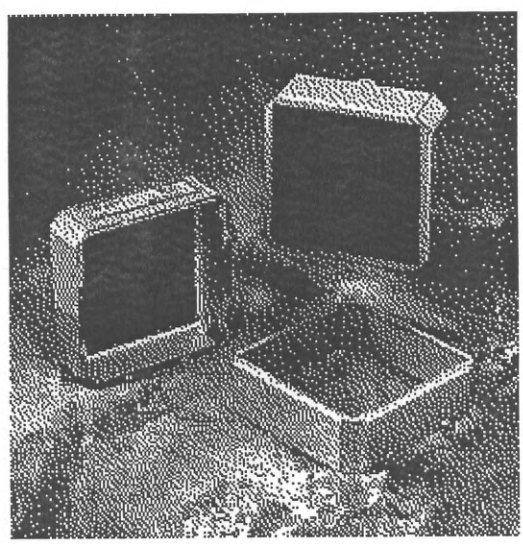


Fig. 3: OIS Product

OIS's financial performance between 1994 and 1992 is summarized in Table 1.[2] Although OIS has not shown a profit, the value of its stock (Nasdaq-OVON) has, at times, appreciated substantially despite a bit of volatility in trading. Some of this activity is due to OIS' recent announcement to make lap top computer screens for Apple computer [3] and the extension of its contract with Honeywell. [4]

TABLE 1

OIS Financial Performance

Year Ending June 30	**1994**	**1993**	**1992**
Total Revenues	$11,700,389	$7,162,035	$5,481,869
Cost of Revenue	11,854,393	8,238,412	4,894,526
Internal Research & Development	688,094	372,242	517,348
SG & A	5,013,587	3,858,733	6,167,353
Net Loss	(5,855,685)	(5,307,352)	(6,097,358)
At Year End			
Total Assets	$38,146,868	$7,088,883	$10,288,994
Long-Term Debt	12,000,000	77,355	544,819
Working Capital	2,616,215	(1,173,905)	2,018,700
Shareholders Equity	9,633,880	3,501,018	1,013,024
Direct Material & Labor	42%	56%	
Indirect Production Costs	59%	59%	
Development Revenue	88%	83%	

Source: OIS Annual Report, 1994

PART 1: INDUSTRY ANALYSIS

I. INDUSTRY STRUCTURE

A. Definition of Industry

B. Manufacturers of FPDs

C. Degree of Rivalry

D. Supplier Power

E. Buyer Power

F. Threat of Substitutes

G. Threat of Entry

H. Government Actions

I. Market Projections

J. Projections for Military Market

II. PRODUCT BENCHMARKING

A. Display Applications

B. Display Performance Review

C. Environmental Performance Across Display Technologies

D. Environmental Performance of the Cathode Ray Tube

INDUSTRY ANALYSIS

Industry analysis consists of (1) defining the flat panel display industry and identifying suppliers, buyers, substitute technologies, entry barriers, and rivalry among competitors; (2) reviewing market segments including supply and demand projections; and (3) benchmarking alternative display product performance.

I. INDUSTRY STRUCTURE

A. DEFINITION OF INDUSTRY

Defining the flat panel display industry requires identifying the major market segments, the degree that displays may be substituted across market segments, the degree that the industry is vertically integrated, and the geographic scope. First, the display industry is defined by the United States Display Consortium as having two distinct segments; military and commercial applications. More specifically, however, the FPD market has five segments as outlined in Table 1-1. Moreover, the FPD industry has a broad array of technologies vying for share within each market segment, including active matrix liquid crystal displays (AMLCD), passive matrix liquid crystal displays (PMLCD), plasma display panels (PDP), electroluminescent (EL), field emission displays (FED), and digital mirror display (DMD) among others.

Second, the degree that displays may be substituted across these segments, or the horizontal scope, suggests that most applications may employ the use of the same technology. For example, AMLCDs may be used across each market segment. Functional or performance requirements may change, but the basic technology and end product is similar. Third, the boundaries around the vertical component should include suppliers of equipment, materials, and components upstream and buyers such as computer manufacturers and the government on the downstream side. Fourth, geographic scope of the FPD industry is clearly global because of the concentration of manufacturers and suppliers in Asia and the growing number of competitors in the G7 countries.

Typology classification indicates that the FPD industry is *capacity driven* and *knowledge driven*. Therefore, physical capital to value added is high and research and development to value added is high. Production of FPDs, especially AMLCDs, is similar to semiconductor fabrication. The cost of developing a high-volume facility will be at least $400 MM in 1996 dollars. In addition, fast advancements in technology will necessitate continuous reinvestment bringing total capitalization over $1B for a state-of-the-art facility.

TABLE 1-1

Flat Panel Display Sectors and Applications

Consumer 14%	Transportation 6%	Business 5%	Industrial/Medical 8%	Computer 67%
• Television • Games • Appliances - ovens - microwaves - stereo	• Automotive - instrument panel - heads up display - passenger entertainment • Avionics - cockpit - passenger entertainment - projection • Navigation • Entertainment • Traffic Control - signage - air traffic controls	• Copiers/Fax • Tiled Displays • Financial Trade • Projection Plates • Videophones/ Videoconferencing • Personal Communication Devices • Closed Circuit TV • Ticketing/Vending • Wall Screens • ATM	• Lab/analytical • Process Monitoring • X-ray security • Inspection Systems • Data Collection Devices • Diagnostic Imaging - Magnetic Field Imagers - Ultrasound • Surgical Assistance • Patient Monitoring • "Filmless X-Rays"	• Desktop Monitors • Portables Displays • PDAs • Sub Notebook • Pen-and-Display • Memo Devices • Workstations • Ancillary Computer Equipment

Source: Display Technology and Manufacturing and Department of Defense

The major AMLCD producers have settled on standard display sizes and types. The standard display was 10.4-inch video graphics array (VGA) in 1994-1995, and is now moving toward SVGA (super-VGA) screens larger than 11 inches; 13-inch extended graphics array (XGA) screens have also been developed.[5]

The FPD industry is complex due to various market segments and alternative technologies as well as the electronics industry present transformation. A great deal of uncertainty exists regarding emerging technologies and products may be substituted in the future by developments such as:

- personal digital assistants
- merging of PCs, workstations, and networked environments
- multimedia applications
- amalgamation of telecommunications and computers
- video telecommunications
- "green PCs" (a potential driver of FPDs)
- new display sizes—large high-definition TVs and small "virtual reality" goggles.[6]

A trend that may have significant implications on the electronics industry and end users of displays products is the integration of "non display functions" into the design and manufacture of the display. Integration adds value to the display by reducing weight, power, number of components, and system costs. This trend would shift margins up the value chain to the display manufacturers and increase the control that FPD manufacturers have over end product functionality. These trends raise concerns among buyers of FPDs because this would give suppliers greater control over end products. Integration opportunities include mounting driver circuits (e.g., on the back of the display panel), integrated circuits (provide the images to the display), memory chips, and microprocessor onto displays.

B. MANUFACTURERS OF FPDS

The FPD market leaders are in Japan. The Department of Defense (DoD) argues that Japanese manufacturers had a cost-of-capital advantage relative to US companies in the

1970s and 1980s leading to their early and large investment in FPD technology. The ability to raise capital, strategic foresight, and the deployment of competencies enabled the Japanese firms to gain "first mover" advantages over US firms.

Within the AMLCD segment of the industry, which is the fastest growing segment, there is a highly concentrated group of manufacturers from Japan. In fact, the top seven firms are Japanese and account for 98% of the AMLCD market, 90% of PMLCDs, 65% of plasmas, and 45% of EL displays measured by market value.[6] The concern in a highly concentrated industry is the ability of the market leaders to exercise monopoly power. However, due to factors within the market place, the author does not foresee this being a significant issue within the next decade.

Table 1-2 is a listing of companies that produce flat panel displays. The list provided here is not meant to be a comprehensive taxonomy of all display producers. Table 1-3 summarizes licensing agreements, alliances, and joint ventures within the industry found in literature searches.[7][8][9][6][10][11][12][13][14][15][16][17][18][19][20][21] [22][23][24][8][25][26][11][27][13][23][28]

C. DEGREE OF RIVALRY

Military Sector

Rivalry in the "military" sector in the US is between OIS, Litton Systems, companies that ruggedize commercial displays, PDP manufacturers, and EL manufacturers. However, rivalry in this market is reduced because each player goes after niche product application. For example, OIS competes directly with Litton and substitutes offered by ruggedizers of commercial displays for avionics displays such as the F-15. However, Kopin, who specializes in smaller head mounted displays and projection systems will compete for a different set of products. Moreover, large Japanese manufacturers such as Sharp will not directly supply displays to the US military. Sharp, however, will sell to companies that ruggedize displays for military applications. In addition, other Japanese and Korean firms such as Hosiden and Sextant Avionique are diversifying their FPD businesses by expanding into niche applications.[5]

Competition in the military sector is not as price sensitive as the computer market; therefore, this segment is attractive to US firms because domestic operations are smaller, flexible and are adept at competing on the basis of product features. Although the government has instituted a number of procurement regulations that required cost-based evaluations including life cycle costs, other government regulations support the purchase of flat panel technologies by providing excess moneys to purchase displays from American manufacturers. Another reason that price is not the most important factor in the military segment is that design service and engineering research are needed by electronics integrators to develop stations for military applications. Notwithstanding these conditions, the military market segment may face increased competition as niche market producers, including OIS, vie for position in a low growth, low demand segment of the market.

TABLE 1-2

Manufacturers of Displays Worldwide

DISPLAY	JAPAN		US	EUROPE/OTHER
AMLCD	Sharp	Futaba	OIS	AEG, Germany
	Toshiba	Rohm	Xerox/AT&T/Standish	Samsung, Korea
	Hitachi	Mitsubishi	Coloray Display Corp.	Goldstar, Korea
	Hoshiden	Optrex	Kopin	Hyundai
	Seiko/Epson	Matsushita	ImageQuest Tech.	FPD Corp
	Citizen	Alps Electric	IBM (Toshiba - DTI)	Dolch Computer
	Casio	Akita Saimitsu	Kent Display Systems	Unipac, Taiwan
	NEC	DTI (Toshiba/IBM)	Litton Industries	PrimeView, Taiwan
			Sariff	Sextant Avionique, France
PMLCD	Sharp		Tektronix	Picvue, Taiwan
	Toshiba		In Focus	NanYa Plastics, Taiwan
	Hitachi		Standish	Chung-Hua, Taiwan
	Hoshiden		Three-Five Systems	Thomson, France
	Seiko/Epson		Panel Vision	
	NEC		Norden Systems	
			Kent Digital Signs	
			Motorola	
PLASMA	Fujitsu		Plasmaco	Samsung
	Matshushita		Photonics Imaging	Thomson
	Mitsubishi		Electro Plasma	
	NEC		Tektronix (1)	
	Oki			
	Pioneer			
	Sony			
EL	Nippon Telephone and Telegraph		Norden	Cambridge Display Technology
	Toshiba		Planar	
			Plasam	
FED			Coloray Display	FPD Corp.: Philips, Netherlands;Sagem and Thomson, France; and Merck
			Crystallume	
			FED Corp.	
			Micron Display Tech.	
			SI Diamond Tech.	PixTech
			Silicon Video Corp.	Sexton Avionique, Thomson SA
			SI Diamond	
			Advanced Technology Materials Inc.	
			Crystallume	
DMD			Texas Instruments	
			Aura Systems	

Source: Heytler et. al, Stanford Resources, and Lehman Brothers
(1) Reported by OMara

TABLE 1-3

Alliances and Joint Ventures

DISPLAY	LICENSES	ALLIANCES	JOINT VENTURE
DMD		• TI - In Focus, Nview, Proxima, Rank Brimar, Sony	
AMLCDs-HMD		• Planar Advance (avionics divisions acquired from Tektronix) - Xerox	• Sarif: In Focus-David Sarnoff Research Center
AMLCD-Projection		• Kopin-United Microelectronics-Unipac • Kopin-Philips • Raychem-Hitachi	• Sarif • Kopin: Wyse Technology and Taiwan Semiconductor Manufacturing (TSMC)
AMLCD	• Nan Ya Plastics -Toshiba • Samsung-Fujitsu • Goldstar-Hitachi • Orion Electric (Daewoo)-Toshiba	• OIS-Guardian • Samsung-Toshiba (Display ICs) • Samsung-Corning (Color Filters) • Fufi-Xerox • Philips-Sagem-Thomson • Asahi-Mitsubishi • Image Quest-Hyundai	• Toshiba-IBM (DTI)
EL		• Pioneer-Showa Shell Sekiky	
Plasma		• Matsushita-Plasmaco (1) • Sony-Fujitsu	
PMLCD	• NuVision-Textronix	• Motif-Sanyo-Kyocera • Panel Vision-Litton	• Motif: Motorola-In Focus (2)
FED	• Ratheon-PixTech • TI-Pixtech • Coloray (Scriptel)- SRI International	• Raytheon-TI-Motorola (with Sandia) • SVC-HP-SAIC-Compaq-Advanced Technology Materials • FED Corp.-Zenith • MCC-SI Diamond • PixTech: Motorola-TI-Raytheon-Futaba	• ADDVent: SI Diamond-Supertex • FED Corp.: Analog Devices, Cetek Technology, BF Goodrich, InfiMed Inc., Kaiser Electronics

Source: Heytler et. al, Stanford Resources, and Lehman Brothers
(1) In negotiations as of January, 1996
(2) Motif has since shut down operations.

Computer Sector

The computer segment is characterized by a number of large Japanese manufacturers, emerging high-volume producers in Korea, and smaller niche players in the US. In the computer market segment, prior to 1994, when demand outstripped supply, display manufacturers were able to command higher prices for displays and rivalry in the form of price competition was not a significant factor. However, as prices have fallen due to increased industry capacity, the degree of rivalry has intensified and display manufacturers are increasingly fighting for share in a maturing sector of the industry. The industry leader, Sharp, has seen its share fall from roughly 50% of the computer market to approximately 30% in 1995.

The high fixed costs, excess capacity, and limited product differentiation between and among AMLCDs and PMLCDs (e.g., dual scans) producers, coupled with the threat of new entrants with substitute products will encourage increasingly tough competition. In addition, there is limited differentiation on the basis of brand name as there are in other electronic markets such as microprocessors.[5] This will benefit buyers/users of displays as prices will

come down and service/performance will increase. Furthermore, the move toward standardized products will make the display component of the portable computer market a commodity-like product (i.e., a products with similar core features that are produced by multiple sources and compete on the basis of price, rather than any distinguishing feature), thus competition will be based on manufacturing costs.[5]

High Fixed Costs

Due to high fixed costs, display manufacturers must fill capacity to make its capital equipment as productive as possible. As each high-volume manufacturer seeks to increase utilization and output, display supply grows and leads to price cutting. Capacity expansions that have already occurred in Japan and Korea, and planned expansions throughout the world, will lead to supply /demand imbalances that are disruptive because of resulting price cutting. This behavior squeezes margins of even the most efficient manufacturers in the industry.

Exit Barriers

Exit barriers facing industry players in each market segment include specialized assets, strategic interrelationships, and potential emotional barriers. Although some assets may be used in similar processes throughout the electronics industry, many assets are designed specifically for flat panel production or are custom configured by the manufactures. Exit may also be complicated because of the vertical relationships that display manufacturers have within the industry. For example, DTI supplies panels to Hitachi and IBM. In addition, emotional barriers may lead managers to stay the course rather than exiting. The existence of high exit barriers means that excess capacity stays in the game and could resort to extreme tactics hurting the whole industry. No evidence of extreme tactics as a result of barriers to exit have been witnessed at this point in time.

Switching Costs

Switching costs will not limit the number of new entrants into the display industry. It is unclear how quickly LCDs will reach a critical mass and create network externalities that dissuade manufacturers from switching to alternative technologies. Arguably, this has already occurred as AMLCD and PMLCD become the de facto standard in the computer industry. Distribution channels, high volume contracts, and familiar performance characteristics will keep buyers from switching technologies rapidly. However, switching costs are low when product, such as the AMLCD, is viewed as a commodity; therefore, price and service are critical competitive factors. Buyers may find it easier to switch among LCD manufacturers as standards are accepted. In contrast to the computer segment, product, service, and engineering skill differentiates suppliers in the military segment thereby creating insulation against competitive warfare because buyers may have preferences and loyalties to sellers.

D. SUPPLIER POWER

Suppliers to the flat panel market include specialized manufacturers of process tools such as large area substrate photolithography equipment, steppers/stichers, color filter material producers, glass substrates, and liquid crystal manufacturers. The equipment supply base is also supported by the semiconductor industry because there are synergies to be gained for equipment manufacturers to serve both types of electronics markets. Supplier power is a function of several factors including the relative cost of the materials and/or tool to the cost structure of the FPD manufacturer, the design and operational skills of the supplier, and the availability or supply of materials.

Relative Cost of Materials

The impacts of inputs on cost or differentiation will elevate the importance of the supplier used for a particular function. In display manufacturing the cost of color filters are a large percentage of the materials cost structure; therefore, increased pressure is put to the suppliers to control costs. However, most high volume manufacturers will now outsource the production of color filter substrates and because of the growth in this industry the price of color filters have come down from $160 per substrate to $60.[29]

Design and Operational Skills

The design skills and operational expertise of the supplier will also determine the amount of influence or power the supplier has over the display manufacturer. For instance, at OIS's Northville facility several tools were the first units produced and supplier teams were on-site for months installing the tools and preparing the equipment for production. This support is necessary for OIS to use the tools effectively. However, this does not create a power imbalance, because the tool manufacturers need to demonstrate their technologies to be successful. It is important to note here that Japanese suppliers are more closely aligned with FPD manufacturers because of the keiretsu system. Most manufacturers will work closely with keiretsu members and source from these vendors exclusively. The risk here is that if vertically aligned keiretsu partners reached a point of self sufficiency by attaining the necessary economies of scale, then US supply of certain inputs could be restricted or priced higher.

Availability of Materials and Equipment

The availability of inputs is a major concern of the US Government's Flat Panel Display Initiative. The government concluded that the US FPD industry may face a serious trade concern because most suppliers are based in Japan leaving US manufacturers dependent on a Japanese supply base. The United States Display Consortium (USDC) has helped to alleviate this problem by coordinating and procuring contracts for the development of domestic suppliers for materials and equipment. Although DoD has raised concern over the Japanese dominance, the Office of Technology Assessment (OTA) concluded that equipment and materials supply has not been a serious issue for FPD manufacturers in the US, particularly small firms serving niche markets.[5] Perhaps, a bigger problem is the tariff structure which is often higher on input materials than end products.[5]

The US infrastructure for equipment and materials is strong in glass production, chemical vapor deposition equipment, steppers/stichers, testing equipment, and driver circuitry. The US participants in each of these sub-markets have high performance products; however, each firm would benefit from a greater US base of manufacturing in terms of sales and to gain feedback on product performance. Some US suppliers have developed joint ventures such as Applied Materials a CVD manufacturer with Komatsu of Japan or alliances, for example, Photon Dynamics a testing equipment manufacturer has an alliance with a Japanese manufacturer.

The Nikkei MD analyzes the TFT glass substrate market in Japan and as of 1995 there is an over capacity of glass substrates in Japan. The manufacturers of glass include Corning, Nippon Electric Glass, NH Technologies, and Asahi Glass. Therefore, the price of glass substrates should not be a material concern within the FPD industry. In terms of equipment production, OMara reports that sales forecast for equipment suppliers to increase as equipment costs jump from 35% to 50% of total investment within the FPD industry. Based on the sizable investment and growth rates for the equipment industry, there should be a sufficient supply of tools.

E. BUYER POWER

Buyer power in the flat panel industry is a function of the following factors:

- concentrated buyers
- the fraction of total unit costs to buyers
- standard or undifferentiated product
- switching costs
- threat of backward integration
- perceived impact on quality.

Concentrated buyers or buyers that purchases large volumes relative to sellers sales can exert power over suppliers. In the military market the US government does represent a significant portion of sales for its suppliers and it also supports companies such as OIS through the Advanced Research Projects Administration (ARPA) grants. However, the government is not an extremely price sensitive customer. In contrast, the OEMs in the computer segment are extremely price sensitive and can use their power stemming from large volume purchases to get the best price possible. However, because many suppliers of FPDs are vertically integrated electronics firms, their first priority is to supply displays for the firm's own end products. Currently, US purchasers of FPD have negotiated early access because of their buying power; however, this may not be the case for firms that require smaller volumes or more specialized products.[5] The extent of competition among the top suppliers should ensure that US buyers will continue to have access to FPDs in the future.

Fraction of total unit costs

Display costs have constituted up to 60% of the sale price of portable computers, therefore, computer OEMs have always been price sensitive in terms of display products. OEM price sensitivity was demonstrated when computer OEMs moved to off shore production facilities in late eighties due to tariffs placed on Japanese displays as a result of the anti-dumping suit.

Standard or undifferentiated

Buyer power is heightened in the computer segment as displays become standardized. In the commercial and computer segment alternative suppliers can be found. However, in the military display markets the buyers of displays will often be large defense contractors that have development agreements with companies such as OIS and then build the entire cockpit electronics system of which the display components are a integral part. In this context, the display manufacturers engineering, R&D, and production capability are important forms of differentiation.

Few switching costs

Although some buyers require displays to be bundled with interconnects and sold as a ready to use product, other buyers purchase the display unit alone and package the display internally. In the military market, knowledge of the most efficient electronic drivers and packaging techniques may be used as a competitive advantage; however, in the commercial segments this skill is less of a differentiation. In fact, standards will be developed soon that commoditize product offerings to a greater extent.

Threat of backward integration

The threat of major computer makers in the US backward integrating on their own is not credible. However, some manufactures including AT&T and Hewlett Packard are part joint ventures or alliances to develop display manufacturing capabilities. A trade problem occurs because some large suppliers of display also compete in the same computer markets as their buyers. Several buyers of displays such as IBM Toshiba or Sharp not only produce high

volumes of displays but also use large quantities of display products in end products. This situation limits the buying power of large concentrated manufacturers in the US in times of low capacity. However, in times of over capacity, US suppliers can exert a great deal of power.

Perceived impact on quality

Buyers are concerned with the quality of displays because information screens may effect customer perceived quality of products. In this case buyers should be less price sensitive. However, because the display is commonly the largest cost component such as in portable computers (50%) or videophones, buyers will seek and encourage competition among suppliers to get the best price/performance characteristics.

F. THREAT OF SUBSTITUTES

Substitutes products perform the same function as the original product and provide a cap on the amount of value the industry can create. The threat of substitutes is the most important industry force in the fast growing FPD businesses. Although LCDs have achieved a critical mass, substitutes products will not only attempt to make incremental improvements in the price-performance ratios thus capping the price of LCDs, but also leapfrog the existing technological standards and make significant jumps in the price-performance ratio. Buyer propensity to substitute will decrease over time as LCDs become the de facto standard. A number of technologies are competing for share in the worldwide FPD industry within each market segment and at different size scales because certain technologies are scaleable to large area while others are best suited for small or projection viewed applications. Fig. 1-1 graphically illustrates in which size categories the various display technologies are competing. Section II describes attributes of substitute technologies in greater detail.

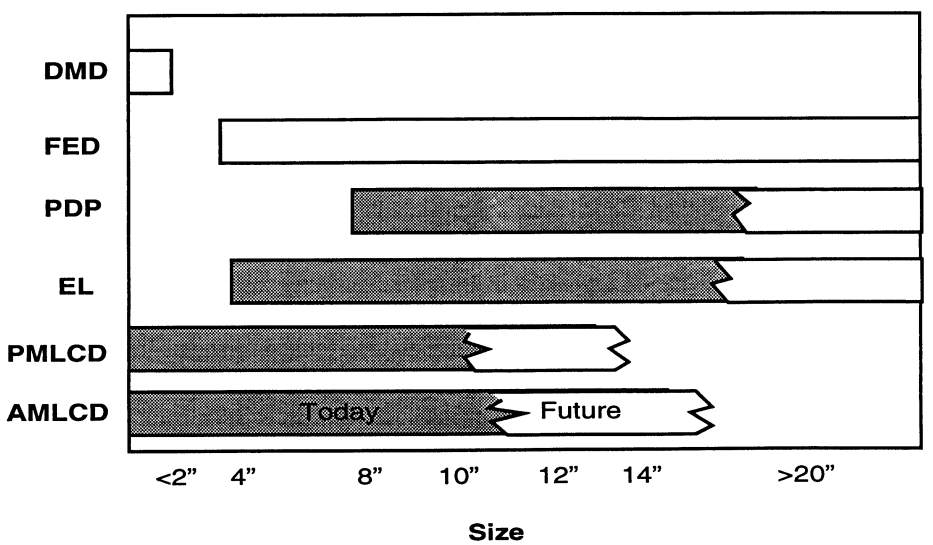


Fig. 1-1: Substitutes by Size

G. BARRIERS TO ENTRY

Barriers to entry into the flat panel display market include:

- capital requirements and scale economies
- learning/experience economies
- retaliatory pricing
- access to inputs.

Capital Requirements

Capital Requirements within the FPD industry are significant. Estimates for the cost of constructing a flat panel production facility range from $800MM to $1 B on the high end to $300 or $400MM on the low end. The need for such large investment is to develop scale economies that will lower unit costs of displays produced and lead to learning economies achieved as cumulative production increases. It is important to note that even though scale economies and learning economies will increase competitiveness in high volume markets, in the military market segment, scale economies could be a disadvantage because continuous production runs limit flexibility to adopt new technologies or meet diverse set of customer requirements. As alluded to earlier, an important differentiation of the niche players is their ability to offer customized displays that require flexible manufacturing lines and skilled marketing/engineering personnel to develop display designs. In addition, product differentiation lead to brand identification and customer loyalties that small firms are developing.

Learning or experience curve

Cumulative experience reduces unit costs. In addition, diversified firms with similar operations or functions will experience cost declines; thus, favoring the larger players in the industry such as Sharp, Toshiba, IBM, and others.

Expected retaliation

Price declines will be expected in the commercial markets if new entrants announce capacity expansion.

Access to inputs

Entrants will have access to inputs whether from Japan or upcoming US suppliers. Favorable access to raw materials is a possibility if shortages occurred in which case preferred Japanese buyers of inputs would receive supplies before US competitors.

Technological advantages of large scale manufacturers is not sustainable because equipment manufacturers provide access to latest tool technology. Access to distribution channels has not been identified as a critical issue in the display industry.

H. GOVERNMENT ACTIONS

Government actions related to the FPD industry include support for R&D and manufacturing and enforcement of anti-dumping laws.[5] Most significantly the government has announced that it will support US manufacturers through the National Flat Panel Display Initiative (NFPDI), the High Definition Display Program, and the Dual Use Technology Program. Funding for FPD R&D has averaged more than a $100 MM per year form 1991 to 1995. Table 1-4, 1-5, and 1-6 summarize the appropriations and awards made under these programs.

DoD is concerned about three things: early access to leading-edge technology; assured access to leading-edge technology; and affordable access to that technology.[30] Historically, DoD has pursued a "defense-unique route" in which DoD invests in production capacity, R&D, and develops a captive enclave to supply DoD. In contrast to this approach, DoD is funding a three part initiative for flat panels: (1) fund core R&D and infrastructure on leading edge product and process technologies under the auspices of ARPA to administer approximately $70MM a year; (2) focus on manufacturing process technology, specifically by funding a second (the first being OIS) manufacturing test bed facility to explore high-volume process technology, and share know-how and learning; and (3) support the industry consortia of users, producers, and equipment and materials suppliers.[30]

The second part of the program is the most controversial because critics argue that the government is attempting to pick technology winners and putting money behind an industry where the US has already lost out to dominant Japanese competitors. However, the government supports this program and intends on funding the development of four manufacturing facilities with the hope of gaining a 15% world market share for FPDs, which is the level DoD and USDC believe would be sufficient to support a self-sustaining infrastructure of equipment and materials suppliers with the US. The government will help to develop markets for FPDs by consolidating government demand across agencies, developing standards, developing leading-edge technologies related to the National Information Infrastructure, and insetting FPDs into new military applications. In addition, the government will help develop external markets by undertaking an export promotion program, work for market access with the Office of the US Trade Representative, and to gain better access to foreign technology.

The Dual Use Technology and International Programs has three parts and will provide $587MM in funding over the next five years. First, the government will continue to support research and development and infrastructure programs through ARPA. Approximately $70MM a year will go into this program. Second, funding will go to a manufacturing test beds. The goal of this aspect of the initiative is to explore high volume process technology, to share know-how, and to involve all elements of the US display infrastructure in learning how to develop effective manufacturing processes. Under this part of the program, the government will stage a number of technologically neutral competitions over the next five years. Third, the government will support the development of industry consortia to bring together US display users, producers, and equipment and materials suppliers.

OTA evaluated the NFPDI and concluded that even though the program is justified solely in national security terms, the dual-use approach does attempt to create a commercial base of domestic FPD producers. OTA argues that FPD requirements closely resemble those for niche commercial segments such as civil avionics, industrial, and medical systems, thus even if NFPDI is successful in meeting military needs, it may have limited impact on the largest commercial market segment—computers.[5] It is not clear how much a large US industry would reduce unit costs for custom military displays. As pointed out earlier, large commercial plants require large runs, whereas military specifications would require small runs with different machines tolerances and product specifications resulting in higher unit costs.

TABLE 1-4

Appropriations

YEAR	APPROPRIATION ($MM)	PROGRAM
1989	5	High Definition Display Pogam
1990	30	
1992	75	High Definition Display Program
1993	161	High Definition Display Program
	25	AMLCD
	60	NCAICM Sandia
	10	HMD
1994	85	High Definition Display Program
	9.3	ARPA R&D
	25	Tactical Display System (TDS)
	40	DoD funds Title III ($30 MM to Xerox//AT&T/Standish, $10MM to purchase incentives in military contracts*)
1995	82	Flat Panel
	15	Requested for TDS

Source: OTA, 1995

* The AMLCD Cockpit project under Title III of the Defense Protection Act provides additional funds for purchase; however, other legislation including the Perry Memo and the Federal Acquisition Streamlining Act require program offices to justify the use of military specifications and afford them more freedom to draw from industry design, standards, and projects when procuring display systems.

TABLE 1-5

1995 US Government R&D FPD Programs

AGENCY	FY 1995 ($MM)	FIVE YEAR TOTAL ($MM)
Defense	72.4	469.5
ARPA	68	447.7
Services	4.4	20.5
SBIR		1.3
Commerce	5.1	26
NIST Internal	1.2	5
Energy	2	11.3
NASA	11.4	28.2
NSF	.4	1.5

Source: DoD, 1994, Presidents Budget Request

TABLE 1-6

ARPA Awards

YEAR	GRANT ($MM)	COMPANY
1993	48MM	OIS
1994	50	Xerox/AT&T/Standish
1993	20	USDC
1995	25 (1)	USDC (1)
1995	7.2	Advanced Diamond Display Venture
1995	50	Silicon Video Corporation

(1) This amount is broken down between equipment suppliers receiving grants

Source: OTA, 1995

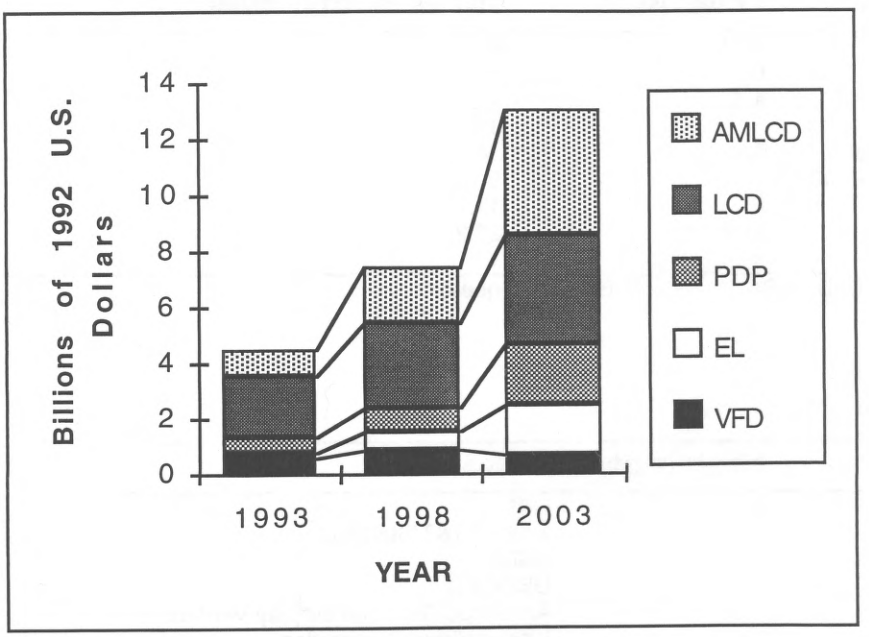
I. MARKET PROJECTIONS

Data are provided on demand forecasts and industry capacity.

Demand Forecasts

The entire display market including both FPDs and CRTs is estimated at over $28B in 1995. By some estimates, flat panels will account for half of the world display market by the year 2000. OTA reported that worldwide sales of FPDs will total $11.5 B in 1995, and will double in value by the year 2000. Based on supply-side estimates by Nikkei Micro devices, the display industry has grown 32% from 1990 to 1995 and LCD production will exceed $47B by 2000 (Note: this is the highest projection found). Stanford Resources prepared demand-side projections that estimate a U.S. market value of $22.5B in 2000, revising its earlier prediction of a global flat screen sales of $9.4 Billion by the year 2000 with LCDs accounting for most of this market.[31] Fig. 1-2 presents estimates of display sales prepared by SRI International published in 1994 (Note: the SRI figures appear to lower then the other industry research sources). Tables 1-7 through 1-9 present display sales by technology and by market sector. Fig. 1-3 presents the share of the display market by product type for 1993. Fig. 1-4 provides a projected global share by application for 2000.

Measured by value of sales, LCDs account for 87% of the FPD market, evenly divided between AMLCD and PMLCD. By 2001 AMLCDs will account for 54% of the market and PMLCDs 34%. Currently 76% of AMLCDs produced are used in computers and this will grow to 83% by 2002. AMLCDs will be 70% of the laptop computer market with total units of 3.3MM for 1995 in US and 10.6MM units worldwide.



Source: SRI International

Fig. 1-2: Flat-Panel Display World Market Projections

TABLE 1-7

FPD Sales

YEAR	SALES ($MM)(1)	SALES ($MM)(2)
1986	1,500	
1992		3,800
1995	10,000	8,400
2000	20,000	15,200

Source: (1) Computer Industry Forecasts; (2) Business Week

TABLE 1-8

Sales By Application

TYPE	1995 ($MM)	2001 ($MM)
Consumer	2,340	3,970
Transportation	530	660
Business/Commercial	1,590	2,220
Industrial	730	1,080
Computers	6,320	14,530
TOTAL	11,510	22,460

Source: Computer Industry Forecasts

TABLE 1-9

Sales By Technology

TYPE	1995 ($MM)	2001 ($MM)
Plasma	310	760
PMLCD	4,980	7,600
AMLCD	4.980	12,140
EL	120	340
TOTAL	10,390	20,840

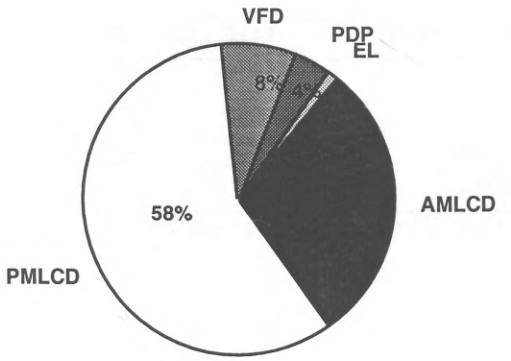
Source: Computer Industry Forecasts

TABLE 1-9

TFT-LCD Sales

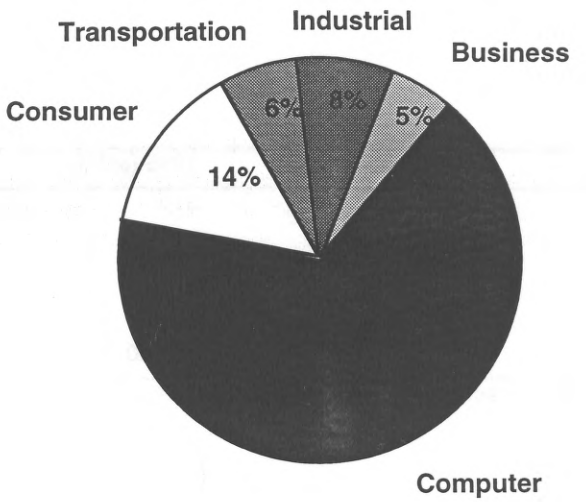
TYPE	1992 ($MM)	1998 ($MM)	AGR (%)
Consumer	227	943	26.8%
Transportation	18	92	31.2
Business/Commercial	8	133	59.8
Industrial	34	141	26.8
Computers	364	2,135	34.3
TOTAL	651	3,444	32.0

Source: Computer Industry Forecasts



Source: Stanford Resources, DoD, 1994

Fig. 1-3: 1993 Market Share by Product Type



Source: Stanford Resources, DoD, 1994

Fig. 1-4: 1993 Market Share by Product Type

Industry Capacity

Capacity is approximately 14MM units in 1995 and should reach 20MM in 1996 for 10 inch color AMLCD. At this level capacity is outpacing demand for FPD product. Table 1-10 summarizes the production capacity of the major manufacturers of displays. The table normalizes the figures to 10 inch diagonal equivalents. The result of this over capacity is that manufacturers will be forced to seek out new markets for AMLCDs including the desktop display market which is valued at 40MM units in 1994 and growing to 54MM units in 2000.

TABLE 1-10

Display Production Capacity

COMPANY	LOCATION	1995 MONTHLY CAPACITY (000)(1)	1996 ANNUAL CAPACITY (000)(2)
Advanced Display	Kumamoto	30	
Advanced Display		60	
Casio	Kochi	20	
DTI	Himeji	40	3,000
DTI	Himeji-2	60	
DTI	Shiga	200	
Fujitsu	Tottori	15	1,200
Hosiden	Kobe	120	1,800
Kyocera		70	
NEC	Kagoshima-I	40	3,000
NEC	Kagoshima-II	80	
NEC	Akita	150	
Sharp	Tenri-NF2	130	5,000
Sharp	Tenri-NF3	90	
Sharp	Mie	150	
Toshiba	Himeji	50	
Goldstar	Kumi	30	3,000 (1)
FPD	Eindhoven	40	
Samsung	Kihung	80	
Hyundai		20	
Monthly Capacity		1,520	
Annual Capacity		14,610	20,400

Source: International Display Report and Nikkei Weekly
NOTE: Merryl Lynch estimates Japan's LCD output to be 890,000 by end of 1995 up from 550,000 in 1994
(1) International Display Report estimates
(2) Nekkei Weekly estimates; Manufacturers not shown Sanyo @ 600,000 and Others @ 1,000,000; figures are not available for each facility.

Corporate Revenue

Estimated production value for the top world producers year ending March, 1994 is contained in Table 1-11.

TABLE 1-11

Revenue By Company

COMPANY	REVENUE ($MM)
Sharp	1,545
Seiko-Epson	682
Toshiba	500
NEC	364
Hitachi	309
Sanyo	291

Source: Business Week

J. PROJECTIONS FOR MILITARY MARKET

FPDs will be an integral part of the battlefield of tomorrow. Data will move in real time from soldiers, tanks, and aircraft through personal digital displays to intelligence databases throughout the globe. FPDs will also be used to help military personnel operate weapons systems. FPDs operate in harsh environments, offer high resolution, require comparatively low power, and provide color capability among other attributes that are necessary for military use. In addition, FPDs are cost effective because FPDs are more reliable and require less maintenance than CRTs, which translates into significant cost savings over the life cycle of the life cycle of a system.(See section on cost comparison for details). Moreover, FPDs have been demonstrated to increase performance of fighter pilot performance in test simulations.[6]

The military market for FPDs is less than 1% of the $10B to $12B FPD world pool; however, military needs far exceed commercial demands. Military displays use electroluminescent, plasma, and LCD technologies that require readability under various light conditions, viewing angles and temperatures, and pressures not required of civilian products. Military conditions dictate that FPDs come in tough, miniature packages, capable of withstanding the shock of combat and electronic interference from friendly and enemy jamming equipment.[32]

Military electronic displays used CRTs due to their low cost, commercial availability, and full color. However, the US industrial base in color CRTs has eroded over the past decade forcing display integrators to use foreign-made CRTs (95% from Japan). Recent indications of constraints on supply of military-grade CRTs has created problems particularly during Desert Storm. Increased use results in greater maintenance and lack of replacement screens can cause serious interruptions.[6]

Future DoD FPD requirements include command and control, aircraft cockpits, ground vehicles, air traffic control, and portable and head-mounted infantry systems. Table 1-12 summarizes the type of military displays procured by the US military.

Military Demand

The military segment demand for flat panels is estimated to average 75,000 units between 1995-1999 with growth of 25,000 units annually from 2000-2009.[6] After 2010, when head mounted displays are expected to become standard equipment for soldiers, annual demand will exceed 100,000 displays. The largest component of future military demand is in displays from .5 to 5 inches in diameter used in projection and head mounted displays.

US military display market will grow from $399MM in 1994 to $448MM in 2001 at a 2% compound annual growth rate projected by Frost & Sullivan.[33] AMLCDs will rise from 6% market share in 1994 to 15% by 2001, while gas plasma grows from 4 to 6%, field emissions from non-existence to 6%, and EL from 1 to 3%. The CRT will slip from 88 to 70%. Unit sales will double from 918MM in 1994 to 1.9MM by 2001. Most display revenue growth is predicted as a result of DoD plans to equip individual soldiers in mobile forces with communications, computing, and information display equipment.[33] Table 1-13 summarizes the total military display market unit shipments and revenue forecasts. Table 1-14 provides an overview of AMLCD demand.

TABLE 1-12

Military Displays

TYPE	DESCRIPTION
AMLCD	25,000 Battlefield systems and portable communication/information systems
AMLCD, PMLCD, and EL	Portable Helmet Mounted Displays, laptops, handheld devices, test equipment, communications equipment
PMLCDs	5,000 handheld terminals-and 13,000 portable computers in the Lightweight Computer Unit
EL, plasma, or AMLCD	Vehicular/Shipboard Navigation, situation, weapons displays in tanks, ground vehicles, ships and submarines e.g., Commander's Tactical Display for The Bradley Fighting Vehicle and Driver Vision Enhancement, and HMDs
Plasma	Large Area Displays: 15,000 workstations in aircraft, surface ships, submarines, and stationary positions (e.g., AWACS)
AMLCD and DMD projection systems and plasma	Workstations and very large area displays: command and control presentations, briefings, tactical and strategic map, simulation and 3-D systems
AMLCD	Avionics: Fighters and transports. 7,000 fixed wing and 2,000 helicopters each with multiple displays. Retrofit market exceeds 25,000. High ambient light, video rate, full color, high resolution required.

Source: DoD

TABLE 1-13

Military Market Sales

YEAR	UNITS (000)	REVENUE ($MM)	GROWTH (%)
1991	753.0	355.5	---
1992	789.3	371.0	4.4
1993	822.4	385.4	3.9
1994	917.9	398.8	3.5
1995	1,031.4	411.7	3.2
1996	1,172.3	428.8	4.1
1997	1,289.8	431.0	0.5
1998	1,420.6	437.3	1.5
1999	1,579.2	442.0	1.1
2000	1,754.5	446.3	1.0
2001	1,926.4	447.9	0.3

Source: Frost & Sullivan

TABLE 1-14

AMLCD Demand 1995-1999

PROGRAM	UNITS
F-22	3,608
F/A-18E/F	609
RAH-66	10,336
Transport/Bombers	5,542
Helicopters	2,695
Fighters	7,034
Ground Vehicles	8,843
Special Aircraft	1,151
Total Military	39,818

Source: Wright Laboratory, US Air Force, 1994

Avionics Sector of Military Market

The avionics sector is where OIS has concentrated its efforts. Although this market does not appear to be large in absolute terms compared to other FPD market segments, a myriad of aircraft systems are being built or upgraded including: the Navy F/A-18, the Marine Corps AV-8B, and CH-46 helicopter, Army AH-64D Apache Longbow, Navy P-3C submarine-hunting plane, Air Force C-141 cargo, F-16, F-4, F-5, and NASAs Space Shuttle and Boeings V-22 Osprey tiltrotor aircraft.[34][35] OIS currently has engineering development contracts will the F-22, F/A-18E/F, F-16, F-15S and the C-141.

Military aviation experts report that the color AMLCDs permit large weight savings, improved reliability and maintainability, countless operational enhancements (i.e., target acquisition, navigation), added flight safety, and provide the catalyst to introduce moving digital map displays in the near future. Kill ratios may also be increased by 30% by using large tactical situation displays (most likely plasma). In general, EL and plasma are more resistant to shock and temperature variations whereas AMLCDs are better in direct sunlight making them more appropriate for cockpit displays and use in conjunction with night vision equipment.

Although specialized or custom displays cost three times as much as ruggedized displays, custom AMLCDs offer superior resolution, wider viewing angle, and greater environmental integrity but this comes at a higher price than ruggedized displays. OTA reported that commercial displays that have similar functionality to military displays cost one third the price.[5] This means that foreign displays available to domestic integrators provide a "promising source" of low cost displays.[32]

The contracts procured to develop the flight instrument systems are valuable. For example, the C-130 contract is worth $43 MM over five years. DoD estimates if options are exercised the value increase to $409MM and to over $1B if foreign militaries retrofit their C-141 and C-130 aircraft.

Procurement Figures

Although the price of displays are not possible to gather, Table 1-15 provides procurement figures released by the government that may be used to estimate the amount spent on a display system for a number of different applications.

TABLE 1-15

Military Procurement Expenditures

Type	Cost	Cost/Display
Apache AH-64D Longbow	$7.6MM	$760,000
CH-46 Chopper	4.23	6,360
C-141 Cargo	3.4	9,042
F/A-18 and AV-8B	1.25	500
P-3C	2.29	6,361

Source: Computer Industry Forecasts

II. PRODUCT BENCHMARKING

This section reviews where different display technologies are used; summarizes performance differences between displays; and compares environmental performance across display technologies.

A. DISPLAY APPLICATIONS

AMLCDs are the most prolific of all the display technologies because of their widespread use in a variety of consumer, industrial, and military products. AMLCD applications include portable and laptop computers, office equipment (i.e., copy machines, fax, and computer terminals), television, portable video tape players, projection TVs, aircraft panels, imaging telephones, personal digital assistants, automotive dashboards, CAD/CAM displays, and process control equipment among others. Table 1-16 summarizes some of the flat panel technologies and their potential applications.

B. DISPLAY PERFORMANCE REVIEW

Display performance is evaluated based on multiple attributes including size, shape, resolution, viewing angle, power consumption, brightness, contrast, color, speed of switching, interface with other components, tolerance of environmental stresses e.g., sunlight readability, physical impact, acceleration, temperature, and electromagnetic energy. Table 1-17 contains a portion of an assessment completed by SRI International that ranks a number of display technologies from excellent to poor for a number of performance criteria. Table 1-18 presents performance ranges for three display technologies identified in various literature searches. Table 1-19 compares the performance of commercially available displays to OIS's product.

AMLCDs match CRTs in resolution, luminance, gray scale, video rate, vibration, power, and volume. Advantages of AMLCDs over CRT desktop monitors include smaller footprint (less volume and weight), power efficiency, flat screen (better for drawing line), pixel sharpness-better sharpness than "fuzzy" dots of a CRT, and reduced electric and magnetic field emissions. CRTs are better in terms of viewing angle, temperature range, and cost. In addition, video rate AMLCD displays are still difficult to produce. Separate IC drivers are attached to each of the back plane data lines to enable video rate displays. This process is tedious and accounts for as much as 30% of the cost of the AMLCD display. Furthermore, since the liquid crystal manipulates polarized light, viewing angle is limited.

TABLE 1-16

Review of Display Technologies

TECHNOLOGY	APPLICATIONS
Light Emitting Diode (LED)	• Audio • Video products (games) • Air conditioners • Cars • Clocks • Business machines
Plasma Display Panel (PDP)	• Computers (stations and portables) • Cash registers • Gas pumps
Electroluminescence (EL)	• Monochrome computer displays (workstation and portable) • Telephones, videophones • Portable and wall mounted TVs • Aircraft
Vacuum Fluorescent (VFD)	• One-line alpha-numeric displays • Auto dashboards and clocks
Liquid Crystal Displays (LCD)	• Calculators • Watches • TV • Computers (workstation and portable) • Auto dashboard, clocks • Marine equipment • Typewriters, word processors • Telephones, facsimile machines • Medical equipment

Plasma displays suffer from low efficiency thus plasma screens require large amounts of power for operation; however, plasma has the greatest potential to meet large area (>21") display applications. Table 1-20 compares the performance of a number of Fujitsu's commercially available plasma display panels.

FEDs do not require power to work in the off state; therefore, the FED achieves power savings because it only uses electricity to power charged pixels (text use about 5% of the pixels and video about 20% of pixels). In addition, phosphors are inherently faster and more persistent than liquid crystal, and field emission devices provide a threshold voltage for emission. Therefore, video-rate displays are possible using simple matrix addressing schemes.[36] Table 1-21 presents the performance criteria for FEDs. Table 1-22 reviews the advantages and disadvantages of the various display technologies

TABLE 1-17

Comparison of Display Characteristics

CRTs	LCDs	ELs	PDP	CHARACTERISTICS
◑	◕	◑	◑	Power Consumption
◕	◑	◑	●	Ultimate Screen Size
○	●	●	◕	Depth
○	●	●	◕	Weight
◑	●	●	●	Ruggedness
◕	◑	●	●	Optimum Temperature Range
●	●	●	●	Speed of Response
●	◕	●	●	Brightness
◕	◕	◕	●	Resolution
◕	●	◕	◕	Contrast
●	●	◑	◑	Gray Scale
●	◑	◕	●	Viewing Angle
●	●	○	◑	Color Capability
◑	●	●	●	Image Stability
Low	Low to Medium	Medium to High	Medium to High	Cost
15 to 20 Watts	12 Watts	5 to 15 Watts	5 to 15 Watts	Power Consumption

Source: Adopted from SRI International

● *Industry Best* ◕ *Above Average* ◑ *Average* ○ *Below Average*

TABLE 1-18

Comparison of Typical Products

Type	Pixel Format (HxV)	Diagonal Screen (in.)	Dot Pitch	Contrast Ratio	Gray Levels	Luminance (nits)	Power (Watts)	Response Time (miilisec.s)	Price ($)
EL	640x480	10	77	30:1	2	120	15	.0001	NA
PDP	640x480	10.4 21	77	6:1	16	20	20	.0001	3,000- 4,000 (21")
TFT-LCD	640x480	10.4 - 12.6	77	60:1 - 150:1	up to 512	60-200	2.8 - 20	70	400 (10.4")

TABLE 1-19

OIS AMLCD Performance Comparison

Criteria	Fujitsu	NEC TFT-LCD	Sharp TFT-LCD	OIS TFT-LCD
Diagonal Size	10.4	6.5"	6.4"	10 inches
Required Power	3.9 - 19 W	4 W	4 W	65 W
Resolution	640x480	640x480	640x480	640 x 480
Brightness	70 - 200 cd/m2	46-65 cd/m2	60 cd/m2	200 footlamberts (peak pixel luminance)
Colors	NA (3-8bit)	4,096	512	4096
Vibration Sensitivity	NA	2 G	2 G	NA
Viewing Angle	120 degrees	± 45 degrees horizontal ± 30 degrees vertical	± 45 degrees horizontal ± 30 degrees vertical	±55 degrees horizontal ±45 degrees vertical
Contrast Ratio	NA	60:1 to 100:1	60:1 to 100:1	60 to 1
Price	$1,400-1,600	$2,300	$1,870	NA

Source: Lehman Brothers, FED Corp.

TABLE 1-20

Fujitsu Plasma Performance

Diagonal Size	21 Inch	21 inches	55 Inches
Pixels	640x3 by 480	640x3 by 480	1,344 by 800 color pixel
Pixel Pitch	.66 mm x .66 mm (.22x3 for RGB)	.66 mm x .66 mm (.22x3 for RGB)	.58 mm
Gray Scale	256 per color	256 per color	256 per color
Peak Luminance	120 cd/m2	200 cd/m2	200 nit (58f-L) output
Contrast Ratio	80:1	80:1	100:1
Power	50 W typical:100 W max	100 W	100 W

TABLE 1-21

FED Performance

CRITERIA	FED
Diagonal Size	7"
Required Power	Under 1W
Resolution	NA
Brightness	200 cd/m2
Colors	32,768
Vibration Sensitivity	TBD
Viewing Angle	>80 degrees
Contrast Ratio	100:1
Price	TBD

TABLE 1-22

Advantages and Disadvantages of Flat Panel Displays

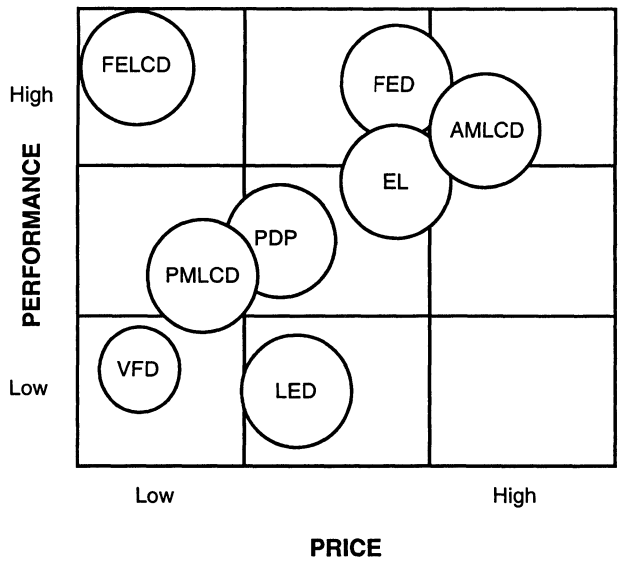
TECHNOLOGY	ADVANTAGES	DISADVANTAGES
Plasma Display Panel (PDP)	• Established technology • Proven to be rugged and reliable–long life • Simplified driving circuit • Simple construction lends itself to low-cost, high volume production • Color is feasible	• High-voltage driver requirements • Washout in bright sunlight • Limited gray-scale ability
Electroluminescence (EL)	• Very thin and compact • High writing speed—rapid response time • Good readability and brightness • Low-voltage operation • No catastrophic failure • Wide viewing angle	• High voltage drivers required • High cost-difficult to manufacture in volume • High power consumption (low efficiency) • Not full-color
Field Emission Displays	• Technology based on cathode luminescence • Potentially high luminous efficiency—very bright images • Limited viewing angle limitations • Insensitive to temperature and high G force • Long history of phosphor development • High-speed addressing and response • Limited multilayer photolithography requirements (fewer masking steps) • Potentially scaleable to large screen displays • Power efficient (Up to 5x AMLCD) • Thinner (50%) and lighter than AMLCDs (70%)	• Efficient low-voltage phosphors not yet developed • Optimum manufacturing process not yet developed • May require high voltage drivers • Large area photolithography is required • High temperature fabrication equipment needed • Critical mass of participants not yet reached
Liquid Crystal Displays (LCD)	• Low power • Low driving voltage • Very thin display • Readable in direct sunlight • Available from many sources	• High processing costs for AMLCDs • Defect free TFT panels difficult to manufacture • High capital equipment investment for TFT-LCDs • Low transmissivity of color filters requires strong backlight • Polarizer set required • Low transmisivity of color filters requires strong backlight

Source: Adopted from Castellano and OMara

Price-Performance Relationship

Fig. 1-5 provides an overview of the price/performance relationship across different display technologies. The figure indicates that the AMLCD is currently the leading technology because its performance is the highest of the commercially available display technologies. Ferroelectric LCDs and FEDs are not manufactured at high volumes. Of the remaining display technologies—ELs, PDPs, PMLCDs, VFDs, LEDs—the AMLCD offers the highest performance. However, higher performance does come at a price and currently AMLCDs are the most difficult to manufacture thereby increasing costs and ultimately the

price of displays. The ability of FED producers to develop high-volume manufacturing will present a significant challenge to AMLCDs because of its better price-performance ratio.



Source: Planar Technologies

Fig. 1-5: Price-Performance Relationship

Research in the military sector demonstrates that FPDs offer lower life cycle costs than CRTs. Even though FPDs have higher procurement costs (i.e., price), the gap is offset by the low maintenance costs resulting from the high mean time between failure (MTBF) and low mean time to repair (MTTR) rates. Table 1-23 shows the results of a study conducted by the Warner Robins Air Logistics Center on replacement of AWACS situation display console CRT with AMLCD, TFEL, and PDPs. The continuing declines in AMLCD prices are making AMLCDs increasingly more attractive.[6]

TABLE 1-23

Life Cycle Cost Comparison

VARIABLES	CRT	AMLCD	TFEL	PDP
MTBF (hrs.)	150	3371	5660	11,600
MTTR (hrs.)	36	3	3	3
Unit Cost ($M)	18	80	45	35-50
LCC ($MM)	42	49	29	23-31

Source: Warner Robins Air Logistics Center

Commercial sector prices are continuing to fall. A 10-inch AMLCD manufactured in Japan cost $1,000 in 1993 vs. $2,500 in 1991; during the same time period manufacturing yields have improved to 60% from 10%. AMLCD prices fell from $1,200 in mid-1994 to $830 in early 1995. In January of 1996 AMLCD prices fell to $400, one-third the price of the same panel last year.[37]

Table 1-24 presents the average selling price of a TFT-LCD from 1994 to 2000. Increased production capacity has also created downward pressure on prices. Japan's total monthly LCD output increased 62% from 1994 to 1995 and AMCLD prices fell 30%. Another factor contributing to the price drop of AMLCDs is that the quality of less expensive passive LCDs has improved.

Currently the price of 14-inch desktop CRT monitor is $200-400 compared to a 12-inch desktop AMLCD which is priced in sample quantities at $3000.

TABLE 1-24

Average Selling Price of TFT-LCD

YEAR	AVERAGE SELLING PRICE
1994	$1250
1995	1100
1996	700
1997	590
1998	515
1999	445
2000	389

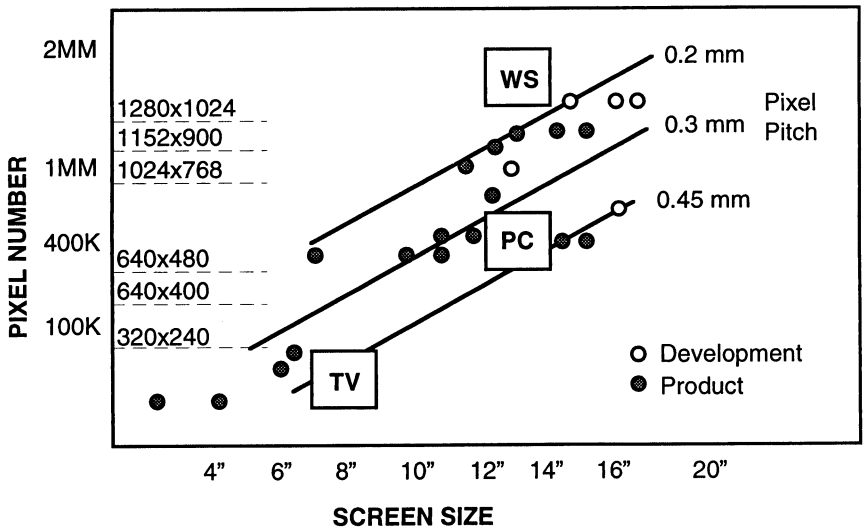
Source: Computer Industry Estimates

Interaction of Performance Criteria

Display product performance is based not only on achieving a certain criteria for one attribute such as size (e.g., a 10.4" or 21" diagonal) but also meeting multiple criteria because the relationship among each criteria is important to the overall functionality of the display. An example of the interrelationship of display performance criteria is resolution, size, and pixel pitch. Resolution is the number and configuration of pixels in a display e.g., a VGA monitor has a 640 x 480 pixel configuration. Size is the diagonal measurement of the display. Pixel pitch is the size of each pixel. As Fig. 1-6 illustrates, displays used for TV, PC or workstations (WS) require different configurations. As indicated, Sharp Electronics has either developed or produced product meeting a wide range of these requirements.

Ruggedized Displays

Ruggedization prepares the display for use in extreme temperatures, shock, and vibrations. Heaters, redundant backlights, electromagnetic interface filters, shock and vibration-resistant packaging, drivers, polarizers, and electronic connectors capable of withstanding wide variations in temperature and humidity are added to the AMLCD to ruggedize it for use. The cost of ruggedization is between one fifth and one third the price of custom AMLCDs. The most frequent cause of problems in ruggedized displays are the failure of polarized adhesives in high humidity and liquid crystal materials in very high temperatures.



Source: Sharp Electronics

Fig. 1-6: Resolution, Size, and Pitch Relationship

C. Environmental Performance Across Display Technologies

The number of masking steps required during manufacturing and the power consumption during use of the display are two significant differentiating factors in comparing display technologies environmental performance.

Masking Steps

Certain technologies such as FEDs may require fewer masking steps (manufacturing process steps requiring the use of resources, materials, and energy) thus resulting in lower environmental burden from the product system. Depending on the type of device used in a TFT-LCD process may require up to nine masking steps. In addition, AMLCD require the application of four masking steps to form the color filters. In contrast, FED technologies may only require four masking step to complete the patterning of electrodes on the display.

Power Consumption

This section reviews the critical issues associated with power consumption for each FPD technology. Power consumption is a critical customer requirement because most FPDs will be used in portable applications or in energy constrained systems. As FPD producers increase efficiencies in this regard, the environmental burden of the FPD product system decreases.

AMLCDs

The trend of power consumption of several different color TFT panels is as follows: In 1992, a 10-in workstation consumed about 20 W, a 9.5-in. VGA panel about 7.5 W, and a 6-in. notebook VGA panel about 5 W. In 1995, a 10.4-in. workstation will consume only about 5 W, a 9.5-in. VGA panel about 2 W, and a 6-in. notebook VGA panel about 1.5 W. This remarkable reduction of power consumption comes from increased aperture ratio, more efficient backlighting, and reduction of light absorption in interfaces and in film materials. Further energy advancements will lead to increased battery life in portable applications thus

limiting the secondary environmental impacts from battery usage. Fig. 1-7 indicates the relative power requirements for thin film transistor LCD and CRT technologies.

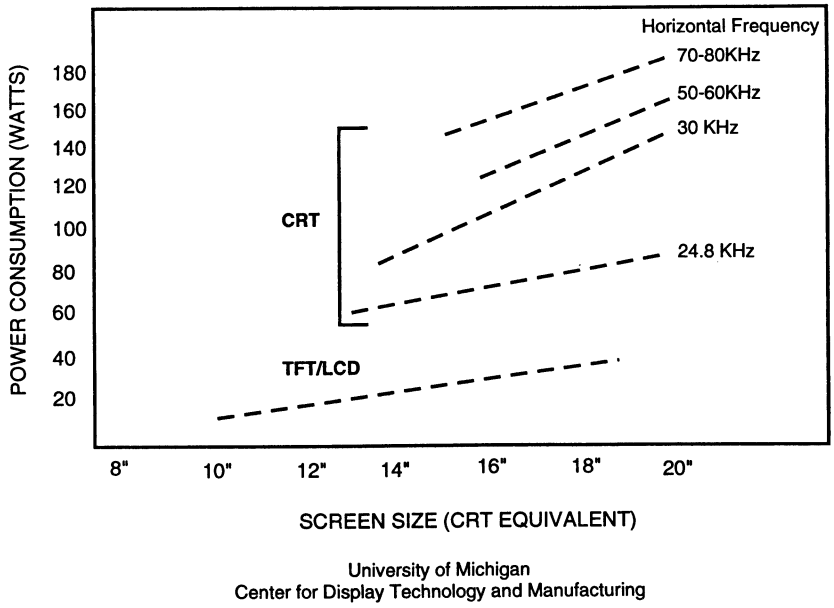


Fig. 1-7: Comparison of Power Consumption

The power consumption of displays is determined by its source of light. Displays are either emissive (generate light) or non-emissive (use a backlight). Backlights standard for the industry is the cold cathode fluorescent lamp (CFL) incorporated with a diffuser to spread the light uniformly behind the liquid crystal.[6] Concern has also been expressed over mercury in the lamps.[38]

AMLCDs emit only 4% of the original light to the viewer, giving an LCD an overall luminous efficiency (the total luminous flux emitted by the electrical power to produce it) of approximately 1 to 3 lm/W. IBM's Rober Wisneif reported that 5% of the light incident on the AMLCD comes out the other side of the device. The light source represents the LCDs main power consumption, accounting for 80-90% of the total power. Single-tube LCDs consume approximately 3 to 4 W, while two-tube versions use double that power level. The small fraction of remaining power in an LCD is taken by switching circuitry, which is needed to drive each pixel and modulate its gray scale. The power inverter between the battery and LCD is only about 70 to 80% efficient. Strategies for lowering power consumption include: improving light diffusers so that they more efficiently transmit uniform light through the screen; improving color filter and polarizers to gain better transmission properties; and increasing each pixels aperture ratio. Aperture ratio is the amount of light that can shine through a pixel in relation to the space taken by a pixel's transistor. Efforts are also being made to increase LCDs contrast ratio. However, there is a tradeoff between contrast ratio and brightness. By increasing contrast ratio, the display can appear to be somewhat brighter. To improve the contrast ratio, the amount of light reflected off the display must be reduced with anti-reflective coatings. Improved coating formulations are being investigated that will simultaneously reduce reflected light and permit a high level of light transmission from the display.[39]

Other panel design factors also play an important part in designing more power-efficient LCDs. Improvements that enhance a panel's light transmission can make an important

contribution to lowering its energy use. A highly transmissive LCD panel would require a less-bright backlight, which is lower power consuming, than a panel that absorbs more of the backlight's output. In addition, the front and rear polarizers in various displays account for a large percentage of its light absorption. Moreover, with color panels, the red, green, and blue color filters are also highly absorptive. Thus, color LCDs require brighter backlights and operate for shorter periods on batteries than monochrome displays.

Backlight efficiency may be improved using a number of approaches. One way involves developing a new backlight design, such as incorporating four CCFLs in an edge lit design, or by incorporating a single bulb design that replaces light diffusion with light diffraction. Ajluni also states that other backlighting schemes with different lights sources such as a serpentine fluorescent lamp, a hot-cathode, or a flat fluorescent lamp may reduce power consumption. Another way to improve backlight performance and overall power efficiency is by introducing a brightness enhancing film. Such a film reduces the illumination angle of the display system, resulting in approximately 50% increase in backlighting brightness. The tradeoff with this approach is that adopting such a technique degrades viewing angle characteristics.[39] Using polymer dispersed liquid crystals (which do not require polarizers) may be another power saving option.

Lowering threshold voltage is another way to reduce power consumption. New liquid crystal materials that lower the threshold voltage of TFTs from 1.4 V to 1.2-1.3 V are being developed by major suppliers such as Merck, Rodic, and Chisso. The LC drive voltage is also being reduced from 12 V to 10 V decreasing the power consumption of the circuit system. Initially LC molecules with high dielectric anisotropy were used to reduce threshold voltage because threshold voltage is inversely proportional to the square root of the dielectric anisotropy. However, there is a problem with this approach because viscosity increases and this slows down the response speed of the material. Therefore new materials, whose viscosity doesn't increase have been developed.[39][40]

Driver and power-inverter losses or efficiency also increase power loss. Typical LCD devices use 3-bit drivers with power consumption about 2W. However, advancements have brought the power consumption down to 1 to 1.5W using 6-bit drivers. To address inverter losses, future research will focus on designing the power inverter to better match the bulb's characteristics, in affect matching impedances.[39]

Cold Cathode Technology (FEDs)

In contrast to AMLCDs, FEDs are highly energy efficient because of the use of cathode-luminescent phosphor materials. The efficiency/power consumption advantage is enhanced by the fact that 90% of its power is consumed only when generating light. The AMLCD, on the other hand, is at full intensity 100% of the time. In addition, because the FED has no shadow mask, most of its current (75% of it) will impinge on the phosphor. The FED luminous efficiency therefore is significantly higher than AMLCDs. For example, Micron Display Technology predicts that 10 in ch, 50-fl, full color FED would use less than 5W of power for operation.[39] Petrovich reported that extrapolations from test data on FEDs predict that color FEDs will consume three to five times less power than an AMLCD. For example, a 10 inch FED could theoretically consume only 2W.[41] An FED research lab reported phosphor efficiency of full color at 4 lm/W, 300cd/m2 at 400V; 6 lm/W, 500 cd/m2 at 800 V; and 10 lm/W, 1000 cd/m2 at 3000 V. A significant issue in terms of reducing power consumption in FEDs is the development of custom electronics drivers, controllers, and power supplies. Furthermore, FED lifetimes may exceed 25,000 hours.[41]

ELs

Power consumption losses in EL displays can be traced to addressing circuitry rather than the light-emission mechanism. This is caused by current flow through circuit resistance in series with the EL capacitance. According to Planar, using "straightforward approaches" it is possible to keep typical power consumption below 5W. This is done by using a two-step, capacitance-charging waveform for both the display's rows and columns. It employs driver ICs with lower substrate capacitance, improves the efficiency of the IC logic circuitry, and reduces the panel fill factor as well as the panel area.[39]

Plasma

Plasma displays do not have as high a material luminous efficiency as ELs; however, plasma displays have 1000 times less electrical capacitance. Therefore, when taking into account the switching loss of the EL panel, the plasma panel frequently consumes less power. Consequently, plasma panels are favored for larger numbers of scanned line and EL panels are more suited to smaller numbers of scan lines. The crossover point is somewhere in the region of a few hundred scan lines.[39]

Nonetheless, the largest technical disadvantage that plasma displays face is their high power requirements. Plasma display manufacturers such as Plasmaco, Fujitsu, and Hitachi have increased the luminous efficiency of their displays. In fact, experimental displays have achieved luminous efficiencies of 0.7lm/W. If luminous efficiency could reach 5 lm/W they would require less power than AMLCDs.[39]

D. Environmental Performance of the Cathode Ray Tube

Flat panels offer tremendous advantages over CRTs for many products because flat panel displays are thin, light-weight, higher contrast, sunlight readable, and the mean time between failure (MTBF) for AMLCDs are approximately 10 to 100 times greater than for CRTs [3]. Because flat panels are more reliable and require much less maintenance than CRT displays, flat panels offer significant cost savings over the life cycle of the product system.

NPPC reviewed literature regarding the environmental impacts of CRTs to compare display technologies in terms of environmental burden. Specific environmental issues regarding CRTs are provided in the Table 1-25.[28] It is widely recognized that flat panel displays offer considerable environmental advantages over CRTs including:

- Decreased volume and weight of display resulting in decreased landfill burden
- Less toxic material components within display
- Decreased power requirements for use of the display
- Less risk of user health impacts.[28].

A complete life cycle analysis is would be necessary to compare the total environmental burden of CRTs and FPDs. Even though the CRT is more material intensive, the manufacturing processes may contribute fewer environmental burdens than the FPD manufacturing process. The reduced weight, toxic constituents, and reduced power consumption of the FPD would have to be compared to potentially less intensive CRT manufacturing processes to make an assessment of the relative environmental advantages of each technology.

Table 1-25

Review of CRTs and the Environment

ITEM	CONCERN/ IMPACT	ACTION/AGENDA
• Weight of 20 inch display ranges from 52 pounds to 72 pounds • Volume of display is increased by housing	• Landfill volume consumed • Weight of display for shipping/handling	• Potential recycling of housing and components to divert waste streams from landfills
• Lead and phosphorous in glass tube (see X-Ray Issue below)	• Leaching from disposal sites	• RCRA land ban rule requires that neck and funnel glass are disposed of in a RCRA site
• Use of nitric acid	• Safety of workers	
• Implosion of CRT during air removal (manufacturing) or malfunction during use	• Safety of workers and users	• Laminated safety window
• X-Rays within tube	• User exposures	• Bureau of Radiological Health and Electronics Industry Association standards—X-Ray absorbing materials used (lead, barium, strontium, and zirconium)
• Electromagnetic Radiation	• User exposures	• "As Low As Reasonably Achievable" ALARA Standards equivalent to Swedish MPR II standard
• Waste water/sludge from manufacturing operations	• Water quality concerns	• Removal of hazardous materials from manufacturing process
• Housing (plastic) and glass	• Ability to recycle and conserve resources	• Overcoming impurities and difficulties of separation • Lack of infrastructure to support take-back
• Power consumption during production and use (e.g., 20 W 150 W for 20-in.)	• Fossil fuel consumption	
• Yield	• Reducing quantity of waste	• Test early

STEP 2: CORPORATE ANALYSIS

I. OIS BUSINESS STRATEGY

A. Options Analysis

B. Cost Reduction Strategies

C. Revenue Generation Strategies

D. Core Competencies

II. STRATEGIC ENVIRONMENTAL MANAGEMENT

A. Core Business Vulnerabilities

B. Stage of Development

III. CORPORATE ENVIRONMENTAL MANAGEMENT SYSTEMS

CORPORATE ANALYSIS

Step 2, Corporate Analysis, consists of three major tasks: Evaluate OIS's business strategy; assess strategic environmental management issues; and review an environmental management system.

I. OIS BUSINESS STRATEGY

The framework for determining whether environmental management will have competitive implications on OIS is as follows: First, using market and product benchmarking analysis from Step 1 define a business strategy that maximizes shareholder value in the long term. Second, determine how improved environmental performance can lead to significant savings in the cost structure of the firm. Third, determine if improved environmental performance can lead to a revenue generating strategy. Fourth, determine what core competencies are needed to lead the organization through with this strategy.

OIS Business Objectives

In 1994 OIS's annual reported stated that, "It is the long-term vision of OIS to be a premier supplier of high quality, high information content flat panel displays worldwide." OIS made some progress toward this end when OIS signed an agreement with Apple Computer to develop displays for its next generation of notebook computers.[42]. To date, however, OIS's business strategy has consisted of developing displays under research contracts with system integrators that service military customers. Other than the Apple contracts, OIS has not made much progress toward high volume production.

The majority of OIS's revenue comes from the engineering contracts not from the sale of displays. Appendix A provides a DuPont Decomposition of OIS business performance. The results of the analysis indicate that OIS is still an R&D operation and has not generated significant revenue through display sales. OIS manufacturing difficulties are evident in reduced productivity of capital assets and in high levels of cost of goods sold. In addition, OIS is currently losing money annually, incurring significant debt, and raising equity capital to finance ongoing operation of the mid-volume facility recently completed in Northville. Although OIS has publicized its intention to build a high volume facility and has purchased land next to the existing Northville facility, it is not clear how OIS could finance the expansion. OIS's deep pocket, Guardian Industries and its owner Bill Davidson may be able to provide the necessary capital or OIS could enter a joint venture with another firm to raise capital.

There are several market factors, timing issues, and operational capabilities that will make it difficult for OIS to compete in a high volume market in the future. As described in the market overview in Step 1, the industry is currently experiencing a surplus of AMLCDs on the market. The disparity between supply and demand has resulted in over capacity at the world's largest display manufacturers and this has caused a price drop. In addition, PMLCDs have improved performance and have kept their prices low; therefore, many computer customers are opting for less expensive models with PMLCDs. Moreover, displays are a commodity in certain market segments notably the computer segment. Standards are being set for these displays and there are minimal price-performance tradeoffs from one producer to the next.

OIS must address significant operations challenges. Besides recovering from a recent fire at the Northville facility, OIS must bring a new facility up to speed using new process equipment, some of which has never been used in manufacturing before. The operational challenges of coordinating the installation, testing, and ramp up to full capacity utilization

will consume management's time and energy. Once operational, OIS must generate significant display sales to fill capacity of the mid-volume plant and by doing so begin developing cumulative production or learning economies that will lead to yield improvement. A new high-volume facility will take several years to construct and operationalize. OIS will have to develop capabilities not only in the use of new process tools for high-volume manufacturing but also generate enough sales in an increasingly competitive world market that will be faced with over capacity until new products are developed.

OIS must also consider the following issues raised by DoD as it attempts to enter high volume display manufacturing[6]:

- high entry costs and uncertainties in pricing, yield, and input requirement
- foreign actions/reactions if display buyers ally with domestic display producers and the availability of input materials and equipment
- "second-mover" disadvantages in terms of learning economies
- market concentration in japan
- foreign partners needed to "buy a line"
- investment barriers include low pay back for first few years; high risk technologies; alternative investment options.

OIS must also consider the threat of substitute products, specifically FEDs. The press reports that FED firms may have the ability to leap frog Japanese producers; however, the AMLCD now has an installed base and has developed network externalities because computer designers, electronics integrators, and customers have learned how to use the AMLCD effectively. Because the AMLCD has become the de facto standard in the industry, slight incremental improvements in the price-performance ratio will not cause the industry to replace the standard. In addition, commercially available FEDs are still several years off. Nonetheless, in 1994 DoD presented five factors that create opportunity for other technologies (i.e., leap frogs): (1) a shortfall in AMLCDs to meet current and projected demand; (2) a desire by large US firms to reduce dependence on FPD suppliers; (3) excessive manufacturing costs of AMLCDs; (4) limited large-screen applications for AMLCDs; and (5) the prospect for a major discontinuity in FPD technology.[6] Although the first two predictions were incorrect, the other observations presented by DoD have held true.

OIS also needs to consider the supply of displays to customers and the availability of materials and equipment. In a market with over capacity it is unlikely that Japanese manufacturers will deny access to supply of displays. In addition, it is not likely that foreign suppliers will stop providing inputs whether materials or equipment to US manufacturers. Lastly, OIS must evaluate the level of US government support through flat panel initiative. Even though the 104th Congress has set out to reduce government spending, infrastructure and manufacturing will be funded.

A. Options Analysis

OIS has a range of options including: (1) Seek firm to acquire OIS; (2) pursue a joint venture and/or vertically integrate; (3) stay the course in the military market; (4) diversify horizontally and pursue growth of core product share; and (5) develop a "new game" strategy. Each of these options will be discussed briefly.

The first option is to seek a firm to acquire OIS. This option may be viewed two ways. OIS could sell off the assets of the firm and allow another entity to continue operation. Alternatively, OIS could become part of another corporation in which synergies exists between OIS and the parent related to the production of the display product or the integration of the display and electronics systems. For example, Lockheed, a customer of OIS, could view OIS as a target in order to ascertain display production competencies. Lockheed would than combine its knowledge of defense systems and electronics to create synergy with the abilities of OIS. The purpose of this takeover would be to position the parent, Lockheed in this example, to develop more advanced display products that incorporate electronics onto the display substrate.

The second option is similar to the first in that OIS is joining with another corporation to take advantage of capabilities not found at OIS or to expand its market reach. OIS could establish a joint venture or alliance with another corporation to develop a high volume production facility. A larger firms financial capabilities as well as technological expertise in semiconductor manufacturing would be good match. Another approach would be to vertically integrate so that OIS would become a captive producer. For example, OIS could develop displays for an automotive manufacturer, a domestic computer manufacturer, or a producer of video telephones. OIS advanced engineering skills, flexible manufacturing, and high quality product may be a good fit with OEM manufacturers needs.

Third, OIS could stay the course in the military market segment. Currently, OIS sells displays for use in a variety of military equipment and the space shuttle. This option would enable OIS to continue developing its relationship with the US government and military contractors such as Lockheed; however, OIS will find it difficult to expand its market share in this segment and develop enough capacity to utilize even its mid volume facility.

The fourth option OIS could pursue to expand horizontally through technology related diversification, market related diversification, international expansion, or globalization. OIS could attempt to gain share in the medical, transportation, or industrial market not currently targeted.

Fifth, OIS could pursue a "new-game" strategy, one in which OIS develops a unique advantage and focuses on a particular niche. As shown in Fig. 2-8, OIS is currently in a selective market (i.e., the avionics-military segment) in which OIS has a niche, developing displays for avionics components. The fifth option is based on the development of a skill in the integration of electronics and the display. Achieving or developing this skill could involve alliances with other firms that specialize in electronics integration, substrate materials, or chip production. To date much value has been created in the development of the actual display product or the driver chips or microprocessors used in the electronics component. As these products become commodity-like products value will be created by offering increased performance and functionality by integrating all of these parts.

OIS's new game strategy could be the development of unique skills in the area of chip on glass technology and the creation of new products that operate using this configuration. The new game strategy should exploit factors that have never been regarded as competitively important. By integrating all components OIS may capture value by reducing the cost of the entire system to the OEM.

Display units may become more critical to electronic products if they incorporate functions that are presently elsewhere in the system. Functions would increasingly be built into the display so that the display is the system e.g., if the driver circuits and computer chips were mounted directly on the glass substrate. In this case, the location of display production and design/development would be critical because that is where most of the value added would be derived. Integration options may be either mechanical or functional or electronic. Electronic integration can be achieved in two ways: (1) mount the IC chips onto the display

glass that are the first level of interface between the display and the system and (2) mounting ICs like microprocessors and memory chips on the glass substrate. In the former case, integration may be achieved by designing the display frame and system cover in notebook computers as one structure to reduce size and weight.[5]

As Fig. 2-1 indicates, OIS is positioned in a niche (i.e., selling custom displays to the government and avionics electronics integrators). By moving into the "third quadrant," OIS may change the way some groups of customers purchase, configure, or use the product or service and in doing so create new segments that no competitor had previously been able to reach effectively.[43]

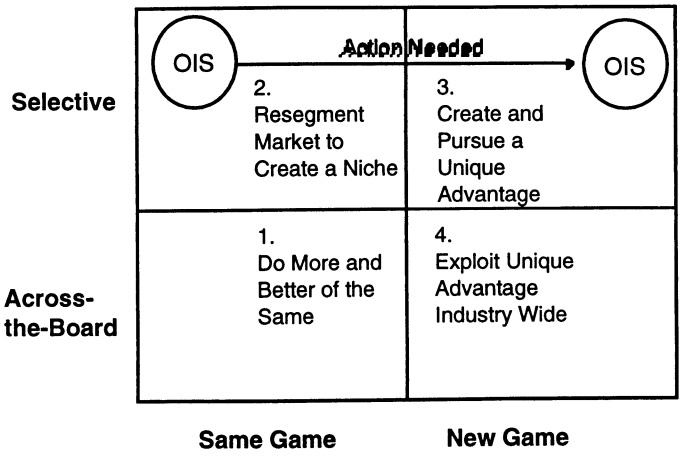


Fig. 2-1: OIS's Migration from a Niche to New Game Strategy

Alliances could help OIS secure a technological advantage over competitors. For example, an alliance with Dense Pac a maker of chip stacks for the military and the aerospace industry could lead to beneficial synergies. Dense-Pac's technology allows up to sixteen chips to be stacked in the space normally occupied by one, increases computing power, and reduces the energy required to run the chips because they are closer together.

Jon Fan, the CEO of Kopin, argues that the, "[I]ndustry will take two directions: create new products and new markets; and offer replacement technology for existing markets. Partnerships and alliances are crucial and science skills from chemistry, physics, electronics, and optics are necessary. A promising area for partnership is in integration of electronic circuitry onto the display. Success will not be based on technical merits, such as brightness or resolution, but on the ability to rapidly assemble the infrastructure necessary to commercialize and manufacturer high-resolution FPDs cost-effectively. Ultimately, what matters to the customer is price per pixel."[44]

The fifth option is based on the assumption that OIS must become flexibile and adaptive in regard to developing new value delivery models. OIS must assess whether increased integration of electronic components and the display will benefit customers five or ten years down the road. Fig. 2-9 depicts a two by two matrix that presents Hamel and Prahalad's view of identifying market opportunities. A new game strategy involving electronics integration may lead to success in "unexploited opportunities."

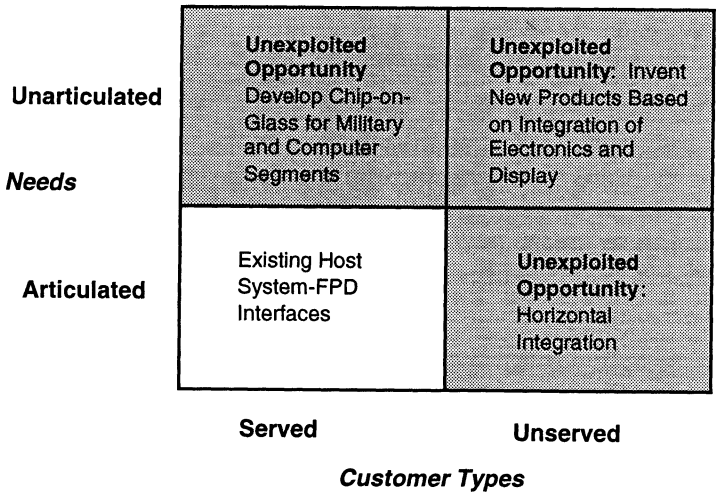


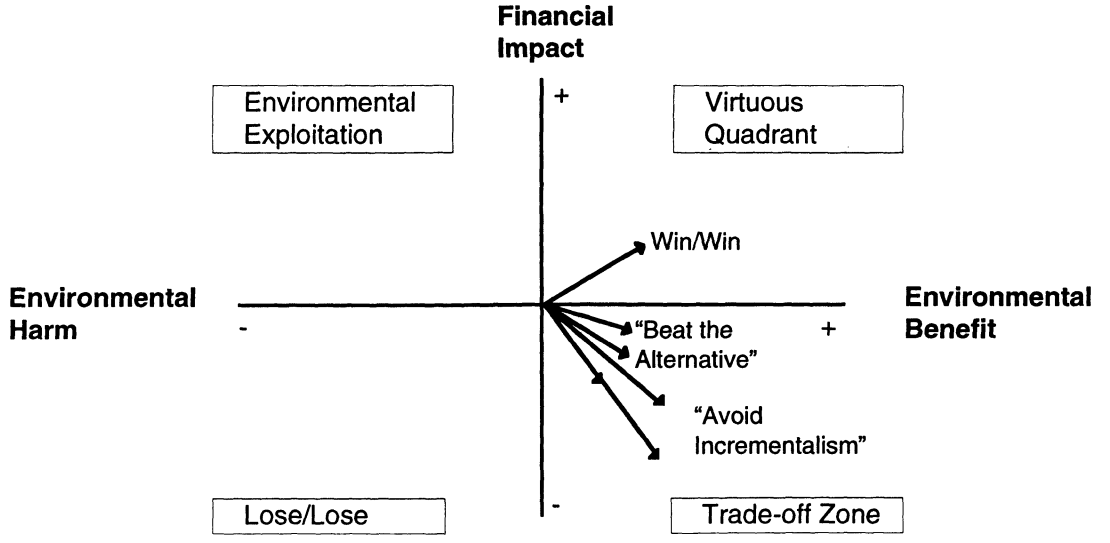
Fig. 2-2, Identifying Future Opportunities

B. Cost Reduction Strategies

Environmental performance will be of strategic importance if the cost structure of the firm will be materially affected by improvements in environmental performance. One of the benefits of environmental management is that often reducing material usage rates or substituting process chemicals will result in reduced environmental risk and reduced costs. Fig. 2-3 depicts the tradeoffs frequently discussed between the environment and costs. The win/win quadrant clearly has both business and environmental benefits. Pollution prevention projects seek out these opportunities and will receive management attention if there is sufficient value created by pursuing the project. Many firms have pursued what is referred to as "low hanging fruit" in these cases. However, greater challenges exist for management in regard to those projects that are in the "trade-off zone." Judicious tradeoffs exist when increased costs are incurred to achieve environmental benefits. Managers must develop a value based approach so that informed trade-offs between costs and benefits may be evaluated.[45] Management's ability to make decisions regarding such tradeoffs will depend on the systems in place to set priorities in terms of impact on shareholder value and environmental impact as well as the amount of management discretion to deal with the environmental problem. Management discretion is bounded by constraints such as regulatory compliance mandates and technological options.

In cases where OIS can be in the virtuous quadrant, it is incumbent upon management to take action to reduce environmental risks and improve shareholder value. Examples of win-win projects are extrusion coaters, yield improvement, and photoresist usage reduction. Each of these examples will be explored in Step 3. Examples of projects that may fall into the trade-off zone include reducing PFC usage, conserving energy and water, and substituting toxic hydride gases or glycol ethers. In these cases, environmental projects should be focussed on managing costs as efficiently as possible by avoiding incremental investments and projects that are less effective at achieving the same results. Because the firm's operations are in compliance, the amount of resources allocated to reducing environmental risks must be weighed against other projects that could yield more benefit to shareholders. Although not always the case, opportunity cost are often associated with working on environmental projects in the "trade-off" zone. For instance, management must consider whether developing energy conservation strategies or greenhouse gas emissions reductions programs will increase or protect shareholder value in the long run greater than a program to increase specific performance characteristics of the display product.

Management's decisions on these matters will also depend on how society views environmental issues including customer demands and legislative or regulatory programs. In addition, management must consider the moral and ethical responsibility of a business to operate in an environmentally conscious manner.



Source: McKinsey & Co.

Fig. 2-3: Forms of Value Creation

Identifying Significant Costs

Two studies have been completed that document the importance of controlling material usage costs and increasing yields. In both studies materials were found to represent roughly a third to one-half the cost structure for a firm operating either six or five years respectively.

The Department of Defense presented results of a study, "Calculated AMLCD Cost Structure" that includes three categories of costs applicable to the establishment and operation of a commercially competitive AMLCD facility: (1) research and development and investment costs; (2) manufacturing costs; and (3) fixed operating costs. Other factors in the model accounted for display selling price, yield, learning curve, and capacity utilization. Fig. 2-4 presents the cost structure for factory construction after six years of operation.

Sensitivity analysis revealed that Internal Rate of Return (IRR) is highly sensitive to materials cost, equipment costs, yield, and learning curve economies.[6] For example, in terms of costs, each ten percent increase in direct costs corresponded to approximately three percentage point change in IRR. Similarly, a ten percent improvement in yield rates leads to a six percentage point increase in the IRR.[6]

Another indication that flat panel manufacturers will move to control materials usage rates is supported by G. Resor's cost analysis of a high definition television factory based on AMLCD displays, "The Surprising Economics of Flat-Panel Production." Resor's study indicated that materials cost dominate over labor, depreciation, and other expenses. [46] Fig. 2-5 graphically illustrates this relationship.

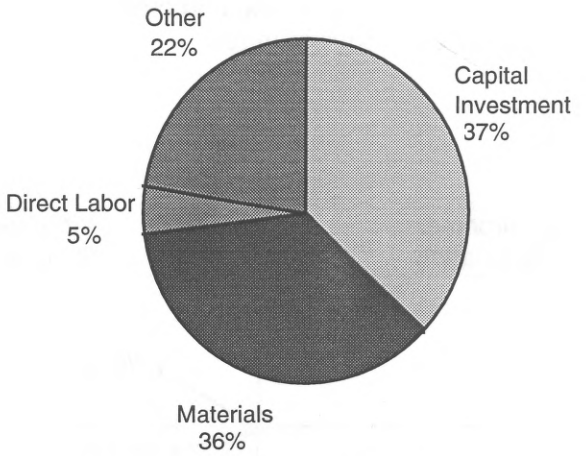


Fig. 2-4: AMLCD Cost Structure

Source: Department of Defense

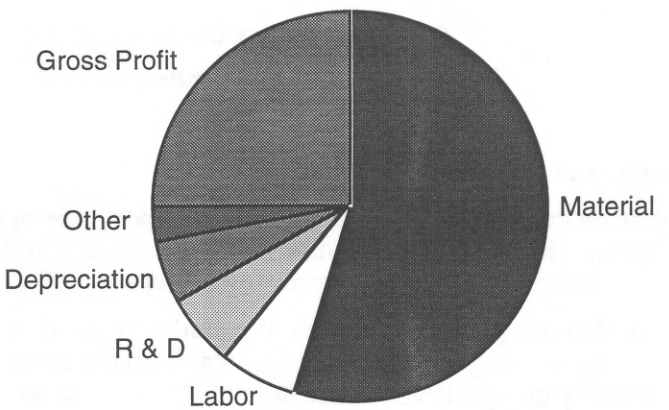


Fig. 2-5: HDTV "Minifab" Manufacturing Costs (5th Year of Project)

Source: G. Resor, 1990

Prioritizing Environmental Improvement Projects

As the Resor and DoD study indicate, reduction in material usage rates will increase shareholder value. If OIS is going to efficiently and effectively allocate funds to improve environmental performance and enhance shareholder value then a prioritization scheme is needed to assist management complete this task. Environmental performance improvement projects should be prioritized based on a number of criteria including:

- regulatory compliance with domestic or international laws
- technological capability and management discretion (i.e., safe alternatives available that are in compliance with applicable and relevant laws and regulations)
- relative risk of environmental impact according to EPA's science advisory board

- volume of material or resources consumed and released as effluent, emissions, or solid waste
- internal costs associated with each category of environmental burden
- environmental justice implications (i.e., does this action harm low-income or ethnic minorities disproportionately)
- industry standards (i.e., protocol developed by trade association).

OIS should prioritize environmental projects by using a matrix that evaluates each environmental concern based on technological flexibility and environmental impact as well as cost as shown in Fig. 2-13. The subjective assessment depicted in Fig. 2-6 uses the information collected in Step 3 as a basis for determining the categories of environmental impacts. For example, greenhouse gas emissions are rated along the vertical axis according to a subjective evaluation of the technological options available to mitigate the environmental burden derived from the use of gases that contribute to global warming. The environmental impact measure along the horizontal axis is determined based on EPA's Science Advisory Boards assessment of the relative risk of each category. In the case of greenhouse gas emissions, the use of these gases contribute to global warming/global climate change and is considered "high" in terms of EPA's relative risk ranking. The internal cost to OIS associated with each impact category is indicated by the size of the circle associated with each category. Estimates on internal costs should include the total operating cost for one year associated with each impact category and the capital costs associated with pollution control equipment. In the case of greenhouse gas emissions, the cost of the specialty chemicals used during one year and the capital expenditure on scrubbers and burn boxes to control greenhouse gas emissions should be estimated. For simplification purposes and lack of complete information, subjective judgments range from high to low.

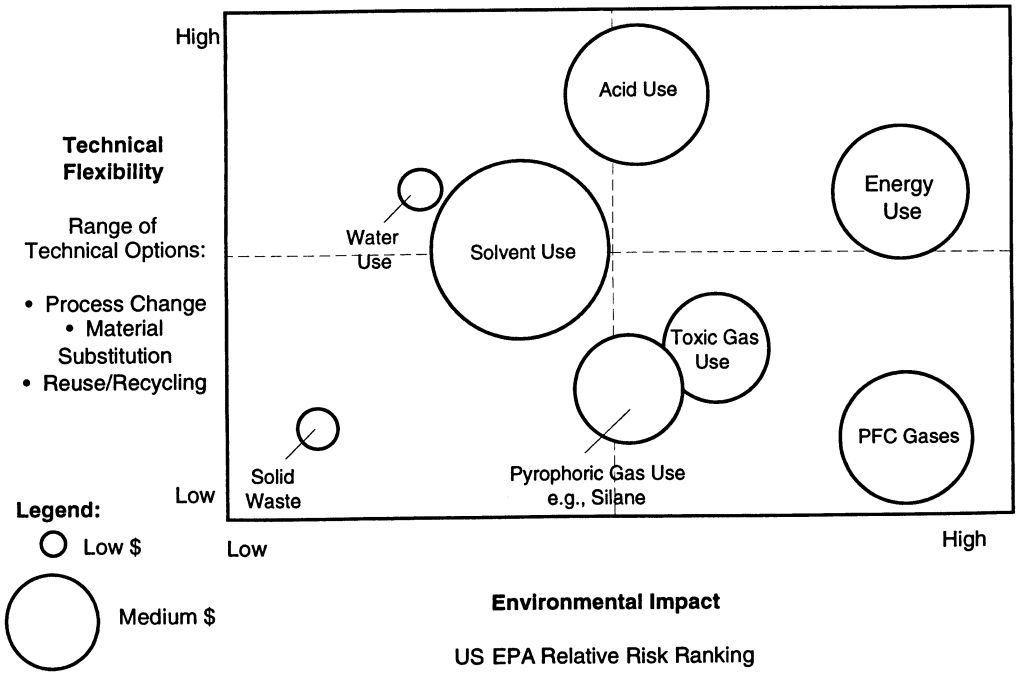


Fig. 2-6: Prioritization Matrix

If OIS were to adopt a prioritization scheme as shown in Fig. 2-6, accounting data and material use and emissions data should be compiled to accurately map out the various environmental impact categories. In addition to using the matrix, management must also consider future regulatory compliance programs, impacts on low-income or ethnic minorities, and industry standards/protocols developed by USDC, SEMI, or SEMATECH.

EPA's relative risk ranking system is as follows:

- High risk problems: global climate change; habitat alteration and destruction; species extinction and overall loss biological diversity; and stratospheric ozone depletion
- Medium risk problems: acid deposition; airborne toxics; herbicides/pesticides; toxics, nutrients, biochemical oxygen demand, and turbidity in surface waters
- Low risk problems: acid runoff to surface waters; groundwater pollution; oil spills; radionuclides; thermal pollution.

As graphically illustrated in Fig. 2-6, "Energy Use" is considered a high impact category because of its contribution to global climate change. Energy reduction programs are assumed to have a high degree of technological flexibility and the costs associated with energy use at OIS are assumed to be medium. Other impacts such as "PFC Gases" are considered high environmental impacts, and medium-high in terms of costs due to the price of specialty chemicals, however, currently there is limited technological flexibility for controlling or replacing PFC gases in AMLCD production. Other impact categories such as solid wastes are less burdensome in terms of environmental impact and cost. In addition, few technological solutions are available to control solid waste streams. Conversely, water consumption is low-medium in terms of environmental impact and cost, however, there is a high degree of technological flexibility afforded to OIS to control water use.

Ultimately, projects that management decides have a high enough impact on shareholder value, have sufficient technological flexibility, and fall on the high end of the environmental impact spectrum, should move on to a detailed analysis of expected costs for each project that can reduce environmental burden.

C. Revenue Generation Strategies

Two revenue generation strategies have emerged related to environmental management. The first is that OIS could enhance product functionality by reducing energy consumption requirements during the use of the display. This is not only a customer requirement but also an environmentally beneficial strategy. Step 3 summarizes results from the energy analysis in which varying watt displays are compared over a 10,000 hour useful life.

Second, if OIS were to pursue a new game strategy that integrated components onto the display substrate, substantial environmental benefit would be derived by eliminating the need for circuit boards and other interconnect devices that contribute significant environmental burdens during production and disposition.

Although these strategies result in environmental benefit, the "green factor" is not a critical marketing point to OIS's customers. Although customers may prefer to buy product from firms that are environmentally conscious in manufacturing it is doubtful that electronic OEMs will select OIS based on its environmentally inspired design of the display and the electronics. However, significant cost savings and performance advantages may be derived from this approach; thus, environmental design strategies are aligned with delivering increased value to the customer.

In the future, if a take back legislation were promulgated that required electronic manufacturers to reclaim components, OIS may be able to offer design solutions that simplified and expedited disassembly and recovery of the display unit and components. In this case, a competitive advantage could be gained. However, the likelihood of a mandatory take-back legislation in the US is currently not high, demand for easy disassembly of electronics is currently not high but is increasing as electronics firms consider asset recovery programs, and it is also likely that OIS's competitors could design the same features. Thus, little advantage will be gained by developing design for disassembly capabilities in advance of a take back law.

D. Core Competencies

One way of assessing how much the market values the competencies obtained by OIS is to compare market to book value. The market value of OIS during first quarter of 1995 ranged from $173,255,371 to $281,058,714 and the book value of OIS is approximately $40 million. The difference between the market and book value indicates that investors have expectations that OIS' management will operate the firm profitably in the future.[47][48] Hamel and Prahalad argue that this difference is an indicator of investors confidence in the core competencies of the corporation.

Hamel and Prahalad state that core competencies coordinate diverse production skills, integrate multiple streams of technology, and organize work to maximize the delivery of value through the use of cross functional teams. OIS's core competency is the ability to plan and control the process of depositing and manipulating microlayers of materials. Critical core competencies exist in large area optical electronics, large area microelectronics on glass, optical characterization of displays, measurement and verification, deposition, metalization, and clean room protocol.

As these competencies suggest and as OIS has demonstrated by successfully producing high-quality, custom-designed displays, OIS has the capability to transform materials, gases, energy, and resources into a high-value display product. It follows then that OIS's ability to improve environmental performance should begin with improving environmental performance that is directly related to its core competencies. OIS should pursue joint research efforts with suppliers to assist in developing less environmentally burdensome process tools because this capability is non-core to OIS. For example, OIS could use its expertise in large area microelectronics to develop a display with as few masking steps as possible to complete an array of transistors. Similarly, OIS competence in deposition could lead to better ways of controlling micro-layers of materials perhaps through selective deposition techniques. OIS could also pioneer the use of real time controls so that deposition and etching processes could react significantly faster than presently achievable.

By linking environmental performance to core competence, it becomes clear that OIS's core competence acquisition strategy will greatly impact the firms environmental performance. Competencies are skills and technologies that enable a company to provide a particular benefit to customers and contributes to competitiveness of a range of products. In addition, a "core competency" contributes to long-term prosperity of corporation and is distinquished from non-core skills using the following criteria:

- disproportionate contribution to perceived customer value
- competitively unique (not ubiquitous across industry)
- imagine array of new products.[49]

Capabilities in electronics integration onto the display (e.g., chip-on-glass) have the potential to meet each of the criteria for a "core competence." The set or bundle of

competencies will affect the environmental performance of the product system. Arguably, environmental excellence will be an indication that OIS has developed the right competencies that will enable success in the future.

Hamel and Prahalad's matrix presented in Fig. 2-7 depicts an acquisition agenda for a corporation. OIS can glean from this matrix the need to use existing competencies in large area electronics manufacturing in new products to fill the white spaces across industry market segments. In addition, OIS should develop new competencies in system integration to capture potential "Premier plus 10" or "Mega-Opportunities."

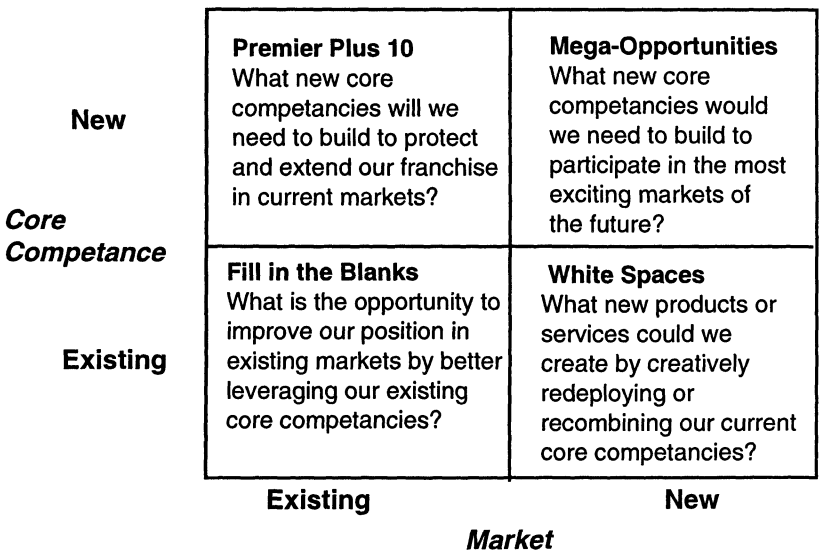


Fig. 2-7, Acquisition Agenda

II. STRATEGIC ENVIRONMENTAL MANAGEMENT

Strategic environmental management requires careful consideration of not only core business vulnerabilities but also management systems that enable continuous improvement of environmental performance.

A. CORE BUSINESS VULNERABILITIES

Walley and Whitehead argue that environmental issues are of strategic importance if core elements of the business are at risk or the cost structure will be fundamentally altered. The impact of environmental management on cost structure reviewed above indicates that there are opportunities for OIS to improve environmental performance and increase shareholder value. OIS must also consider whether "core" elements of the business are at risk as a result of poor environmental performance.

OIS should evaluate a number of strategic environmental issues that may impact core business operations including (1) a potential ban or industry phase out of per fluorocarbons, a class of global warming gasses used in etching and deposition processes[50][51], (2) supply chain concerns including the effective control of PFC gasses [52] or the dissemination of information regarding the use of ozone depleting substances [53], (3) maintaining a good environmental record to avoid permitting problems for future operations; (4) avoiding explosions or other accidents that could lead to facility shutdown or process tool contamination; and (5) potential regulatory changes such as take-back legislation, carbon

taxes, or ISO 14,000 certification requirements by customers.[54] Table 2-1 provides a litany of strategic environmental management issues that may affect OIS's core businesses.

Consumer pressure for "greener" products are not currently significant competitive drivers within the flat panel industry. OIS's position in the supply chain as a supplier to OEM or military contractors limits OIS's public consumer pressure; however, OIS's customers such as Apple may require OIS to commit to certain environmental policies in order to secure a contract.[53] Similarly, EPA or consumer pressure to manufacture energy conserving computers could increase demand for flat panel displays.

TABLE 2-1

Summary of Strategic Environmental Issues

VULNERABILITY	ISSUES
Regulatory Pressures	• Consider OIS' ability to respond to regulatory pressures and how this matches competitors ability to respond - potential phase out or further restrictions on the use of perflouro carbons, HCFCs, solvents - ability to handle take-back regulation or capitalize on asset recovery (i.e., reuse operations) - ISO 14,000 certification.
Raw Material Inputs	• Sustainable resource base specifically for water (e.g., siting facilities in arid regions)
Supply Chain	• Fulfill OEM/customer requirements that may demand specific levels of environmental performance e.g., elimination of ozone depleting substances from manufacturing operations, Apple contract requirements
Federal or State Support	• Influence in grant process with government • Establish a "good environmental" record to avoid problems throughout permitting procedures and public relations
Marketing Considerations	• Market advantages of AMLCD technology over CRTs after conducting a comparative assessment in terms of environmental performance
Facility Operations	• Explosion/fire or accident leading to worker health and safety risks, clean room contamination, and loss of confidence in the community.

B. STAGE OF DEVELOPMENT

Management literature describes the progression that young companies make from start up, through pilot stage, and out to large scale manufacturing. Firm growth requires changes in focus from research and development to production efficiency. As this transition takes hold complex administrative systems necessarily substitute simpler management styles that were sufficient for a small organization. The transformation is also accompanied by increased fiscal restraint as the firm struggles to deliver product and gain share. OIS, roughly speaking, is at a the pilot stage of development and is experiencing the growing pains associated with scale up to a mid-size facility. At this stage of development it is difficult for a firm to take on more risk by attempting to change its production processes to improve environmental performance. OIS must also challenge the cultural influence that is engrained in an industry that is historically wasteful and change from a culture that is technology development focused to one that is deployment and production focused.

In this state, environmental performance improvement is difficult because such projects are viewed as distractions from transitioning to production, are not seen as profit enhancing strategies, and are not widely recognized as a "problem" for the firm. Factors that influence willingness to change processes include available capital, demonstrated technologies from equipment suppliers, and management acceptance/championing of environmental vision. Therefore, the opportunity for environmental improvement seems to be either at the beginning phases of the firms life cycle or as the firm transitions from pilot to high-volume manufacturing. Fig. 2-8 conceptually illustrates the relationship between environmental opportunities measured subjectively from low to high (i.e., the ability to reduce environmental burden through process changes, materials substitution, etc.) and the stage of development of the firm. The firm's ability to change may be a function of the resources allocated to environmental management including management time, expertise in environmental issues, and financial support.

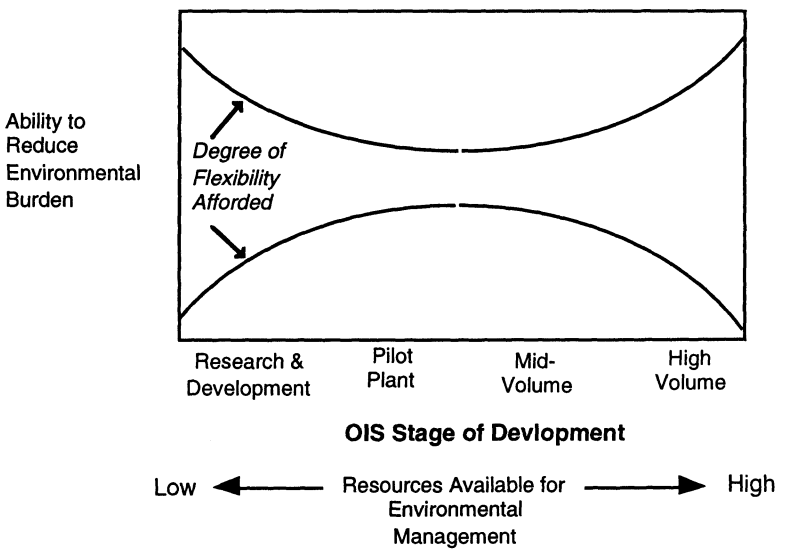
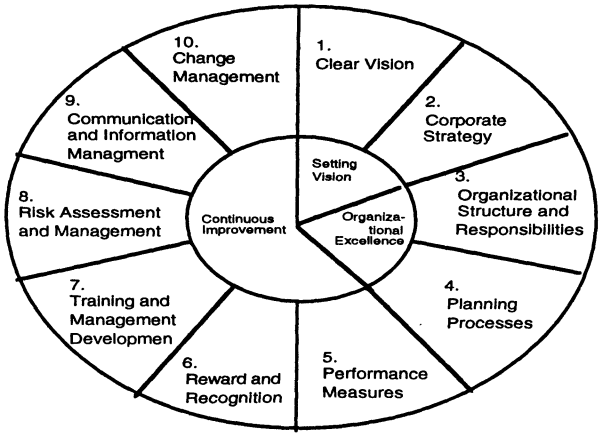


Fig. 2-8: Stage of Development

III. CORPORATE ENVIRONMENTAL MANAGEMENT SYSTEMS

Environmental performance improvement will depend on the firm's vision, organization structure, and continuous improvement programs throughout the corporation. Fig. 2-9 graphically illustrate the key issues considered to assess OIS's environmental management [55][56] Table 2-2 summarizes findings, recommendations, and OIS's proposed actions to begin its process of change.



Concept Developed by Booz•Allen & Hamilton, Inc.

Fig. 2-9: Environmental Management System Analysis

TABLE 2-2

Environmental Management System at OIS

FINDINGS	RECOMMENDATIONS	OIS PROPOSED ACTIONS
Setting Vision • Environmental priorities and product stewardship are not reflected in current mission and vision.	• Expand the corporate mission statement to include the environment • Create a set of firm values that reflects the ethical and moral importance of environmental stewardship • Develop a corporate environmental policy statement • Recognize the product life cycle framework as part of the environmental management system	• Develop a statement of policy in lieu of changing the corporate mission statement • Communicate moral obligation to the environment and sense of corporate responsibility.
Organizational Excellence • OIS does not have an environmental officer at the senior management level nor is there a formal environmental group (a safety committee meets monthly)	• Appoint a corporate environmental officer • Incorporate environmental programs into firms planning processes.	• Assign responsibility for environmental management to the head of Manufacturing.
Continuous Improvement • No formal auditing system exists to track facilities • Lack of environmental metrics on firm-wide and process level • Employees evaluations do not consider environmental responsibilities • Environment responsibilities do not cascade throughout the organization • Not clear if technology development and deployment evaluate or address environmental concerns.	• Develop mechanisms to analyze and measure facility level environmental performance e.g., through auditing, incentive system, and metrics • Establish metrics that facilitate the modeling of process-level environmental performance • Coordinate research programs with suppliers and USDC to assess and test "cleaner" production methods.	

As indicated , OIS does not measure environmental performance beyond regulatory requirements of State and federal law. Although targets or goals to guide environmental improvement were considered, due to limited information and lack of understanding of the costs associated with achieving reductions in materials and energy use, numerical targets were considered to be unrealistic. Table 2-3 presents a number of corporate-level environmental metrics that OIS could use to track environmental performance.

TABLE 2-3

Corporate-Level Environmental Metrics for OIS

CRITERIA	PARAMETER	METRIC
Manufacture	• Water usage	• Total facility and usage per unit of on-spec product area
	• Energy consumption	• Total natural gas, electricity, and fuel oil by total Btu and Btu per unit on-spec product area
	• Materials usage for all photolithography processes	• Total quantity of solvents, acids, and gases per unit of on-spec product area
	• Packaging materials	• Total packaging received from suppliers.
Waste - Emissions	• Municipal Solid Waste	• Pounds
	• Hazardous Waste	• By RCRA and SARA standards
	• Ozone Depleting Substances	• Pounds per time period and per unit of on-spec product area
	• Volatile Organic Compounds	• Pounds per time period and per unit of on-spec product area
	• Global Warming Potential	• Pounds per time period and per unit of on-spec product area
Liabilities, Penalties, and Compliance	• OSHA reportable incidents	• Number of incidents
	• OSHA citations	• Number of citations, number of citations per total hours in OIS work year or month, lost time in days, lost workday cases
	• Accidental releases	• Number of accidents and types and reportable quantity spills
	• Audits	• Number of completed audits
	• Penalties and fines	• Amount and number of fines for each statute e.g., CAA, RCRA

Although there is room for improvement, OIS's effort to construct a state-of-the-art AMLCD manufacturing facility does include a number of features that will lead to good environmental performance. Engineers, managers, facilities staff, and consultants toured numerous plants throughout the world to prepare for design and construction of the Northville facility. OIS's extensive research and experience resulted in the implementation of a number of systems that will lead to a high level of environmental control including:

- Continuous DI water system
- Combination of gas and oil powered chillers operated by an energy management software program to reduce costs (real-time feedback from Detroit Edison on rates)
- Installation of scrubbers and "burn boxes" to control emissions
- Installation of "state-of-the-art" gas delivery systems and construction of safe storage facilities for process materials and waste
- Substitution of CFC cleaning processes with alternatives including UV ozone cleans, DI rinses, and detergent cleans where feasible
- Installation of "state-of-the-art" process equipment.

STEP 3: ENVIRONMENTAL PROFILE

I. OIS AMLCD MANUFACTURING PROCESS

II. RESULTS OF ENVIRONMENTAL PROFILE

A. Material, Energy, and Resource Accounting

B. Environmental Metrics

III. OVERVIEW OF ENVIRONMENTAL ISSUES

A. Energy Use

B. Air Quality

C. Global Climate Change

D. Resources Depletion

E. Land Use Development

F. Solid and Hazardous Waste

G. Water Quality

H. Human Health & Safety

IV. ENVIRONMENTAL LAWS AND FUTURE TRENDS

A. PFC Reduction

B. Take Back Legislation

C. Carbon Taxes

V. PROCESS/OPERATIONS EXCELLENCE

A. Color Filter Application

B. Materials Usage Reduction

C. Yield/Defect Rate

D. Equipment Utilization/Throughput Control

E. Semi-Aqueous and All Dry Processing

F. Computer Integrated Manufacturing

ENVIRONMENTAL PROFILE

The environmental profile includes:

I. Review of AMLCD manufacturing process
II. Results of an environmental profile of OIS operations including environmental metrics and a yield improvement analysis
III. Overview of environmental issues related to AMLCD manufacturing
IV. Review of environmental laws and future trends affecting the industry
V. Operations issues related to environmental management.

I. OIS AMLCD MANUFACTURING PROCESS

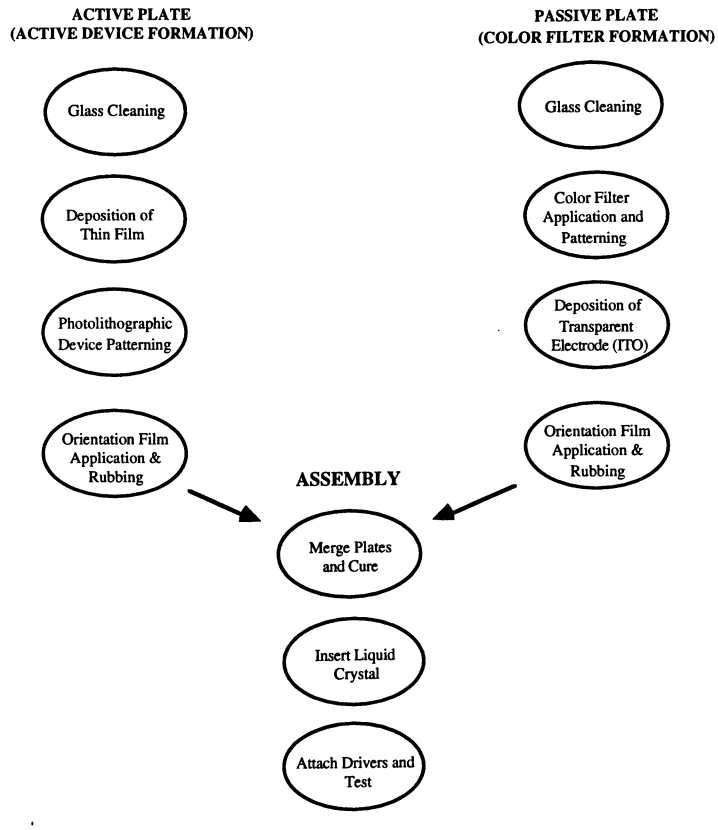
The following section describes the process steps necessary for producing AMLCDs. This section reflects the author's best understanding of OIS' manufacturing process based on literature and interviews with DTM and OIS personnel.

A. PROCESS FLOW

The manufacture of AMLCDs is a time consuming, exacting process that requires over 200 process steps. In many cases the processes used are similar to those employed by the semiconductor industry, the manufacture of integrated circuits, and the production of printed wiring boards. AMLCD manufacturing has three basic components. Two glass substrates are processed separately, then joined together. [17] One of the substrates is patterned with colors and then covered with a conductive layer and an orientation film. The other substrate is covered with a series of thin films that are then patterned to form active switching devices. Both plates are cleaned numerous times throughout the process as each glass substrate preparation requires multiple stages to form the intermediary products which are then assembled, filled with a liquid crystal material, cut down to the size needed for the displays application. Lastly, the electrical circuits are hooked up to the display and the product is ready for market. Fig. 3-1 represents the manufacturing process.

Glass Preparation

The glass substrates are trimmed to size, heat treated to control thermal processing during display manufacturing, and cleaned.[17] First, the glass is cut to the appropriate size for use in OIS's process equipment. Second, the glass is put through a thermal annealing process to control expansion and shrinkage during device formation. Lastly, the glass is cleaned in a de ionized water rinse. It is important to point out that there are a number of methods for cleaning the glass substrate: physical, chemical, or dry cleaning. At this stage of the process the cleaning method is not as crucial as compared to stages that follow the application of organic films, metals, or resists (materials used at different stages of the process) because these materials may leave particles on the substrate that could impair performance of the final product. OIS uses a mixture of cleaning techniques depending on the process step.



Adapted from [57][58]

Fig. 3-1: Schemata of AMLCD Manufacturing Process

Color Filter Formation

Fig. 3-2 illustrates the sequence of process steps for applying the color filters to the glass substrate. These steps will be repeated four times, three primary colors are formed and then a black filter is formed which acts as a border around each color element for contrast. [57][59] As Fig. 3-2 indicates, the substrate is dried in a conveyor oven. Next, the substrate undergoes a series of steps that make up the photolithography process. This procedure includes:

- coating the substrate with a color filter resist with a spin coater tool
- "soft" baking the substrate to evaporate solvents remaining on the substrate
- exposing the substrate to UV light with a stepper
- developing the areas exposed to light
- "safe" striping the resist off of the substrate
- cleaning the substrate with DI water.

After each photolithographic process (i.e., spin coating through clean), the substrate is cured in a conveyor oven. This process is repeated for each color filter a black border. After the filters are formed, the surface is non-planar, therefore, a layer of material is laid down to planarize the surface. Next, a layer of Indium Tin Oxide (ITO), a transparent electrode material, is sputtered onto the plate. A layer of ITO forms throughout the chamber where substrates are aligned to receive the ITO. Lastly, a crystal alignment polymer layer is laid down which orients the liquid crystal material during the assembly stage of the process.

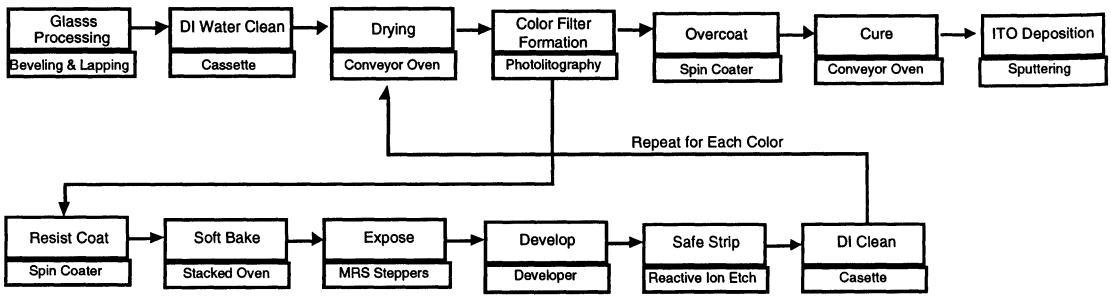


Fig. 3-2: Color Filter Formation

Active Device Formation

Fig. 3-3 illustrates the process used for forming the thin film transistor that enables the display to respond to electronic impulses generated by the host system (e.g., computer terminal). As Fig. 3-3 indicates, there are many steps that are repeated throughout the formation of the active device.

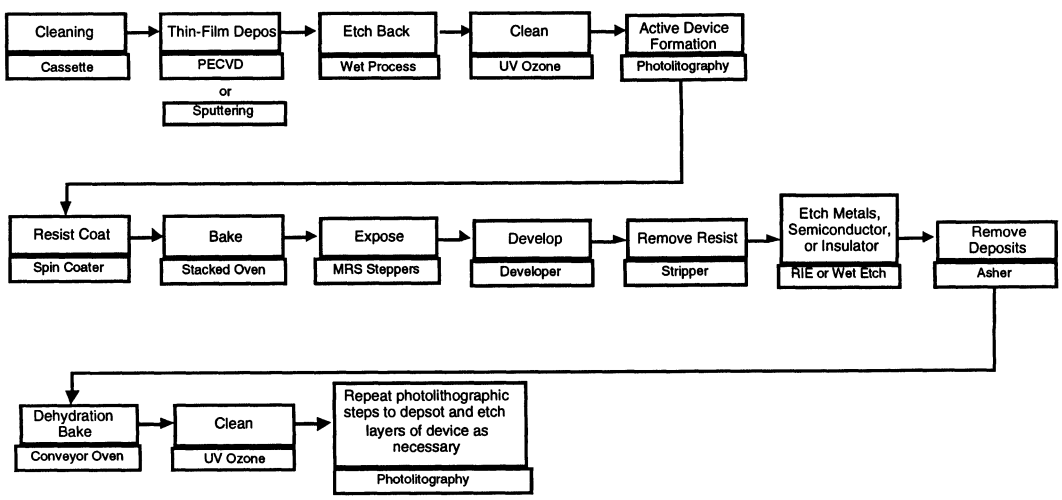


Fig. 3-3: Active Device Formation

Stated simply, the process is a sequence of depositing materials and then taking off those materials from the places where they are not needed for the final device. The device is built up sequentially. The device structure used in OIS's flat-panels consists of six layers. Fig. 3-4 depicts how the each device on the substrate looks after it has been formed. As shown, the first layer is Tantalum or Molybdenum. These metals are deposited by sputtering in the same manner described above for the ITO layer. Next, the metals are etched backed and then the

substrate is cleaned. A series of photolithography steps follows, similar to the procedure used in the color filter formation. A layer of resist is applied, then baked, exposed, and developed. This procedure leaves a pattern on the substrate indicating where the metal should remain. The area that is patterned to be removed is taken off by an etching process. OIS uses both dry etching and wet etching processes to remove the metals from the areas that are not needed. The dry etch process, or reactive ion etching (RIE), does not produce as much water borne waste as wet etching, however there are numerous atmospheric emissions that result from the dry processes. After etching, the materials are removed from the substrate with a stripper (Shipley 1800 series) and then the substrate goes through an asher which is used to clean resist deposits not fully removed by the stripper. After being dried and inspected (and repaired if necessary), the substrate moves on to receive another layer that forms the device.

The next two layers are deposited by plasma enhanced chemical vapor deposition (PECVD) or glow discharge. Silane (SiH_4), ammonia compounds (NH_3), and NF_3, and phosphine (PH_3) are combined in a chamber in the presence of nitrogen, hydrogen, or argon to form the appropriate chemistries that make up the Si_3N_4, amorphous silica (a-Si), and N+ layers. As with the first metal layer, each of these layers is formed after a series of photolithographic steps determines the pattern to be left on the substrate. The deposited layers are then etched off, stripped, and ashed before it is dried, inspected, and cleaned.

After these layers have been built up another layer of metal, molybdenum (Mo), is sputtered onto the substrate. Again, the substrate goes through the photolithographic steps, etching, stripping, ashing, and cleaning. Lastly, a layer of Si_3N_4 is laid down, patterned, etched, etc.

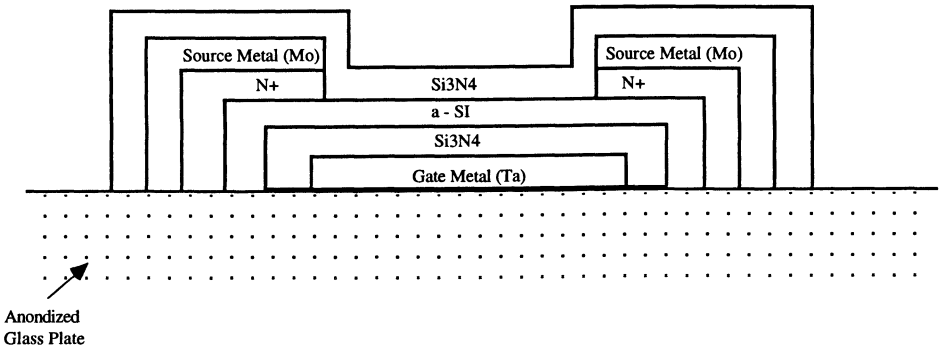


Fig. 3-4: Device Structure

II. RESULTS OF ENVIRONMENTAL PROFILE

This section contains a materials, energy, and resource accounting summary and a review of environmental metrics. The materials, energy, and resource accounting exercise details the major process steps associated with active device and color filter formation. The review of environmental metrics presents a recommended set of metrics for OIS to use within an internal factory simulation model as well as a set of metrics that describe the overall environmental burdens from the AMLCD product system. Data for the environmental profile were ascertained through meetings with OIS's facilities manager, process engineers, and from the utilities spreadsheet developed by OIS's cleanroom consultant.

A. MATERIAL, ENERGY, AND RESOURCE ACCOUNTING

Table 3-1 lists the materials and resources used in the color filter and active deice formation phases.

Table 3-1:

Inventory of Materials and Resources

Process Step	Material and Gases		Resources
Color Filter Formation			
Cost-Bake Color Filter	• Brewer Science Color Filter (APX) • Shipley 1800 Series Resist	• Hexamethyl-disilazane	
Develop-Bake Color Filter	• Developer (Tetramethyl-ammonia hydroxide, TMAH)	• Nitrogen	• DI Water
Solvent Cleaner	• NMP/Acetone • Brewer Science Safe Strip (PGMEA)	• Nitrogen	• Process Cool Water
Active Device Formation			
Coat-Bake Resist	• Shipley 1800 Series Resist • HMDS	• Nitrogen	
Develop-Hard Bake Resist	• Developer • Nitrogen		• DI Water • Process Cool Water
Plasma Ash Etch	• CF4 • Argon	• Nitrogen • Oxygen	• Process Cool Water
Wet Strip Clean	• Shipley 1165 • NMP	• Nitrogen	• DI Water • Process Cool Water
Develop-Soft Bake	• Developer • Nitrogen		• DI Water • Process Cool Water
Anondize	• NH4F/HF • Tartaric Acid	• Nitrogen	• DI Water
Wet Etch	• Phosphoric Acid • Nitric Acid • HAC	• Nitrogen • Acetic Acid • Hydrochloric Acid	• DI Water
RIE Cluster	• SF6 • CF4 • BCL3 • Cl2	• Nitrogen • Oxygen • Hydrogen	
CVD Cluster	• N2O • SiH4 • NH3 • PH3	• NF3 • Nitrogen • Argon • Hydrogen	• Process Cool Water
Sputterer	• Molybdenum • Tantalum • Argon	• Nitrogen • Oxygen • Indium Tin Oxide	• Process Cool Water
Cleaning Processes			
UV Ozone Clean	• Alkaline Developer • Nitrogen		• DI Water • Process Cool Water
DI Rinse			• DI Water
Detergent Clean	• Detergent • Isopropyl Alcohol		• DI Water • Process Cool Water

A template based on the illustration in Fig. 3-5 was adopted from Keoleian and Menerey's work on Life Cycle Design and EPA's guidance on Life Cycle Analysis. [60] The purpose of compiling the templates is to inventory materials and energy inputs-outputs throughout the manufacturing process and assist OIS in moving towards a mass balance

approach in evaluating its operations. Accounting for materials and energy in this manner enables the identification of processes that require: (1) significant energy use; (2) materials of concern for human health or environmental reasons; and (3) significant resource consumption (i.e., water use). Table 3-2 provides a synopsis of the process steps that are most intensive in each of these three areas. The materials, energy, and resource accounting templates also characterize the waste streams form each process step. NPPC used this set of information to focus our studies on areas that appeared to have potential for the greatest overall risk reduction.

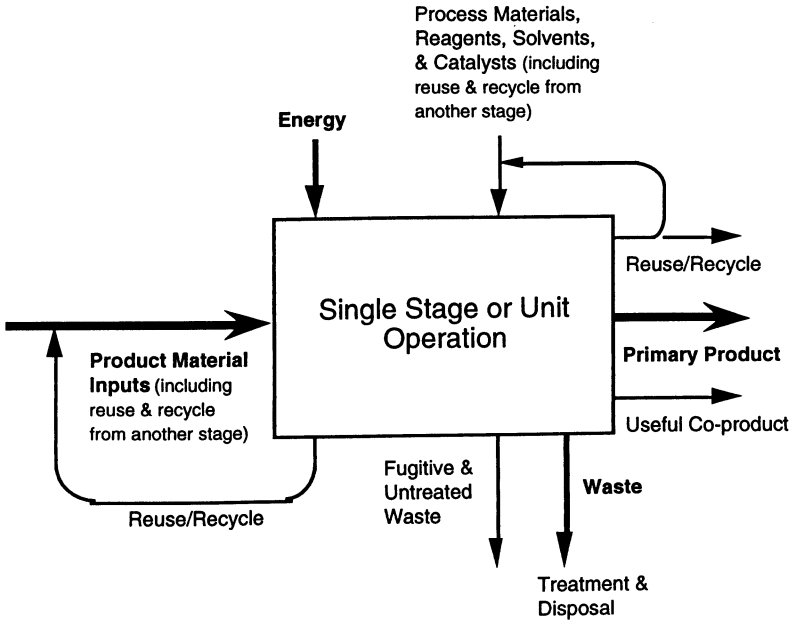


Fig. 3-5: Materials an Energy Accounting Template

TABLE 3-2

Process Input Impact Categories

ENERGY USE	MATERIALS OF CONCERN	WATER USE
• PECVD Cluster	• PECVD Cluster	• PECVD Cluster
• Sputterer	• RIE Cluster	• Sputterer
• RIE Cluster	• Solvent Cleaner	• RIE Cluster
• Coat-Bake	• Detergent Clean	• Detergent Clean
• Develop Bake	• Ozone Clean	• Ozone Clean
• Wet Strip	• Utrasonic Clean	• Wet Strip
• Stepper/Sticher	• Wet Strip Clean	• Wet Bench
• Solvent Clean	• Wet Bench	• Wet Etcher
• Detergent Clean	• Wet Etcher	
	• Coat-Bake	

NOTE: Processes not listed in order of magnitude of impact

Appendix B contains templates for most of the color filter and active device manufacturing process steps deemed to have significant contributions to the overall environmental burden of the product system. The templates distinguish between process materials and product materials. In addition, waste outputs are differentiated by three categories: atmospheric emissions, solid wastes, and waterborne wastes. In many cases the only information regarding outputs consisted of data on (1) air emission outputs as solvent exhaust or acid exhaust or (2) waterborne effluent through the solvent or acid drains. Primary product and useful co-products were identified and recycle (or recirculation systems) were delineated where appropriate and where known to the author.

Understanding each unit process input-output is necessary but not sufficient for managing environmental risks of the entire facility. Appendix C contains the pilot demonstration facility's solvent, exhaust, acid, DI water, and process water systems. Each figure depicts the process machines that are hooked up to the system and, where known, the effluents attributed to each process. These diagrams help to understand how the facilities aggregate wastes are managed.

B. Environmental Metrics

Similar to measuring other business functions such as sales or market share (i.e., indications of firm performance), management should also measure environmental performance. Environmental metrics should be simple and easily understood. Complex, time-resource consuming measurement systems to measure environmental burdens are not acceptable to management. The metrics should identify efficiency of product and process use so that the outputs of the metrics are useful in driving continuous improvement. Responsibility for tracking environmental performance should fall upon those groups that have the greatest control over improvement programs. In addition, metrics should be communicated to all individuals involved in the improvement process. Lastly, metrics should indicate the level of expenditure associated with each environmental burden. Cost data, however, is not considered as part of this analysis. Table 3-3 reviews the metrics recommended to OIS for use in an internally developed factory simulation model.

Appendix D contains a set of environmental metrics based on the utilities spreadsheet provided by OIS's cleanroom consultant. The metrics presented in Appendix D document the materials, energy and resource consumption for the pilot demonstration facility on a substrate basis. Due to a lack of information on the configuration of displays on each substrate and actual deposition rates of product materials it is not possible to compute the metrics recommended above. Table 3-4 provides a number metrics that indicate the level of material, energy, and resource intensity of the flat panel display product system.

TABLE 3-3

Environmental Metrics

CRITERIA	PARAMETER	METRICS
Product	• Efficiency of use of product materials throughout the production process	$\text{Material Efficiency } j \text{ Stage} = \left[\frac{Md}{Mi}\right]_j$ and $\frac{Md \text{ Final Product}}{Mi \text{ Total (all stages)}}$ M_d = Materials deposited on substrate M_i = Material input for process
Process	• Efficiency of use of process materials	• Material input per unit substrate: (e.g., solvents) S_m / T_s = Solvent use per m^2 substrate S_m = Solvent usage in gallons per unit time T_s = Substrate throughput in area per unit time
	• Efficiency of energy use	• P_m / T_s = Energy per cm^2 substrate Pm = Power of machine in energy per unit time Ts = Substrate throughput in area per unit time
	• DI Water use per area of substrate	• W_m / T_s = DI Water use per cm^2 substrate W_m = Water usage of machine in gallons per unit time T_s = Substrate throughput in area per unit time
	• Rate of recycling	• Material recycled per material input
Product Steward-ship	• Power consumption during operation	• Energy required for operation (including backlight) / average useful life of the product • Mean Time Between Failure (MTBF)
	• Material consumption throughout distribution	• Weight of packaging per units based on product type
	• Asset recovery rates	• Number or percentage of units reused • Percent of product by weight reused • Number of displays down cycled for future use.
	• Disposal	• Weight

TABLE 3-4

Select Environmental Metrics

CATEGORY	METRIC	VALUES
Energy	Energy Use in Manufacturing	Primary: 849M Btu per substrate Operating: 438
	Energy Use per Display from Operation (65 W display operating for 10,000 on national power grid)	Primary: 6,963 Operating: 2,217
Resource	DI Water Consumption per Display from Manufacturing	94.3 gallons/substrate
Solvents	Safe Strip	553.27 ml/substrate
	Thinner	9.54
	Photoresist	47.70
	Remover	953.92
	Acetone	109.70
	IPA	109.70
Gas	Silane	.22 g/substrate
	Phosphine	.56
	Chlorine	8.91
	Tetraflouromethane	.01
	Sulfur Hexaflouride	.004
	Nitrogen Triflouride	.48
Acid	Phosphoric	856.26 ml/substrate
	Nitric	1,151.52
	Acetic	179.62
	HCL	223.91
	Acrylic	24.61

III. OVERVIEW OF ENVIRONMENTAL ISSUES

The manufacture of AMLCDs is a complex operation involving physical and chemical processes such as photolithography, metalization, acid and reactive ion etching, doping, and cleaning. This section discusses the impacts of AMLCD manufacturing on the environment including seven impact categories:

- Energy use
- Air Quality
- Global Climate Change
- Resource Depletion

- Land Use Development
- Solid and Hazardous Waste
- Water Quality
- Human Health.

A. ENERGY USE

Energy use may be the most important environmental issue facing AMLCD manufacturers and other semiconductor and electronics producers world-wide. Energy is supplied to OIS by Detroit Edison from a new switch which currently has low usage. The power is generated mostly from fossil fuel combustion at Detroit Edition's generators. The pollution resulting from these operations is of great environmental consequence. Carbon Dioxide (CO2) is a by-product of incomplete fossil fuel combustion and is a non-toxic gas that leads to global warming. Energy consumption at OIS' Northville facility will be substantial in order to power process equipment, clean room machinery, waste disposal equipment, and the facility's daily requirements for computers and lights.

Clean Room Design

Clean rooms are mechanically intensive facilities which consume enormous amounts of power Good design is crucial to a mechanical system if it is to remain both cost and energy efficient.[61] The mechanical system is the primary energy consumer in cleanrooms because the air exchange rate is typically between 50-750 times per hour. In addition, this air is forced through High Efficiency Particulate Air filters which have a much higher pressure drop than typical diffusers. Thus the resulting blower and distribution systems are usually quite large for the square footage served.[61] The air conditioning systems are also intensive to supply hundreds of tons of air conditioning to reach desired operating environments and compensating for equipment exhaust and blower heat of compression. OIS's Northville facility contains a 50,000 square foot clean room area which will require a Class 100 environment 365 days a year. Fig. 3-6 describes the amount of energy required per display from operating the HVAC equipment for specific areas of production.

Reducing clean room energy use requires reducing the blower BHp and obtaining efficient air conditioning systems. Air conditioning may be designed to economize by taking cool air directly in from outside. Insulating cool areas and using alternative humidifying systems (e.g., atomizing or gas fired steam boilers) may yield substantial savings. In addition, a variable mechanical system that allows for set back during non-critical use is a method for controlling BHp resulting from blower speed and thus saving energy.[61]

Chillers

Chillers cool the water and air conditioning systems for the facility. OIS has installed both gas (two 175 Ton marine boat powered) and oil fired (two 500 Ton electric powered) chillers in the Northville plant to optimize its energy efficiency. The decision-making criteria for this dual system was based on the ability to save money by running either chillers during different times of the day. OIS clean room will be controlled by a computer software program that adjust the type of power used based on rate information passed on from Detroit Edision throughout the day. This system, designed by Allerton Energy Management Systems, called Direct Digital Control will also be used to track use and provide maintenance histories such as hours run and oil changes.

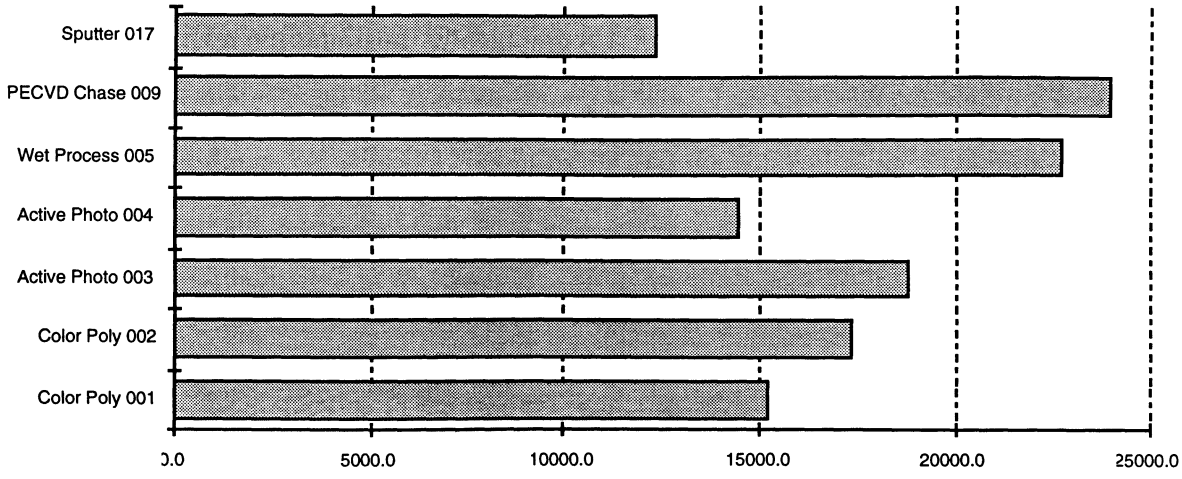


Fig. 3-6: HVAC Btu/Substrate for Specific Production Areas

Equipment Power Requirements

OIS's process equipment will demand power for daily operation. Based on the Utilities Matrix, the Northville facility will require over 3.1MM KwH per year to operate the process equipment. This requirement alone is substantial and may indicate an area for further study to ascertain which equipment manufacturers have designed energy efficient machines. Fig. 3-7 describes the amount of energy required per display from operating the process equipment for specific areas of production.

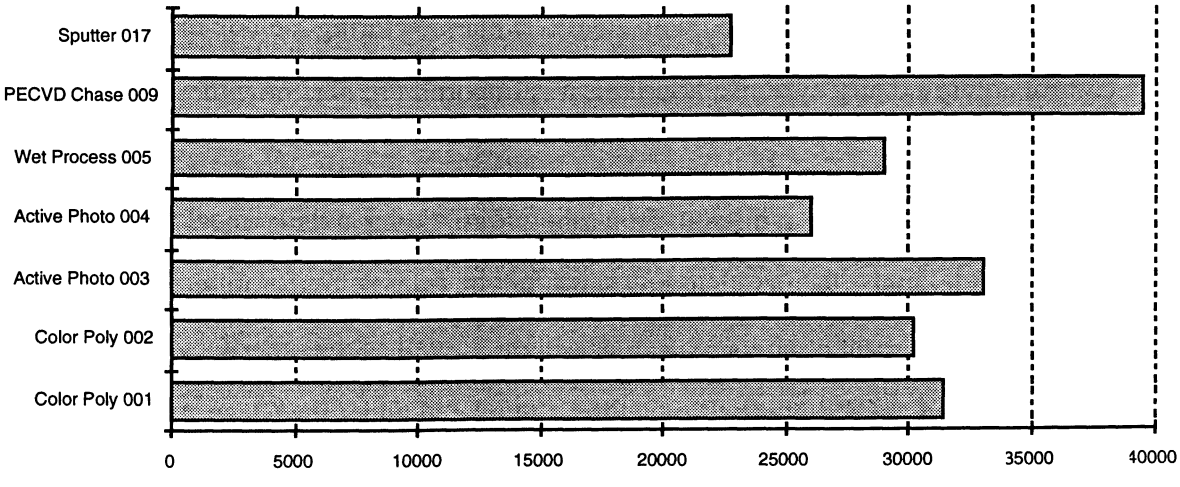


Fig. 3-7: Equipment Btu/Substrate for Specific Production Areas

Product Use Over Lifetime

Considering the life cycle impacts of AMLCDs, NPPC recognizes that the energy requirements over the lifetime of the screen will also result in environmental impacts. Whether the products are powered by fossil fuel or battery power, the efficiency of its power

use will impact the environment. Fig. 3-8 graphically illustrates the relative magnitude of energy consumption of production equipment, HVAC, and use of the display.

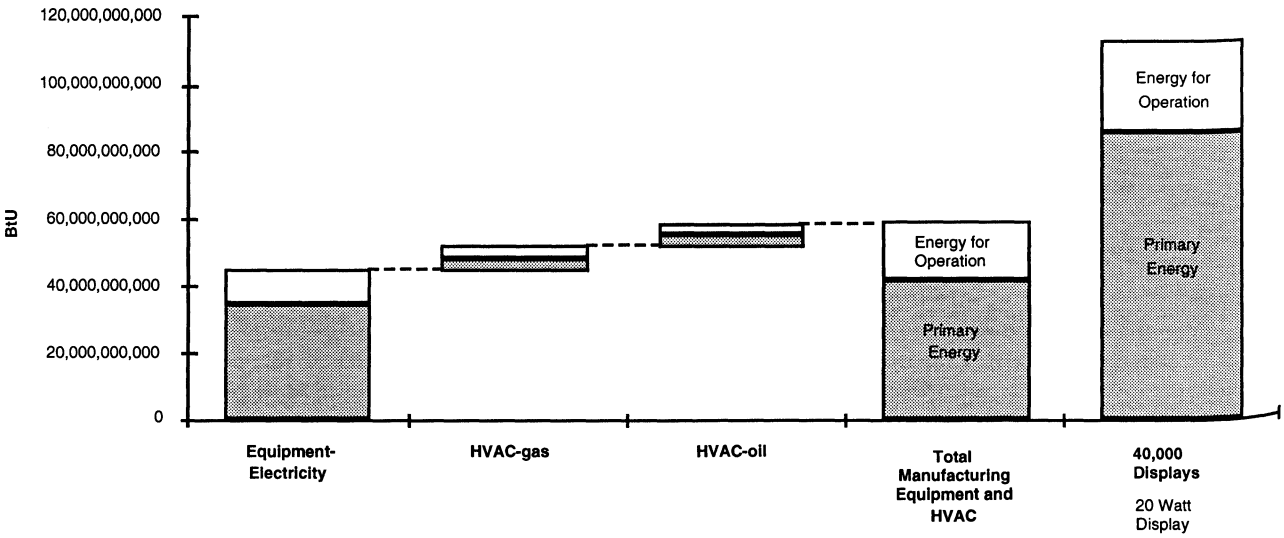


Fig. 3-8: Relative Magnitude of Energy Consumption from Production and Use

B. AIR QUALITY

Air quality issues associated with AMLCD manufacturing include the release of toxic and hazardous air pollutants, solvent exhaust, and acid exhaust. Most air pollutants are controlled via exhaust systems; however, it is important to note how these substances are characterized and how these gases degrade air quality.

Hazardous and Toxic Air Pollutants

Hazardous and toxic emissions from photolithography and chemical vapor deposition may present health risks to receptors in the vicinity of the plant. The fate of air pollutants is determined by many factors including stack height, release temperature, meteorological conditions, and the rate of emission. The concentration of a particular contaminant at a receptor is dependent upon its molecular weight as well as the other factors affecting plume concentrations including weather conditions, mixing height, and air stability. Each of the chemicals used at OIS' Northville facility is regulated under the Clean Air Act and may present a health risk if exposure reaches a certain level.

Solvent Exhaust

Solvent exhaust is generated from photolithographic process and produces volatile organic contaminants (VOCs). VOCs are also regulated under State and federal statutes because of the potential to react with other atmospheric gases to form photochemical smog. OIS' Northville permit application indicated that solvent emissions would not be significant enough to require the installation of pollution control devices. Appendix D contains data on the controlled and uncontrolled emissions rates of VOCs from the facility.

Acid Exhaust

Acid gases are produced from etching and photolithography processes that use phosphoric, hydrochloric, and nitric gases among others. These substances are of concern because of their potential health risk to workers and local populations, ecosystems, and degradation of buildings. Appendix D contains data on the controlled and uncontrolled emissions rates of acid gas from the .

C. GLOBAL CLIMATE CHANGE

Global Warming

A greenhouse gas is one that is transparent to incoming solar radiation but traps long-wave infrared radiation. The primary greenhouse gases are water vapor and carbon dioxide. Ozone (O3), methane (CH4), and nitrous oxide (N2O) are also considered greenhouse gases, but they contribute only 5% to the greenhouse effect.[62] These gases trap heat in the atmosphere by absorbing infrared radiation from the Earth. Although the long-term effects and interactions with other pollutants are yet unknown, chemicals with extremely long lifetimes and the ability to absorb long-range radiation coming from each are being emitted into the atmosphere every year by electronics manufacturers.[62]

Global warming gases such and carbon tetraflouride or tetraflourmethane (CF_4), hexaflorehane (C_2F_6), nitrogen triflouride (NF_3), sulfur hexaflouride (SF_6), methane (CH_4), C_3F_8 (Freon 38) and nitrous oxide (N_2O) will be used in OIS' Northville facility for a variety of purposes including chemical vapor deposition, etching, and cleaning chambers. These chemicals have each been determined to have a Global Warming Potential (GWP) based on the atmospheric lifetime of a chemical and its infrared absorption spectrum relative to carbon dioxide. Table 3-5 presents the GWPs for each of these PFCs. Fig. 3-9 depicts the relative impact from the use of these chemicals to the use of fossil fuels from energy to power the equipment and HVAC at OIS's Northville facility. The CO_2 emissions are based on the cumbustion (i.e., emissions associated with pre-combustion not included) of fuels to provide energy to power equipment and HVAC system. The GWP is based on pounds of emissions for a year of operation.

The semiconductor and flat panel industry use perflouro carbons because their stable nature as a feed gas eliminates the need for special handling and delivery equipment when used in radio frequency (RF) based plasma systems.[62] Dissociation of the PFC gas in an RF field under low-to-moderate process pressures provides the free fluorine and CF radicals necessary to initiate thin-film etching. PFCs are also used for in-situ cleaning of PECVD tools resulting in more reproducible and predictable deposition processes.[62] In addition, PFC are nonflammable and non toxic because of their stability and low reactivity making these class of gases even more attractive to AMLCD manufacturers. SEMATECH reported that PFC emission rates associated with semiconductor manufacturing are small portion (5 to 10%) of global emissions.[62] In a similar vain, research by AirProducts concludes that the actual ratio of temperature rise for all PFCs emissions relative to CO_2 is estimated to be $1.4x10^{-4}$ by the year 2010.[63]

TABLE 3-5:

Global Warming Potentials

CHEMICAL	LIFETIMES (YEARS)	GWP (100 YEARS)
CF4	>50,000	10,900
C2F6	>10,000	11,500
NF3	<179	24,200
SF6	3,200	21,000
C3F8	>10,000	N/A
CO2	120	1
CH4	10.5	11
CFC-11	55	3400
CFC-12	116	7100
N2O	132	270

SOURCE: SEMATECH

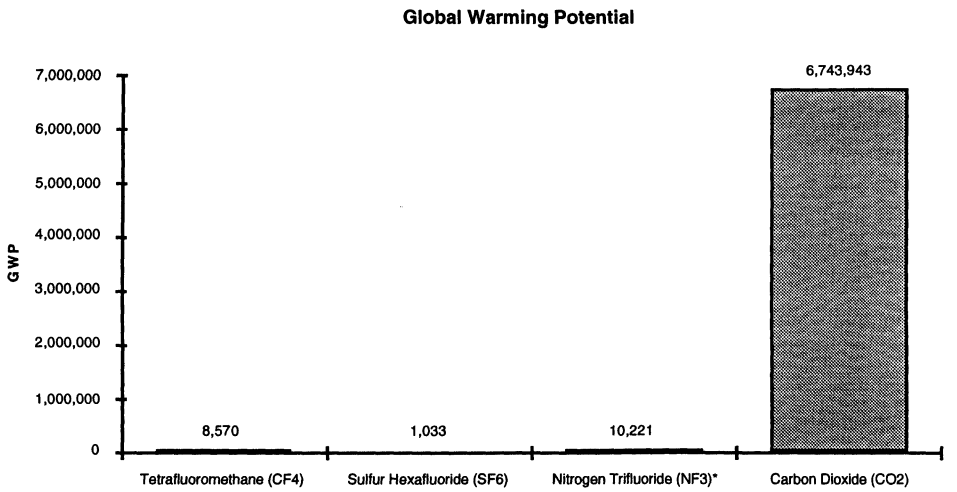


Fig. 3-9 GWP (Based on lbs. of emissions) from OIS Northville Plant

Ozone Depletion

At the top of the stratosphere, where ultraviolet radiation is intense, CFC molecules begin to dissociate and release energetic chlorine atom. These chlorine atoms then react with O_3 to release a molecule of oxygen, resulting in ozone depletion. It is believed that some of these reactions occur continuously, therefore, one Cl atom may destroy many ozone molecules. The destruction of the ozone layer in the stratosphere may present a health threat to inhabitants of earth because of increased solar radiation leading to skin and eye problems and potentially other ecosystem impacts.[62]

With a thinning of the protective ozone layer, the Earth is hit by more of the sun's radiation and more radiation is potentially reflected back to the Earth. In addition, CFC molecules also absorb the long-wave radiation. The CFCs essentially block the release of infrared radiation and thereby disrupt the heat balance of the Earth. However, ozone is also a greenhouse gas, therefore warming by CFCs may be offset by cooling from stratospheric ozone depletion; diminished amounts of ozone decrease the amount of solar and long-wave radiation absorbed. The net effects of ozone depletion on global warming depend on where in the atmosphere the ozone is destroyed.[62]

OIS has changed a number of its cleaning operations to avoid using CFCs, however, the chillers used to produce air conditioning and process cool water may contain either CFCs or HCFCs. HCFCs are currently acceptable substitutes for air conditioning under EPA's significant new alternatives program or SNAP as of March 18, 1994.

D. RESOURCES DEPLETION

Water Use

OIS' Northville facility will use roughly 460 gallons per minute of water for air conditioning and process cool water and 100 gallons per minute for DI water production (recirculating/recycling rates are not know). This rate of use results in a huge demand for municipal water over the lifetime of the facility. The impact of this demand is relative to the area in which the facility is built and the capacity of local water systems to supply this rate of flow to OIS. Fig. 3-10 summarizes the rate of water use at the OIS facility for three different recirculation rates.

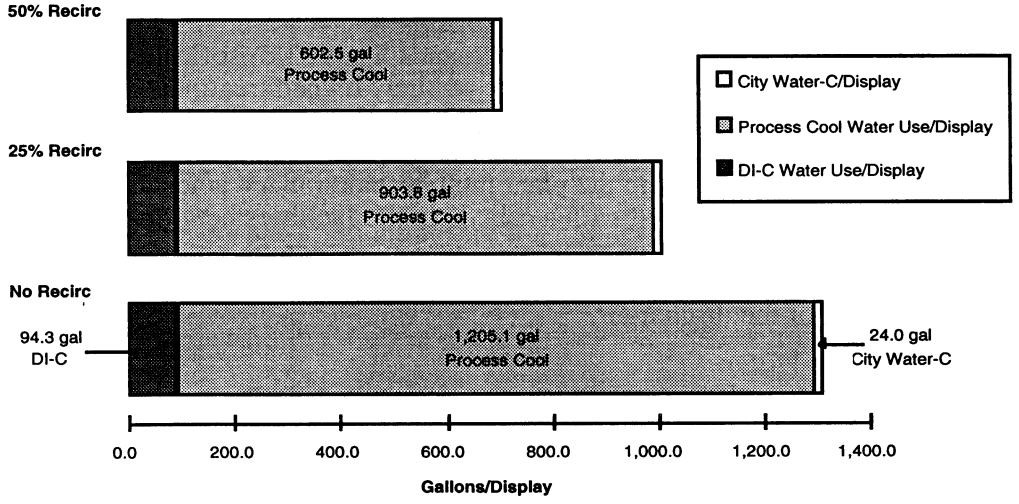


Fig. 3-10: Water Consumption Rates

Non-Renewable Energy Consumption

Due to the energy intensity of AMLCD production, OIS will consume a tremendous load of energy produced from non-renewable resource supplied by Detroit Edison. As discussed above, the impact of this consumption is primarily the emission of CO2, sulfur oxides, and nitrogen oxides and the impacts range from global warming to acid rain affecting populations at local, regional, and global levels.

E. LAND USE DEVELOPMENT

Location of Facilities

The construction of a AMLCD factory may have several impacts on land use development. Specifically, the facility will increase the number of industrial buildings in a particular area and increase traffic of cars commuting to the area, maintenance vehicles, and delivery/disposal trucks. Community safety/protection from accidents are a critical issue to be addressed in case of emergencies.

F. SOLID AND HAZARDOUS WASTE

Solid Wastes

AMLCD manufacture does not generate a large quantity of solid waste. Solid waste streams include scrap glass and packaging materials received from suppliers.

Hazardous Wastes

Hazardous waste resulting from the manufacture of AMLCDs include solvents used in cleaning agents, spent photoresist materials, and heavy metals used for metalization processes. OIS is responsible for storing the solvent wastes from the photoresist processes in tank and transporting them to a RCRA registered facility. The fate of the solvent is arranged by the company that transports the chemicals, Federal Environmental. Currently these chemicals are refined by a chemical company in Georgia and sold as a waste fuel to a cement kiln operator. Pump oil, Fromblin™ or Crytox™, must also be disposed of as a hazardous waste or sent back to the manufacturer.

G. WATER QUALITY

Effluent Discharges

The AMLCD manufacturing process demands a large flow of water. This water is used on site and is ultimately discharged into the publicly owned treatment works of the Detroit metropolitan region. Based on OIS's status as a semiconductor manufacturer, the company is required to obtain a permit and prove its discharges are meeting strict water quality requirements. The effluent from the plant includes neutralized acids and metals and solvents. The metals and acids are treated with a caustic in the facilities neutralization system, therefore, the effluents impact on water quality is mitigated before leaving the facilities boundaries. Environmental impacts beyond this point are external to OIS and not currently the responsibility of the discharger.

Impact on Surface Water

Leaking storage tanks or accidental releases of chemicals could result in impacts to surface water (or soils). OIS's facility has a structure that protects its on-site, above ground solvent storage tank from weather that can lead to erosion and controls run-off in case of spills.

H. HUMAN HEALTH & SAFETY

The semiconductor industry has received attention over the past decade for a number of human health and safety related issues including the use of ethylene glycol ethers (EGE), pyrophoric gases, and toxic hydride gases. Several studies have documented the effects of clean room environments, specifically where glycol ethers are used, on the reproductive health of employees. Studies by Johns Hopkins University (JHU) for IBM and University of California, Davis (UCD) for the Semiconductor Industry Association both reported on the extent of the human health risk posed by working in silicon based semiconductor cleanrooms. The JHU study concluded that their were no consistent, statistically significant differences in the rates of miscarriages among women working in IBM clean rooms when compared to IBM employed women working in non-manufacturing areas. There are no differences in the rates of miscarriages among pregnancies to the wives of men working in clean room environments as compared to the wives of men working in other manufacturing jobs. There were no adverse effects of material or paternal employment in clean room areas compared to non-clean room areas with respect to rates of preterm delivery, low birthweight, birth defects, and infertility or subfertility. However, there was an increased risk of

miscarriage in pregnancies among women working on processes that require use of EGE-based photoresist mixtures compared to women working on other processes within the clean room. It is estimated that less than 10% of the miscarriages among all pregnancies to female clean room employees might be attributable to work with processes requiring EGE use.[64]

The UCD study concluded that work in semiconductor fabrication facilities was associated with an increased rate of spontaneous abortion (miscarriage). The average magnitude of this increase is approximately 240 to 560 basis points over the average rate or 12 to 14%. There was a suggestion that rates were higher in photolithography and etching areas but this was not consistently observed. Exposure to EGEs are likely causal agents of the miscarriages; however, exposure to other photoresist/developer chemicals could have contributed to the miscarriages. In addition, a reduced conception rate was observed among women in fabrication work compared to non-fabrication work. Other significant health effects identified by UCD include an increase in upper respiratory symptoms, musculoskeletal symptoms such as hand, wrist, elbow and forearm pain, and dermatitis and hair loss were reported frequently.[23]

Pyrophoric gas use, mainly silane, is a major concern to manufacturers in the semiconductor and flat panel industry. A recent benchmarking survey was conducted by SEMATECH to identify silane safety strategies by users, distributors, and suppliers. The use of limiting flow orifices may prevent explosions but further testing is needed for standardization. Point of use generation offers potential distribution safety, but is not yet practical. Bulk delivery may appeal to large volume users, but system designs need to be developed. Losses due to silane have dropped to $1.66MM from 1989-1993.[65]

Toxic hydride gas use for doping processes such as phosphine is also of concern to the industry because such gas is an extreme respiratory irritant and can be lethal. Work has been done on arsine and phosphine replacements and the use of benign precursors or in-situ generation of gas to avoid health problems associated with the use of these materials.[66][67][68][69][70] Table 3-6 provides and overview of the primary health hazards of chemicals and radiation used in semiconductor/flat panel manufacturing.

TABLE 3-6

Primary Health Hazards

PROCESS	SUBSTANCE	PRIMARY HAZARD
Cleaning	Sulfuric Acid	Chemical Burns
	Hydrochloric Acid	Chemical Burns
Wet Etching	Hydrofluoric Acid	Chemical Burns
	Acetic Acid	Eye and Respiratory Irritation
	Phosphoric Acid	Chemical Burns
	Nitric Acid	Chemical Burns
Plasma/RIE Etching	Carbon Tetrachloride	Liver and Kidney Damage
	Carbon Tetraflouride	Anesthesia
	Chlorine	Eye and Respiratory Irritation
	Sulfur Hexaflouride	Asphyxiation
	RF Radiation	Thermal Damage
Photolithography	Xylene	Narcosis, Liver and Kidney Damage
	n-Butyl Acetate	Eye and Respiratory Irritation
	UV Radiation	Erythema, Skin Cancer
Photoresist Stripping	Organic Acids	Chemical Burns
	Alkyl Benzenes	Nacosis, Liver and Kidney Damage
	RF Radiation	Thermal Damage
Doping	Diborane	Respiratory Irritation
	Phosphine	Respiratory Irritation
	Phosphorous Oxychloride	Respiratory Irritation
	X-Ray Radiation	Cancer
Pre-CVD Clean	Hydrochloric Acid	Chemical Burns
	Sulfuric Acid	Chemical Burns

Source: Baldwin and Stewart, 1989

IV. ENVIRONMENTAL LAWS AND FUTURE TRENDS

Management must remain abreast of current legislative, regulatory, and administrative policy developments so that the operations of the firm will remain in compliance environmental laws and regulations. Three key issues that OIS should keep on its radar screen include phase-out of PFC use, product take-back, and carbon taxes.

A. PFC REDUCTION

Based on interviews with officials from SIA and EPA, the most likely action to be taken to reduce PFC emissions is a Memorandum of Understanding to reduce greenhouse gases to 1990 emissions levels as specified by President Clinton's Climate Change Action Plan.[71][72] The program is targeting six long-lived greenhouse gases including: SF_6, NF_3, CHF_3, C_3F_8, CF_4, and C_2F_6.

The goal of the Climate Action Plan is to return to 1990 emissions levels by the year 2000. EPA is working on finding substitutes with a team from MIT that has evaluated 30 chemicals however none have proven effective yet. Recycling methods are also being explored by Proxair and AirProducts. In addition, process optimization techniques are also being targeted as a means to reduce emissions. EPA and SIA are committed to achieving these reductions have agreed to do so through a voluntary agreement.

B. TAKE BACK LEGISLATION

Discussions are ongoing in the US, Europe, and Japan regarding the most effective mechanism for promoting electronic-product disposition. The approaches range from mandatory means to a system that relies on market forces to establish the infrastructure needed for effective disposition.[73] State governments have initiated take back regimes including recent efforts such as: Wisconsin's legislature is working on encouraging recycling and reclamation schemes; New Jersey proposed a demanufacturing systems; Rhode Island won an EPA grant to create a self-sustaining disassembly, processing, and recycling center; and Texas has initiated discussions on establishing an integrated electronics recycling facility.[73]

Take back programs have received attention internationally as well. Germany drafted take-back legislation for electronics products that requires manufacturers to reclaim products after their useful life. Although this law has not been passed, the program is similar to packaging laws recently promulgated that require manufacturers to reclaim product packaging. Germany has also proposed that consumers should pay for disposal of products. In contrast to Germany's approach, MCC found that most foreign actions have focused on municipalities through infrastructure improvements or through government programs to use more environmentally sound practices rather than legislation.[73] OIS should be cognizant of the take back movement so that design issues related to disassembly and product end-of-life management are addressed in a timely fashion.

C. CARBON TAXES

Carbon taxes have been considered for years but have been dismissed in favor of other less politically contentious and administratively expeditious programs. Proponents of a carbon tax argue that taxing the carbon content of coal, oil, and gas would raise enough revenue to wipe out much of the budget deficit and simultaneously restrain energy consumption. The Council of Economic Advisers suggested that a tax of $28 per ton of carbon might raise $163B over five years and stabilize America's output of greenhouse gases in the 1990s. Opponents argue that taxes are inflationary, regressive, and harmful to the country's competitive position abroad.[74]

Based on OIS's high degree of energy intensity, carbon taxes may be of material concern. The objective of the tax would be to encourage investment in alternative technologies that conserve energy. OIS's ability to make process changes or use alternative energy sources is limited by a number of factors including its partnership with suppliers to develop low power tools, the installation of energy conservation devices in the clean rooms, and the availability of alternative energy sources from Detroit Edison.

V. PROCESS/OPERATIONS EXCELLENCE

This section describes a number of manufacturing issues that will have a substantial effect on the flat panel industries ability to improve environmental performance. The flat panel industry is actively engaged in technology development and deployment that will lead to increased efficiency because there are cost savings to be realized. These programs will have a synergistic affect on environmental performance—as efficiency improves, environmental burden may be reduced. The following manufacturing related topics are reviewed:

- Color filter application
- Materials usage reduction (e.g., photoresist usage)
- Yield/Defect Rate Control
- Equipment Utilization
- Semi-Aqueous and All Dry Processing
- Computer Integrated Manufacturing.

A. COLOR FILTER APPLICATION

An example of inefficient usage of an expensive material is the application of color filters to substrates using spin coater technology. Spin coating normally uses high-cost color filter materials (approximately $1000 per liter) or photoresist and coats a substrate while leaving a large percentage of the material on the tool's chamber walls to be flushed out and stored as spent solvent and later hauled away at some expense. Spin coaters waste as much as 98% of the material, may not handle large substrate sizes, and have low throughput rates.[75] Moreover, spin coating or roller coating may not be able to adequately coat large substrates; therefore, liquid extrusion coating has gained a significant level of interest. FAS Technologies under contract with SVG and funded by the United States Display Consortium, has developed a liquid extrusion coating process that is much better suited for high-volume flat-panel display manufacturing.

In contrast to spin coating where process fluids are dispensed onto a glass substrate and excess fluids are thrown off, extrusion coating emits liquid from a linear extrusion head that is moved controllably above the surface of the substrate. OIS collaborated with FAS Technologies to develop and test the technology that is capable of coating uniformities of roughly 1.5% on 380mm square substrates and in a wide range of thickness (1500Å to more than 100μ). In addition, substrates can be coated at speeds of 25 to 75mm per second faster.

From an environmental perspective the most important advantage of the extrusion coating technologies is that virtually 100% of the process fluid is used, thus there is essentially no material waste. Moreover, extrusion technology enables coating in selected areas of the substrate; thus, areas on the edge of the substrate may be excluded. A secondary impact of this level of efficiency is that disposal costs are reduced. Extrusion coating also enables the use of materials with higher stoichiometric solid content compared to spin coating resulting in a decrease in the amount of solvent that is vaporized and emitted into the atmosphere. The process fluids dispensed from an extrusion coater include photoresist, alignment layer polyimides, and color filter materials.[75]

Some simple calculations demonstrate that extrusion coating is a win-win proposition for businesses. In a spin coating operation 22 grams consumed in coating 1 part results in 21.7 grams of waste. [75] Whereas an extrusion process, which can coat three parts in the same time, consumes .3 grams in coating 1 part. In the case of polyimide coating SVG has calculated the following: 5 micron polyimide coating on 320mm square substrate; 6 substrates per minute process rate; color polyimide price of $1,000 per liter; spin coater uses 6 ml per coating with 20% utilization; and extrusion coater use .6 ml per coating with 90% utilization. Conservative process cost savings with extrusion coating result in $14 million per year. [75]

B. MATERIALS USAGE REDUCTION

The AMLCD manufacturing process is a materials and energy intensive process. The proportion of materials actually used in the final product is quite small. However, advancements in materials usage, and associate cost savings, are in many cases contingent

upon the available equipment or supply networks. Manufacturers are also wary of employing new technologies that may improve material efficiencies but have not been proven in a manufacturing line. The risk of installing a new process tool that does not meet specifications is high considering the fiscal pressures already burdening most producers of flat panel displays.

Although there are challenges to overcome, manufacturers and equipment suppliers will still seek to improve material use efficiencies. MCC investigated the chemical photoresist process to demonstrate the point that semiconductor manufacturing (similar to many flat panel process steps) does not use materials efficiently. MCC determined that the actual amount of chemical purchased far exceeded the actual amount required by formulation and equipment specifications. The excessive amount purchased was determined to be the result of both over formulation during application and an inventory problem resulting from short shelf life of the chemical. Inventory methods were evaluated, and the potential savings were estimated to be about 40% of the total purchases cost of the photoresist material. Photoresist is one of the most expensive chemicals to buy and one of the most expensive to dispose of.[28] Fig. 3-11 shows the discrepancy between the amount purchased and the amount used.

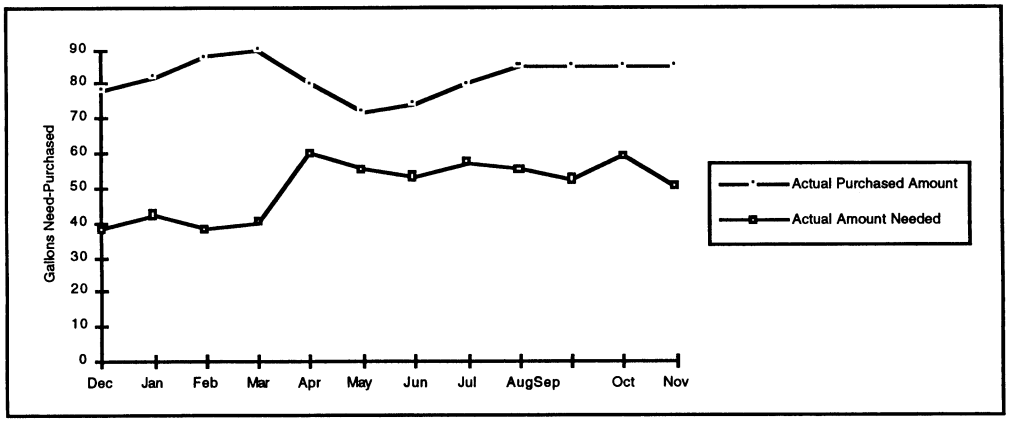


Fig. 3-11: Efficiency of Photoresist, Amount Purchased vs. Amount Needed

C. YIELD/DEFECT RATE

A critical issue and manufacturing challenge facing the flat-panel industry is the yield and defect rates currently achievable with existing process tools and "know-how." AMLCD manufacturers reported yield rates around 10% when production began in the 1980s. Japanese manufacturers have reportedly reached the 90% range. Business interest alone will drive research to improve yield, and by doing so, minimize the environmental burden of the product system.

A multitude of manufacturing issues may impact the yield and defect rates achievable by AMLCD manufacturers including:

- Detection, inspection, and repair methods
- Real-time controls
- Particle control.

Detection, Inspection, and Repair

In-process testing is required to prevent assembly of faulty panels. Finding defects after final assembly is expensive since the entire panel must be thrown away. Many of these defects are shorts and opens that occur in the deposition of conductors for the TFT circuits and pixel electrodes on the glass substrate of the display. Defects also commonly occur in the color filter or the assembly process. Testing should detect all these defects during manufacturing and pinpoint the causes so that the process can be altered to prevent them.[7]

One method developed to improve yield is laser repair. Repairs are often needed to correct shorts and open defects. Shorts usually occur as a result of contamination affecting the photolithography and etch steps. Open defects and shorts can occur at the assembly stage of manufacturing as well. Recovering panels at this stage is critical to achieve profitability because the display has gone through most of the process steps needed to produce the flat panel. Electrostatic discharge is the principal cause of opens. If an open is detected in a primary metal line, a laser is used to connect the redundant line. Laser techniques such as those developed by Florod, Signatone, and Photon Dynamics assist flat panel manufacturers in repairing defects as throughout the production process, thereby conserving energy, materials, and resources used to produce the panel.[76]

Other methods for inspection and repair operations include electrical open/short tests, optical inspection, charge sensing, hot electron mapping, forward admittance sensing, and voltage imaging. Automated Optical Inspection (AOI) is used because electrical testing is not possible before the array is completed. AOI may be performed for each deposition, photolithography, etch and strip. Engineers can then identify the major defect sources and adjust processes to eliminate problems.[77] To meet display manufacturers needs, AMLCD inspection equipment must be: Automated and work in-process to maximize reliability and throughput; and quickly and accurately measure voltages on the active panel without imparting defects during inspection (as happens when contacting a displays surface with probes).

Real Time Controls

Real-time, sensor-based feedback control is a key enabling technology. The benefit of real-time control is that the manufacturing process is guided or "steered" by computer assisted programs. Steerable manufacturing processes are accomplished by using sensors in-situ, ex-situ, and post-process. Statistical process control and run-to-run analysis also helps to steer the process tools to achieve a more efficient manufacturing system. Although these concepts are applied in aerospace, chemical, and power industries the semiconductor industry (hence the flat-panel industry) has not developed viable real-time control mechanisms. Real-time control has the capability to improve semiconductor manufacturing by:

- making smaller devices possible
- reducing run-to-run variability
- simplifying specification of "process recipes," and improve transportability and scaling
- maximizing throughput
- increasing yield.

For example, control of reactive ion etching process through real-time mechanism could: stabilize etch rate, control selectivity, control side wall angles, and achieve uniform etching across the substrate. However, many difficulties exist in applying real-time controls, including:

- lack of sensors
- lack of direct actuators
- lack of control oriented models for the process
- lack of computer architecture to support multivariable real-time control.

Particulate Control and Minienvironments

Particle control in-situ, the cleanroom, and minienvironments (where used) is a priority concern for manufacturers of flat panels. The presence of particles on a substrate may result in a number of defects, thus decreasing product yield.

As defined by SEMATECH/SEMI/JESSI, minienvironments are composed of three elements: an isolation enclosure for the process or measurement tool coupled with a source of clean air or other gas environment for the isolation enclosure, a container or pod to hold and transport product, and an I/O device to extract parts from the pod or container and present them to the process tool. The most apparent an widely applied benefits of minienvironments are their ability to reduce the environmental volume that must be controlled and their ability to isolate process tools and substrates from particulate contamination. Minienvironments may also offer the following benefits:[78]

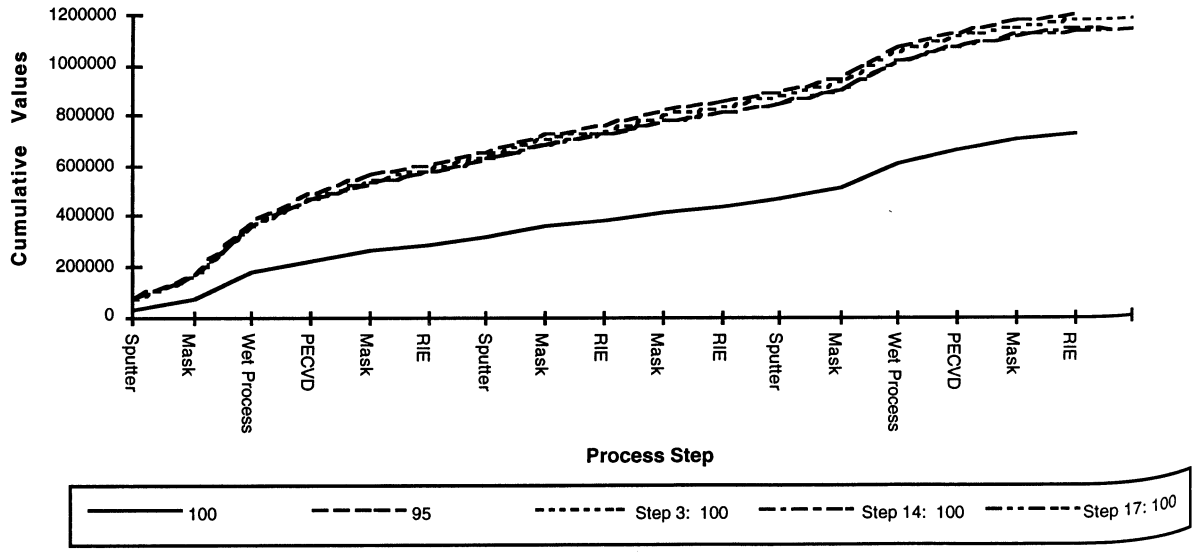
- storage of substrates in an inert gas environment
- flexibility allowing flat panel manufacturers the ability to alter process tool sets and support several generations of product advancement
- elimination of the need for new air-handling and contamination control systems thus reducing energy demand
- immunity to overhead or floor-based contamination
- reduced footprint, faster substrate access time, and accurate substrate positioning mapping as a result of direct integration of the i/o function with the cassette indexing function
- protect worker health and safety by affording a direct channel for exhausting the process tool air into a separate exit path, thus preventing chemical fumes from mixing with general cleanroom air recirculation patterns.

Yield Testing

Appendix E contains the results of a spreadsheet model developed to measure how sensitive environmental performance is to yield. The analysis uses a generic approach for constructing active devices and color filters described by OMara.[17] Each grouping of process steps is modeled using the utilities matrix of OIS's pilot demonstration facility. The model uses the aggregate values for all of the tools in a process area to model a particular phase of the AMLCD fabrication process. In doing do, the models assumes that each substrate must go through all of the tools in a cluster to complete each phase of the process. As a base case, each process step is assumed to have a 95% yield. The number of substrate starts is based on the assumption that OIS will manufacture 40,000 substrates at year end. Given these parameters, the base case assumes a yield of 57% for color filters and 40% for active devices. Sensitivity analyses were also conducted on each process phase. Yields for processes were increased sequentially to determine which process had the greatest impact on the overall performance of the system. Appendix E provides the results of the evaluation.

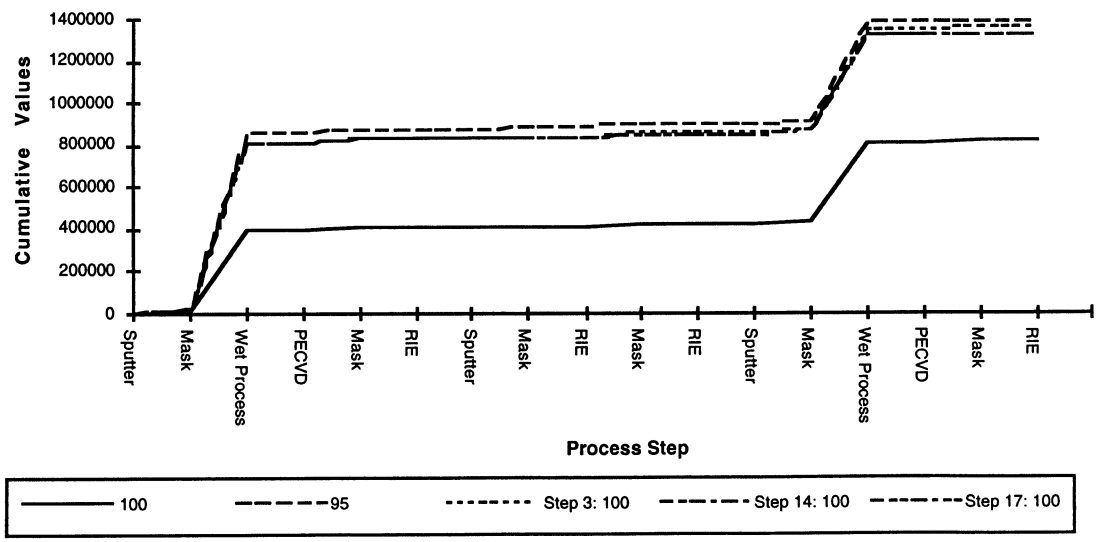
The analysis indicates that energy and water use is reduced as yields improve. The data provided in Appendix E demonstrate how improved yield rates will lead to greater overall environmental performance. As Fig. 3-12 through Fig. 3-15 depict, the analysis revealed that improving yield on process steps later in the production process decreased energy and water use slightly more than improvements that increased yield at earlier stages. The analysis also

indicated an intuitive result—a 100% yield rate is the least environmentally burdensome given the system's current performance.



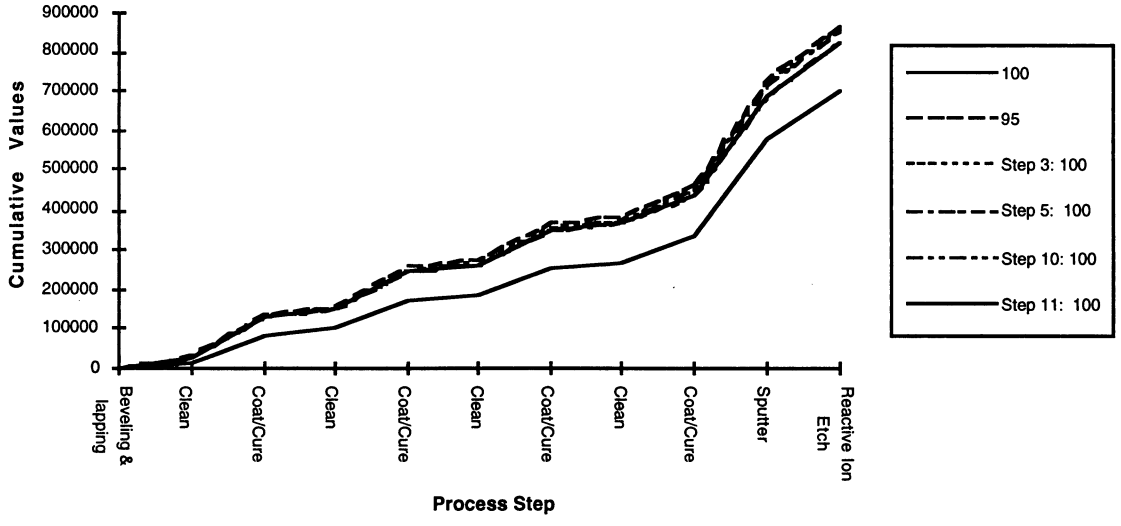
Cumulative Values are in KwH. Legend denotes yield rate (%). Where individual steps are shown to have 100% yield rate, the other steps are assumed to have 95% yield rates.

Fig. 3-12: Active Device Energy (KwH) Consumed Based on Varying Yield Rates



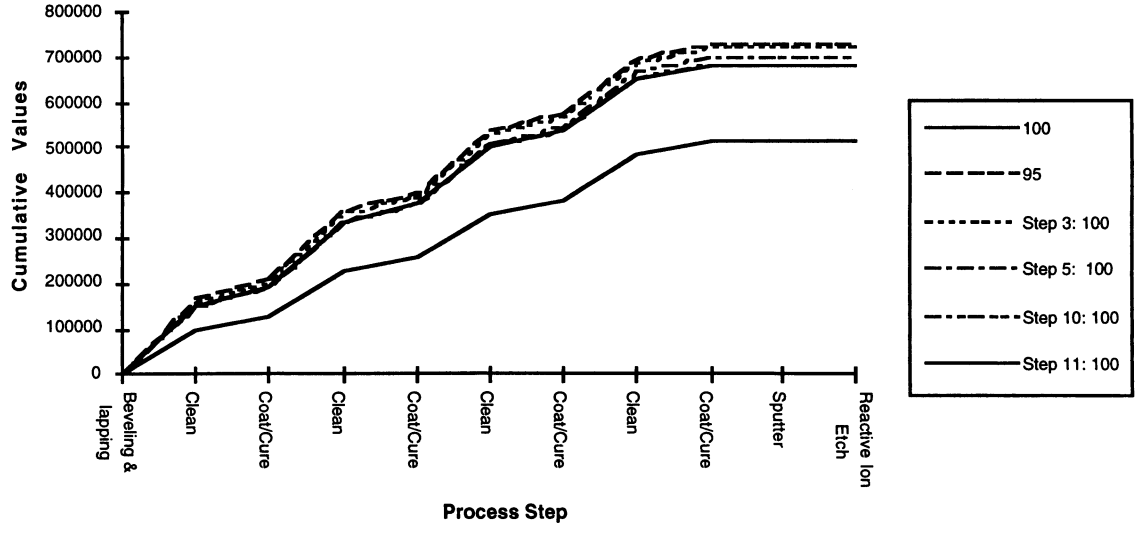
Cumulative Values are in Gallons. Legend denotes yield rate (%). Where individual steps are shown to have 100% yield rate, the other steps are assumed to have 95% yield rates.

Fig. 3-13: Active Device DI Water Use (Gallons) Based on Varying Yield Rates



Cumulative Values are in KwH. Legend denotes yield rate (%). Where individual steps are shown to have 100% yield rate, the other steps are assumed to have 95% yield rates.

Fig. 3-14: Color Filter Energy (KwH) Consumed Based on Varying Yield Rates



Cumulative Values are in Gallons. Legend denotes yield rate (%). Where individual steps are shown to have 100% yield rate, the other steps are assumed to have 95% yield rates.

Fig. 3-15: Color Filter DI Water Use (Gallons) Based on Varying Yield Rates

The analysis also indicated which process areas resulted in the greatest amount of environmental burden. For example, improving the yield rate in the early stages of active device formation is critical to reducing DI water use. At the beginning of the active device formation a wet process pass is completed for each substrate; thus requiring large amounts of DI water. The environmental burden is intensified because excess substrate starts are needed

to meet a 40,000 per year output of on-spec substrates because of yield losses throughout the system.

D. Equipment Utilization/Throughput Control

Flat panel display and semiconductor manufacturers face a number of similar problems in terms of throughput due to process steps that cause "bottlenecks" in the production line such as chemical vapor deposition, reactive ion etching, and photolithography exposure of large area substrates.

Optimizing equipment utilization rates will result in improved environmental performance because machine unproductive, up-time is limited resulting in a decrease in non-productive use of energy to support machines and the clean room environment. Improvements including the use of optimal batch sizes, more efficient cluster tools, and improved handling and automation systems will lead to improved equipment utilization.

E. Semi-Aqueous and All Dry Processing

All dry processing techniques eliminate the need to use a number of acids used for wet etching and solvents used for cleaning. Process steps that are effective replacements to wet processes are reactive ion etching and ultrasonic or UV ozone clean technologies. Although there are environmental issues associated with each of these processes, the amount of materials consumed and disposed of are reduced considerably. However, the shift to all dry processes, particularly in the case of RIE, presents a new host of environmental issues such as the use of global warming gases.

Much research has been conducted on the replacement of cleaning agents such as CFC-113 because of their effect on the ozone layer. Companies that have replaced these cleaning processes with less environmentally harmful techniques, such as AT&T, have found that they are able to achieve cost savings as well. However, one issue of concern in the use of substitute cleaners is the safety/flammability of substitute materials. Although a significant environmental burden has been reduced, other risks have been introduced to the manufacturing environment.[79]

F. Computer Integrated Manufacturing

CIM is a distributed system architecture that integrates process information with the user's needs in a multilevel communication system. Information regarding process-control parameters, manufacturing recipes, scheduling , preventative maintenance tracking, statistical quality control techniques, data collection, and on-line equipment performance monitoring may be collected stored, and used for analysis.[28]

Processing equipment can be tied into a factory's local area network, as are workstations, so that there is easy access to functions such as factory planning, scheduling, simulation and modeling, report producing, WIP tracking, and performance monitoring. CIM supports flexible, just-in -time manufacturing, which enables the fab to better schedule all operations. If properly implemented it can increase equipment utilization, decrease WIP, and decrease cycle times. CIM is used not only to improve product quality, but to reduce chemical consumption thus generating less waste.[28] The use of CIM architecture can provide the necessary information to conduct mass balance assessments of individual processes thus providing a more complete inventory accounting of the inputs-outputs of the product system.

STEP 4: ENVIRONMENTAL IMPROVEMENT STRATEGIES

I. MULTI-CRITERIA REQUIREMENTS

II. FRAMEWORK FOR IMPROVEMENT

ENVIRONMENTAL IMPROVEMENT STRATEGIES

Step 4 contains two sections: Multi-criteria assessment and a framework for improvement strategies. The purpose of this section is to assist OIS in organizing its environmental improvement projects and for mobilizing the organization to implement programs that lead to environmental excellence.

I. MULTI-CRITERIA REQUIREMENTS

Multi-criteria assessment in the context of environmental management has been advocated by NPPC research on Life Cycle Design.[60][80] Life cycle design seeks to integrate environmental design requirements into the product development and management process. The life cycle design morphology includes the development of multi-criteria matrices that evaluate design requirements for cost, performance, legal and environmental criteria. Design criteria are broken down by life cycle stage including manufacture, use, and end-of-life management and by product system components including product, process, and distribution. Table 4-1 provides definitions of each element of the life cycle design morphology.

TABLE 4-1

Life Cycle Design Definitions

TERM	DEFINITION
Cost	Amount of money needed for specific functions or activities associated with the product system
Performance	Specifications and attributes required of a product or process to achieve functionality of a product
Environmental	Requirements that manage the input and outputs used throughout the product system
Manufacturing	Life cycle stage that refers to the process of converting raw or engineered materials in a product
Use	Life cycle stage that refers to the operation of a product throughout its useful life
End-of-Life-Management	Life cycle stage that refers to the disposition of a product at the end of its useful life
Product	Product system component that refers to all materials embodied in the final product
Process	Product system component that refers to all materials and energy used to convert inputs into usable product, support operation of the product in the use phase, and enable disposition at the end-of-life phase
Distribution	Product system component that refers to the means by which product or process materials are transported from one life cycle stage to the next

The purpose of using multi-criteria requirements is to organize improvement strategies and to highlight interactions or conflicts among criteria. Requirements matrices in conjunction with the results of the environmental profile are helpful for mapping out environmental categories in the prioritization scheme presented in Step 2. The matrices are also useful for evaluating which requirements impact customers directly versus in-house,

manufacturing issues and determining which requirements effect the functionality of the product versus the process for making the display.

Tables 4-2 through 4-5 present matrices for performance, environmental, legal, and cost criteria. Each matrix identifies high level requirements. In order for OIS to use the matrices, engineers and managers must develop second and third level requirements that define more precisely the specifications for each criteria.

TABLE 4-2

Performance Requirements Matrix

Product		
Manufacture	*Use/Service*	*End-of Life Management*
Meet State-of-the-Art Measures: - Diagonal - Pixel Format - Dot Pitch - Luminance (nits) - Response Time - Colors - Weight - Viewing angle - Resolution - Brightness - Contrast - Temperature Range - Ruggedness - Substrate • flatness and surface finish • reflectivity • static charge • exposure control - TFT • Ion , Ioff • capacitance • scan line resistance • stability • thickness - Aperture ratio - Channel threshold/voltage	- Extend the useful life of the display - Reduce power requirements - Reduce failure rate (MTBF) - Reduce mean time for service (MTTS) - Maintain reliability of reused products	- Enable reuse - Test components of reuse
Process		
Manufacture	*Use/Service*	*End-of Life Management*
- Increase efficiency of process tools: • set goals for deposition, sputtering, and etching processes - Cleaning effectiveness - Reduce Defect Rate, Increase Yield • open and shorts on metal interconnect • static charge - Lithography • uniformity of image quality • cleanliness • line width • switching accuracy • alignment • resist thickness - PECVD • particle control • metalization reproducibility • selectivity • film thickness • uniformity • machine cleaning	N/A	N/A
Distribution		
Manufacture	*Use/Service*	*End-of Life Management*
- Ensure protection of display	- Ensure protection of display	

TABLE 4-3

Environmental Requirements Matrix

Product

Manufacture	*Use/Service*	*End-of Life Management*
- Use environmentally safe glass - Use least toxic color filter material	- Ensure safety during operation	- Design displays that can be easily disassembled and reused - Ensure that metal constituents, liquid crystals, color filters, and polarizers are not hazardous - Develop methods to reclaim and reuse TFTs, color filters, or glass - Develop modular design - Reduce volume and weight of display - Enable easy disassembly of driver components

Process

Manufacture	*Use/Service*	*End-of Life Management*
- Minimize defect rate - Use energy efficient process equipment • Use mini-environments • Design clean room to maximize efficiency of HEPA - Reduce water usage • Re-circulate DI water • Capture excess water from DI water process for other processes • Re-circulate process cool water - Eliminate VOC emissions and health hazards throughout cleaning and photoresist processes • Reduce solvent usage or use alternative cleaning processes • Maximize efficiency of developer • Reduce use of NMP, acetone, PGMEA, HMDS, PUMA, and toluene - Reduce use of IPA • Use detergent, DI, or alternative method (e.g., ozone or ultrasonic) - Reduce acid use • Use dry processes when possible • Minimize quantities of NH4/HF, tartaric, phosphoric, nitric, and HCL acid - Use gases efficiently and safely • Replace hydride, toxic, and pyrophoric gases • Use CVD tools that maximize deposition of SiH4, PH3, NH3, and NF3 • Use state-of-the art gas delivery systems - Reduce emissions of global warming and ozone depleting gasses • Eliminate perflouro carbons from RIE process e.g., SF6, CF4 • Reduce CL2 and BCL3 emissions - Reduce particulate emissions from sputtering operations (e.g., metals) - Use energy efficient chillers and eliminate use of CFCs or HCFCs - Recycle/dispose of used pump oil - Handle, store, and dispose of solvents safely • recycle solvents • refine solvents for use in other application	- Reduce energy consumption - Maximize serviceability	- Develop efficient systems to recover, disassemble, and test displays

Distribution

Manufacture	*Use/Service*	*End-of Life Management*
- Require suppliers to reduce packaging - Require recycled content %	- Reuse packaging	- Develop infrastructure to reclaim displays

TABLE 4-4

Legal Requirements Matrix

Product		
Manufacture	*Use/Service*	*End-of Life Management*
- DoD specifications - Customer Contract Specifications	- Comply with FCC standards - DoD or customer requirements on performance parameters e.g., power, color, luminance, etc.	- Future regulatory programs • electronics take-back ordinance
Process		
Manufacture	*Use/Service*	*End-of Life Management*
- Uniform Fire Code, Building Codes, Mechanical Codes - Occupational, Safety, and Health Administration Regulations - Environmental Protection Agency Regulations and permits: • Clean Air Act • Clean Water Act • Resource Conservation and Recovery Act • TRI Reporting - Michigan regulations and permits - International Treaties/Certification • Montreal Protocol • UNEP • ISO - Liability/Insurance coverage - DoD requirements - Protocols set by trade associations such as USDC, SEMATECH, or SEMI • PFC gases will be voluntarily reduced by electronics industry	N/A	N/A
Distribution		
Manufacture	*Use/Service*	*End-of Life Management*
- DOT regulations and EPA regulations hazardous materials transport	N/A	N/A

TABLE 4-5

Cost Requirements Matrix

Product		
Manufacture	*Use/Service*	*End-of Life Management*
- Minimize amount of home scrap and pre-consumer scrap through improved yield and efficient processes - Minimize costs of materials: • glass • metals • color filters	- Meet competitive market price i.e., purchase price - Delivery must meet customer contract costs - Minimize service costs	- Retrieve residual value of retired products
Process		
Manufacture	*Use/Service*	*End-of Life Management*
- Reduce energy costs - Reduce water usage costs - Minimize cost of process materials and gases: • photoresist • developer • thinner • solvents • hydride gases • acids - Reduce costs associated with solvent disposal - Use recycled solvent and acids to reduce usage rates - Minimize potential liabilities e.g., storage and transport • gases • solvents • hazardous waste	- Minimize service costs - Minimize operating costs	- Reduce cost of recycling, reuse, or remanufacturing by using design for disassembly techniques
Distribution		
Manufacture	*Use/Service*	*End-of Life Management*
- Reduce cost of packaging - Use most economical transportation	- Reduce cost of packaging - Use most economical transportation	- Establish economical recovery system to reclaim displays

II. FRAMEWORK FOR IMPROVEMENT

Strategies for improvement may be organized into three categories: Incremental, Reengineering Solutions, and Future Approaches. OIS needs to manage its short-term environmental issues by employing incremental improvements, such as the extrusion coater or process control improvements that lead to increased yield; however, reengineering solutions that completely change the way displays are manufactured may also be considered by management.[81] Such solutions will consider the most efficient way to produce product. As OIS determines its strategies for "competing for the future," environmental performance should become a core business issue. Measures of energy, resource, and materials utilization should be considered as one of the indicators of how successful their operations will be in the future. Eliminating harmful process gases or materials will benefit the environment and human health and assist in transforming the manufacture, use, and disposal of flat panel displays. Future approaches should expand on the environmental benefits derived from incremental and reengineering approaches. Table 4-6 describes the framework for improvement from incremental, to reengineering, to future approaches.

TABLE 4-6

Continuum of Strategies

INCREMENTAL	REENGINEERING SOLUTIONS	FUTURE APPROACHES
Incremental improvements will positively impact environmental performance as materials and energy are used more efficiently.	*Reengineering solutions fundamentally change the way in which displays are manufactured including significant changes to the amount and type of materials, energy, and resources that are consumed.*	*Future approaches enable OIS to compete in a manner completely different than today.*
• Water usage • Energy consumption • Efficiency of materials use • Process control • Solvent recycling • Reduce power in use phase	• Reduce photolithography steps • Adopt new deposition technologies • Eliminate pyrophoric and toxic hydride gases • Eliminate use of solvents • Standardize driver circuits to facilitate recycling/reuse	• Invent new product • Specialize to take advantage of competence in a specific area of production such as chip-on-glass technology

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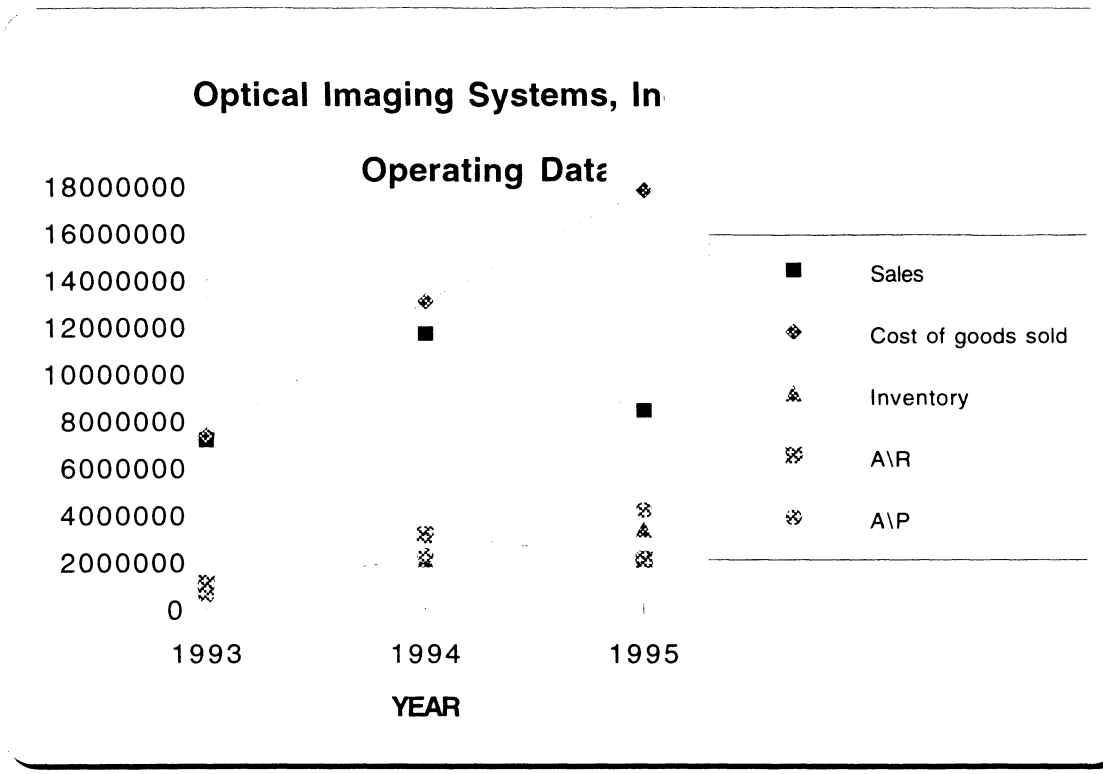
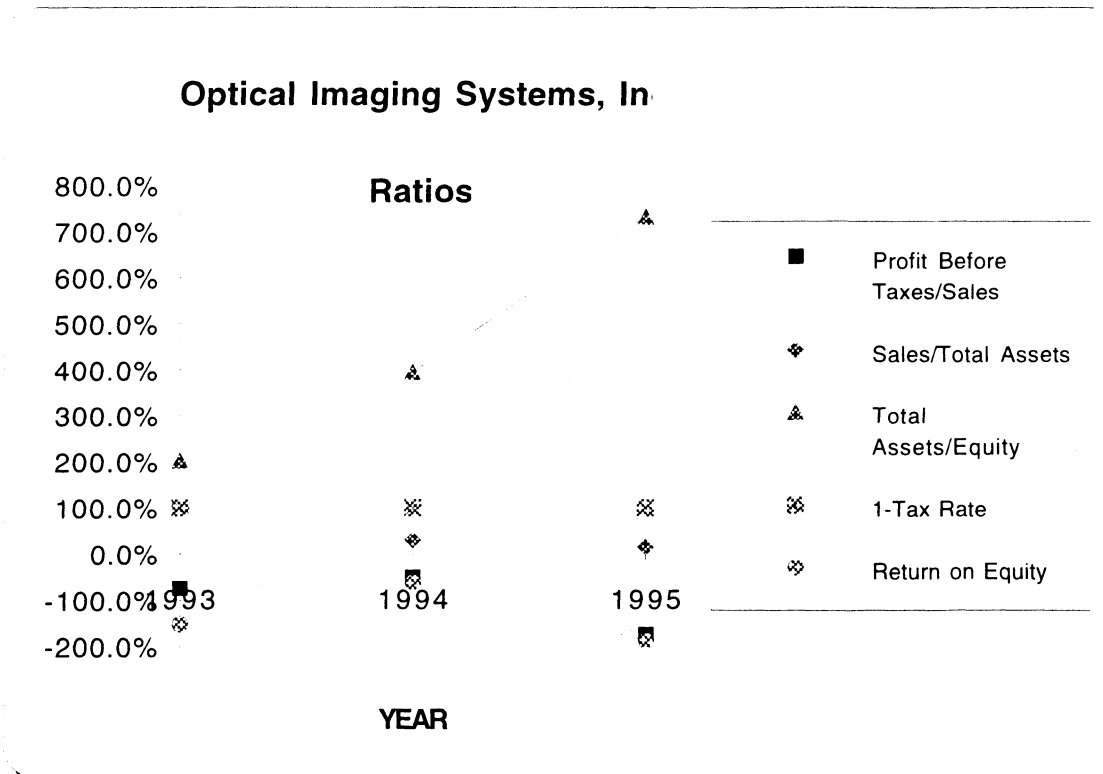
APPENDIX A: DUPONT DECOMPOSITION

	Optical Imaging Systems, Inc.	1995	1994	1993
	Return on Equity			
	Return on Equity	-187.1%	-60.8%	-151.6%
=	Profit Before Taxes/Sales	-173.7%	-50.0%	-74.1%
x	Sales/Total Assets	0.15	0.31	1.01
=	Return on Assets	-0.26	-0.15	-0.75
x	Total Assets/Equity	7.32	3.96	2.02
x	1-Tax Rate	1.00	1.00	1.00
	Return on Sales			
	Return on Sales	-173.7%	-50.0%	-74.1%
=	Gross Profit/Sales	-111.4%	-11.8%	-2.5%
-	SGA/Sales	50.3%	31.3%	35.2%
-	Net Interest/Sales	0.1%	0.6%	3.2%
-	Tax/Sales	0.0%	0.0%	0.0%
	Turnover Ratios			
	Asset Productivity (Sales/Assets)	0.15	0.31	1.01
	Days Inventory (365 x Inventory/CGS)	68.86	58.15	53.20
	Days Receivables (365 x A\R/Sales)	90.87	97.93	54.72
	Days Payable (365 x A\P/CGS)	85.63	62.71	28.98
	Other			
	Sales Growth	-28.0%	63.4%	30.6%
	Debt Ratio	0.86	0.75	0.51
	Cash Flow Adequacy	-0.59	-0.35	-3.66
	Sustainable Growth	-1.87	-0.61	-1.52
	Asset Quality Ratio	0.09	0.17	0.16


Optical Imaging Systems, In
Operating Data
18000000
16000000
14000000
12000000
10000000
8000000
6000000
4000000
2000000
0
1993
1994
1995
YEAR
Sales
Cost of goods sold
Inventory
A\R
A\P


Optical Imaging Systems, In
Ratios
800.0%
700.0%
600.0%
500.0%
400.0%
300.0%
200.0%
100.0%
0.0%
-100.0%
-200.0%
1993
1994
1995
YEAR
Profit Before Taxes/Sales
Sales/Total Assets
Total Assets/Equity
1-Tax Rate
Return on Equity

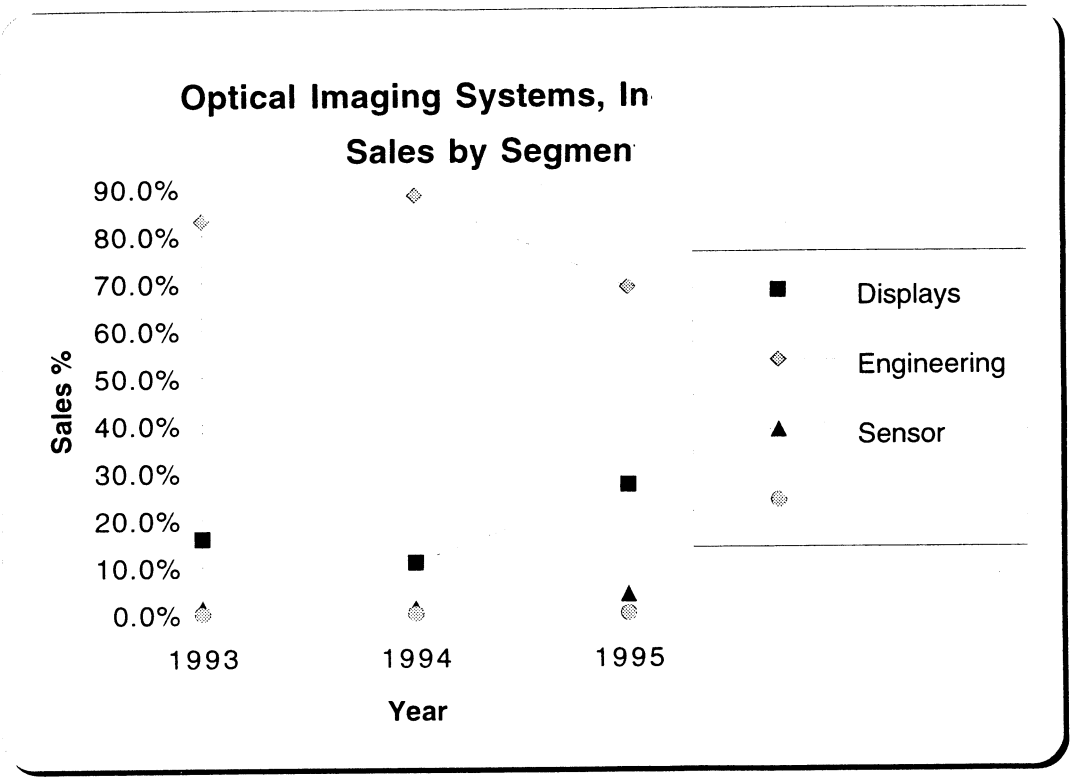
Optical Imaging Systems, Inc.
SEGMENT ANALYSIS

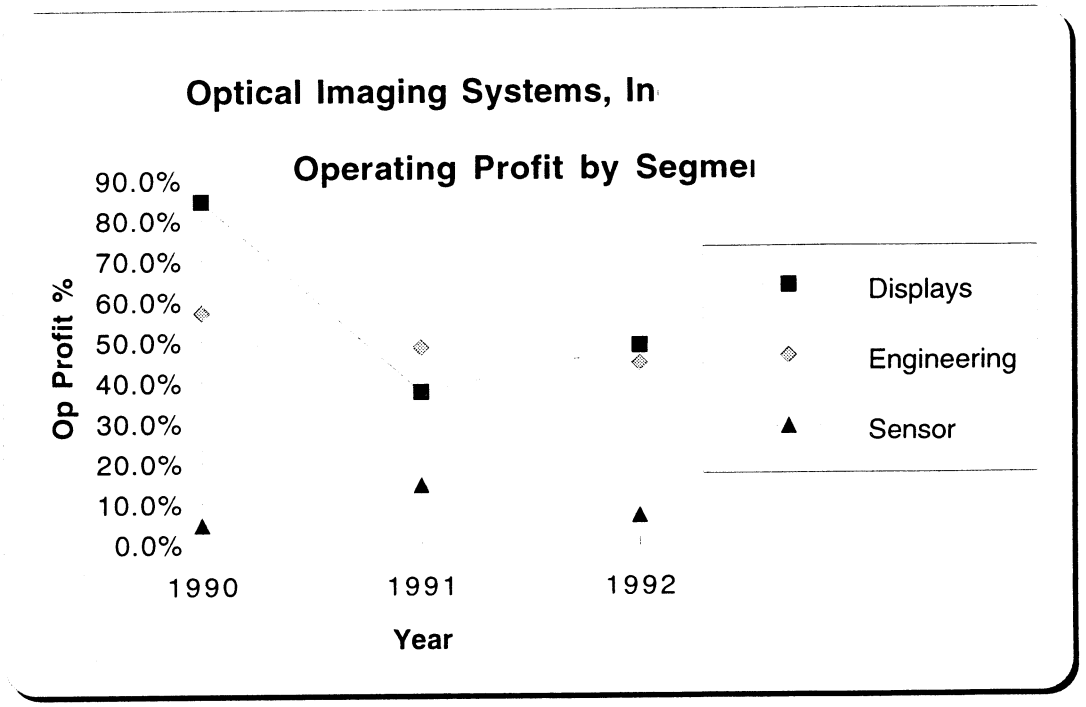
Panel A: Importance of Segments

	1995		1994		1993	
	Sales %	Op Profit%	Sales %	Op Profit%	Sales %	Op Profit%
Displays	27.2%	48.8%	10.7%	37.4%	15.9%	84.5%
Engineering	68.9%	44.4%	88.2%	48.3%	83.0%	56.9%
Sensor	4.0%	6.8%	1.0%	14.4%	1.2%	4.5%

Panel B: Ratios by Segment

	1995			1994			1993		
	PM%	ROA%	Turnover	PM%	ROA%	Turnover	PM%	ROA%	Turnover
Displays	-318.0%	-62.1%	19.5%	-170.3%	-37.9%	22.3%	-360.7%	-426.2%	118.1%
Engineering	-114.3%	-22.1%	19.3%	-26.8%	-19.2%	71.5%	-9.0%	-21.8%	241.5%
Sensor	-305.7%	-44.6%	14.6%	-677.6%	-74.7%	11.0%	-262.8%	-115.7%	44.0%


Optical Imaging Systems, In
Sales by Segmen
90.0%
80.0%
70.0%
60.0%
50.0%
40.0%
30.0%
20.0%
10.0%
0.0%
Sales %
1993
1994
1995
Year
Displays
Engineering
Sensor

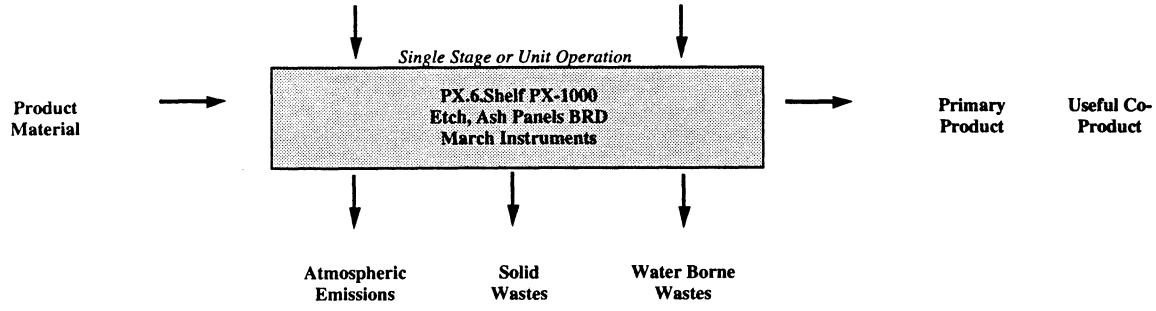

Optical Imaging Systems, In
Operating Profit by Segmei
90.0%
80.0%
70.0%
60.0%
50.0%
40.0%
30.0%
20.0%
10.0%
0.0%
Op Profit %
1990
1991
1992
Year
Displays
Engineering
Sensor

APPENDIX B: MATERIALS AND ENERGY ACCOUNTING

MATERIALS AND ENERGY ACCOUNTING

Process Stage: Active Photo/Plasma Ash Etch (68)

Energy		Process Materials	
Power Requirement (W)....	42100	*Material:*	CF4
		Quantity:	200 SCCM
		Cost:	
KVA.....	7.6		
		Material:	Process Cool Water
		Quantity:	.4 GPM
		Cost:	
		Material:	Oxygen
		Quantity:	1 LPM
		Cost:	
		Material:	Nitrogen
		Quantity:	.4 CFM
		Cost:	
		Material:	Argon
		Quantity:	.5 LPM
		Cost:	



Atmospheric Emissions		
Material:	Solvent Exhaust	
Quantity:	50 CFM	
Cost:		
Material:	CO2	
Quantity:		
Cost:		
Material:	CH	
Quantity:		
Cost:		

Metrics

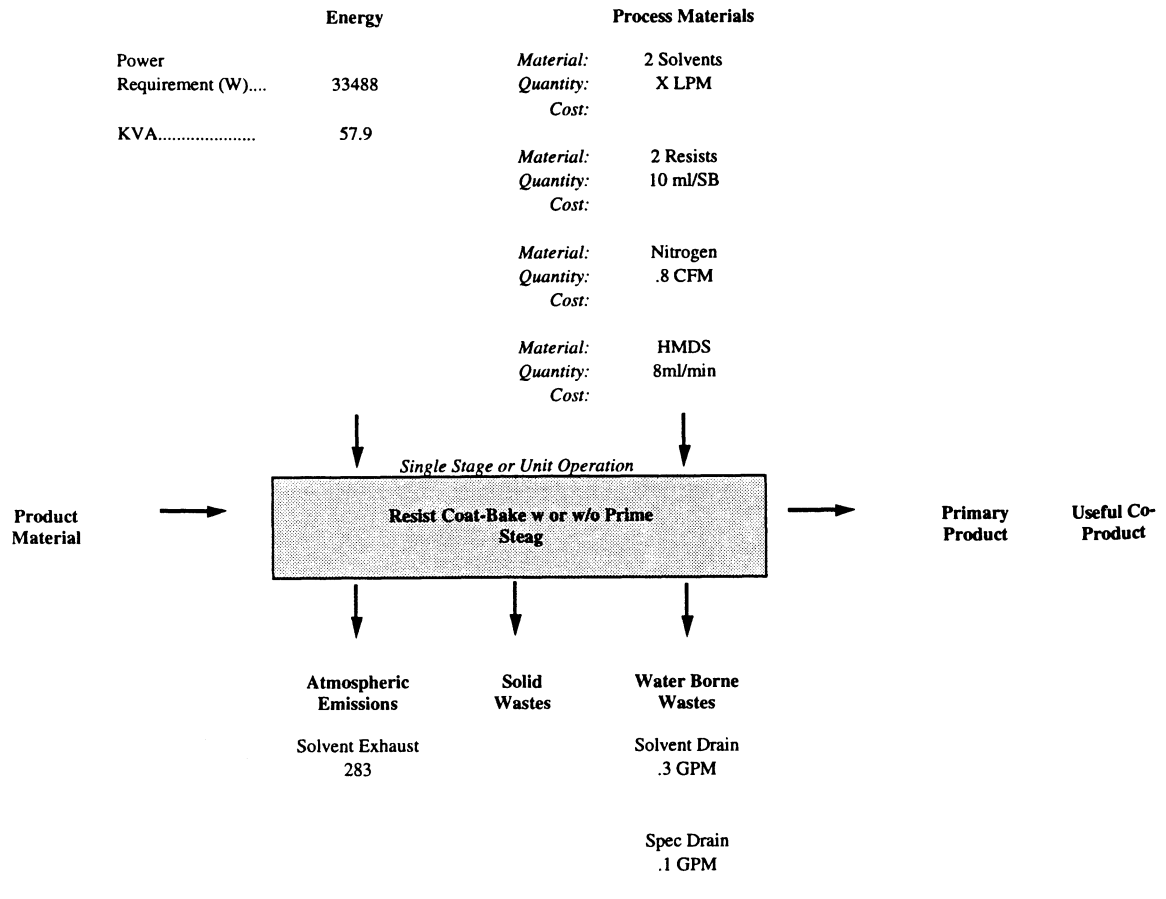
E/mm2

CF4/mm2

Solvent Exh/mm2

MATERIALS AND ENERGY ACCOUNTING

Process Stage: Active Photo/Coat-Bake Resist (41)(39)



Metrics

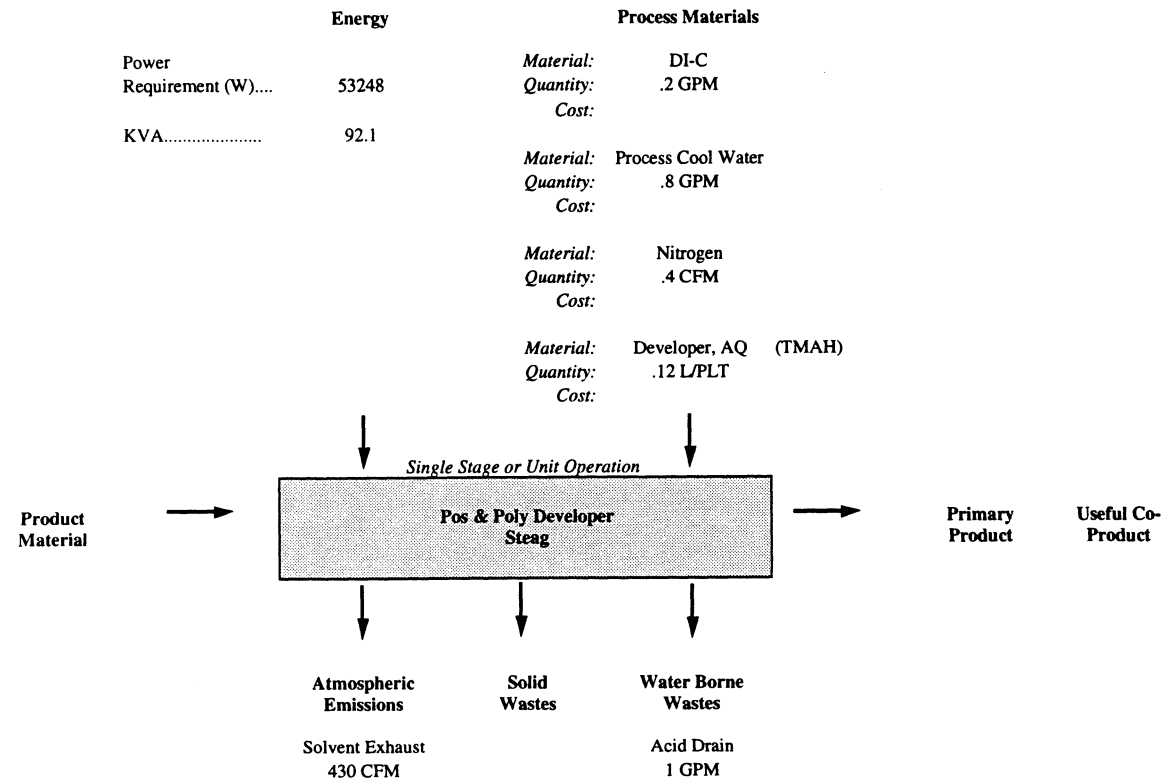
E/mm2

Solvent Exh/mm2

Solvent/mm2

MATERIALS AND ENERGY ACCOUNTING

Process Stage: Active Photo/Develop-HP Bake (48)



Metrics

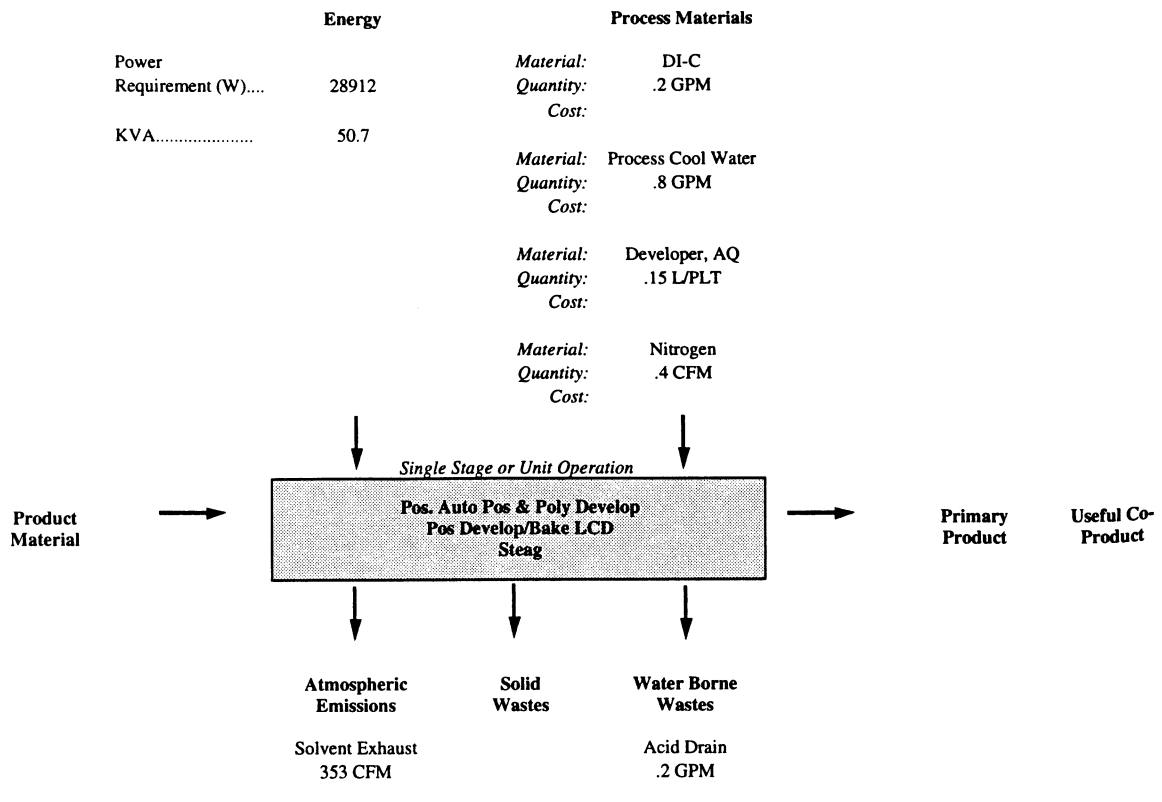
E/mm2

TMAH/mm2

Solvent Exh/mm2

MATERIALS AND ENERGY ACCOUNTING

Process Stage: Active Photo/Develop-Bake, 2H



Metrics

E/mm2

Dev/mm2

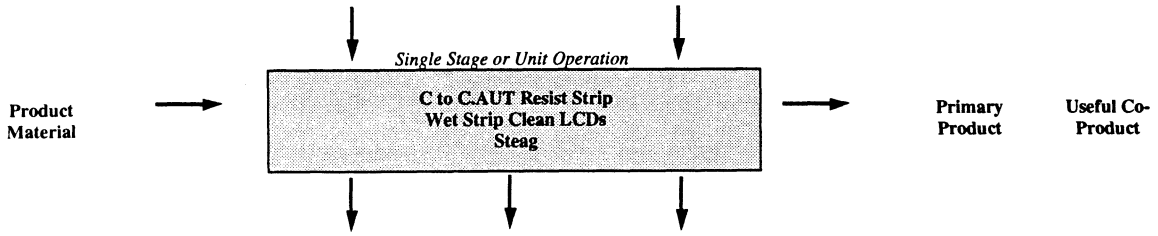
Solvent Exh/mm2

DI/mm2

MATERIALS AND ENERGY ACCOUNTING

Process Stage: Active Photo/Wet Strip/Clean (72)(904)

	Energy		Process Materials
Power Requirement (W)....	14976	*Material:*	DI-C
		Quantity:	.2 GPM
		Cost:	
KVA.....	25.9		
		Material:	Process Cool Water
		Quantity:	.8 GPM
		Cost:	
		Material:	Sipley 1165/NM P
		Quantity:	50 ml/min
		Cost:	
		Material:	Nitrogen
		Quantity:	.2 CFM
		Cost:	
		Material:	Recycled Chem DS
		Quantity:	
		Cost:	



Atmospheric Emissions	Solid Wastes	Water Borne Wastes
Material:		
Quantity: Solvent Exhaust 253 CFM		*Quantity:* Acid Drain .2 GPM
Cost:		

Metrics

E/mm2

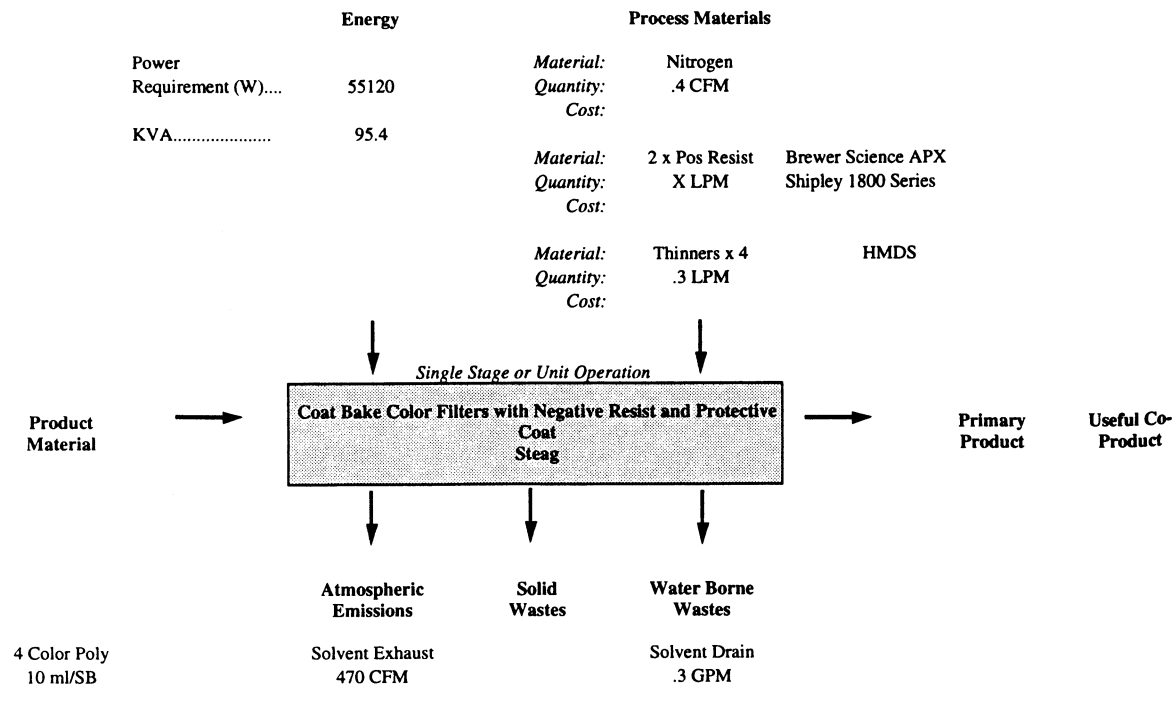
Shipley Strip/mm2

Solvent Exh/mm2

DI/mm2

MATERIALS AND ENERGY ACCOUNTING

Process Stage: Photolithography/Color Poly/Coat-Bake (45)(44)



Metrics

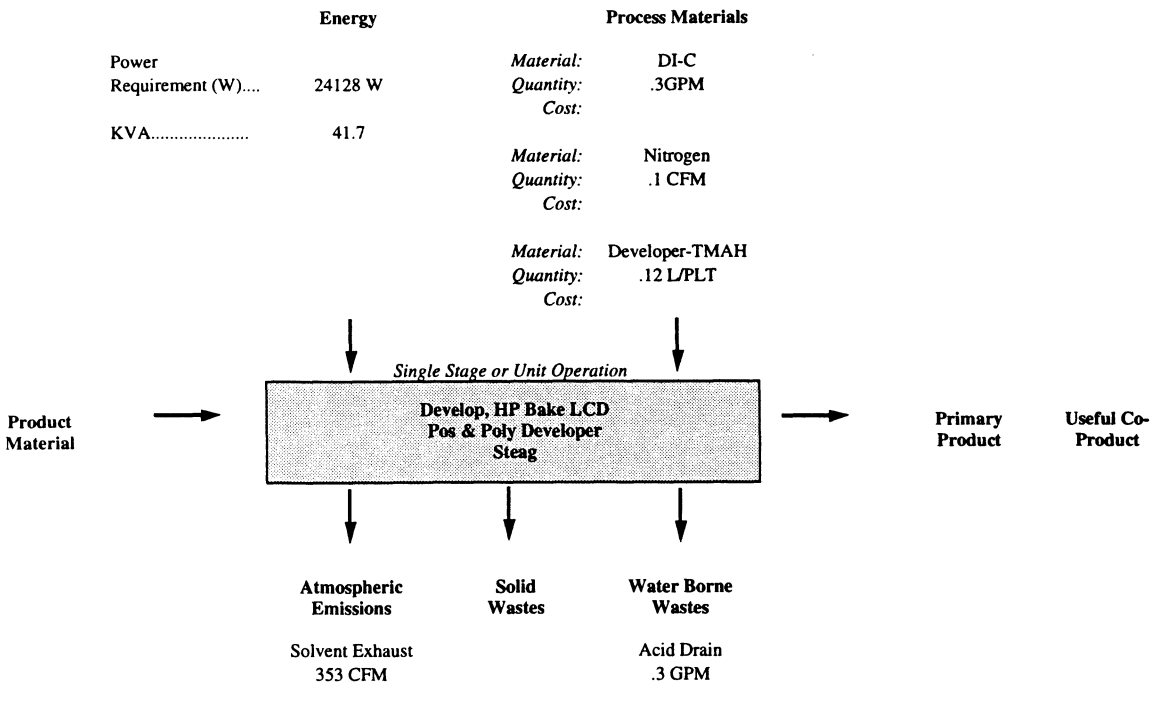
Color Poly SB/Color Poly Total x 100%

Color Filter/mm2

HMDS/mm2

MATERIALS AND ENERGY ACCOUNTING

Process Stage: Photolithography/Color Poly/Develop Bake (50)



Metrics

% Reuse Developer

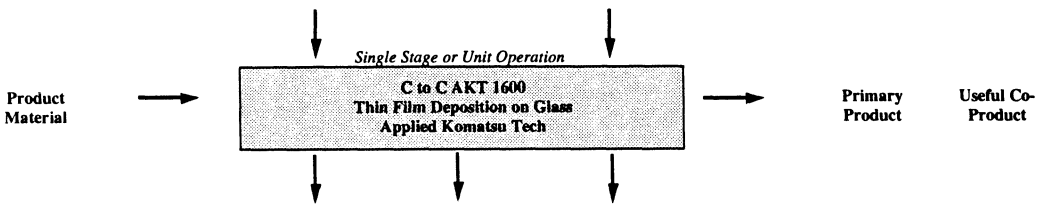
Solvent Exh/mm2

Acid/mm2

MATERIALS AND ENERGY ACCOUNTING

Process Stage: PECVD Chase/CVD Cluster (84)

	Energy	Process Materials	
Power Requirement (W)....	62400	*Material:*	Cool Water
		Quantity:	36 GPM
		Cost:	
KVA.....	108		
		Material:	SiH4:NH3
		Quantity:	1 LPMEA
		Cost:	
		Material:	PH3 (in H2, 5 kppm)
		Quantity:	.2 LPM
		Cost:	
		Material:	N2O
		Quantity:	.2 LPM
		Cost:	
		Material:	NF3
		Quantity:	8 LPM
		Cost:	
		Material:	N2
		Quantity:	180 LPM
		Cost:	
		Material:	Argon
		Quantity:	1 CFM
		Cost:	
		Material:	Nitrogen and Hydrogen
		Quantity:	3 CFM
		Cost:	



Material:	a-Si	Solvent Exhaust
Quantity:		707 CFM
Cost:		
Material:	ł, NH3, Phosphine, N+	Acid Exhaust
Quantity:		417 CFM
Cost:		

AIR EMISSIONS
SIHX
H2
N2
SiN
NH2
P

Metrics

E/mm2

a-Si/mm2

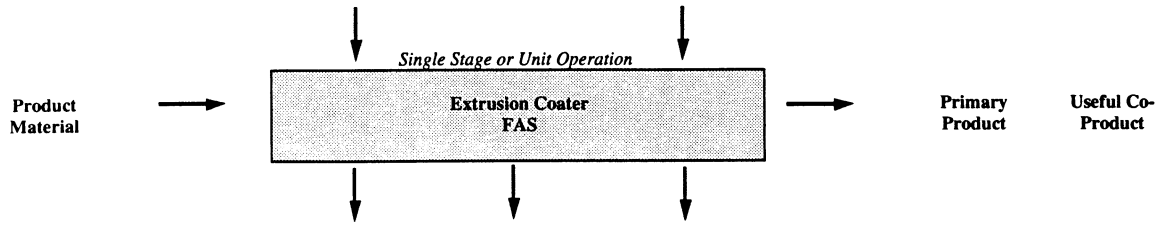
Solvent exhaust/mm2

Acid Exhaust/mm2

MATERIALS AND ENERGY ACCOUNTING

Process Stage: Detergent Clean (4)

	Energy		Process Materials
Power Requirement (W)....	22672	*Material:*	Detergent
		Quantity:	100 ml/min
		Cost:	
KVA.....	39.2		
		Material:	DI-C
		Quantity:	.4 GPM
		Cost:	
		Material:	Process Cool Water
		Quantity:	.8 GPM
		Cost:	
		Material:	Nitrogen
		Quantity:	.3 CFM
		Cost:	
		Material:	CO2 Ionization
		Quantity:	.35 CFM
		Cost:	
		Material:	IPA
		Quantity:	.3 GPM
		Cost:	



			IPA and detergent
Material:			
Quantity:			
Cost:			
Material:			Spec Drain
Quantity:			.5 GPM
Cost:			

Metrics

E/mm2

a-Si/mm2

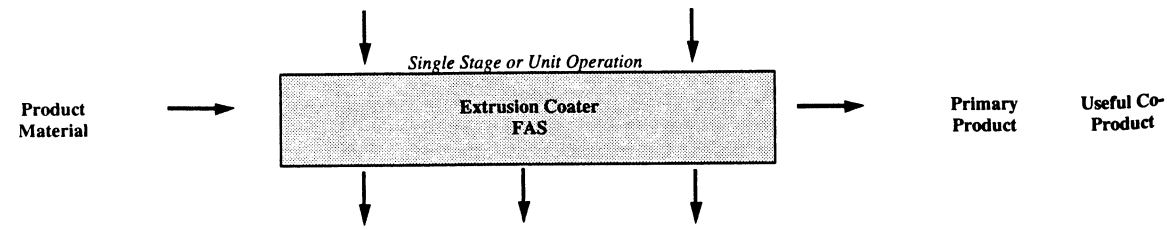
Solvent exhaust/mm2

Acid Exhaust/mm2

MATERIALS AND ENERGY ACCOUNTING

Process Stage: LCD Assembly/Coat-Bake Resist (995)

	Energy	Process Materials
Power Requirement (W)....	13520	*Material:* MIBK Thiner *Quantity:* 2 LPM *Cost:*
KVA.....	24	*Material:* Pos Resist *Quantity:* 10 ml/SB *Cost:*
		Material: Nitrogen *Quantity:* .2 CFM *Cost:*



Metrics

E/mm2

a-Si/mm2

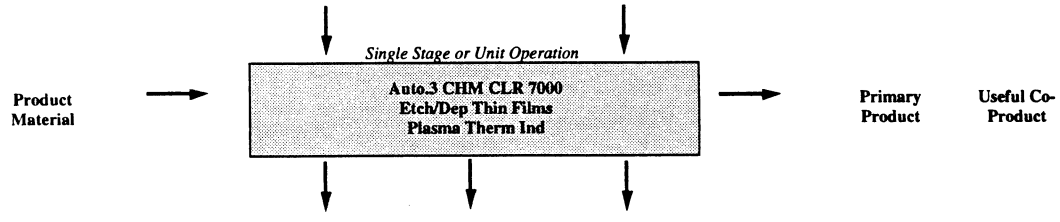
Solvent exhaust/mm2

Acid Exhaust/mm2

MATERIALS AND ENERGY ACCOUNTING

Process Stage: PECVD Chase/RIE Cluster (67)

Energy		Process Materials		
Power Requirement (W)....	52000	*Material:*	Process Cool Water	
		Quantity:	5 GPM	
		Cost:		
KVA.....	90			
		Material:	SF6	
		Quantity:	200 SCCM	
		Cost:		
		Material:	CF4	
		Quantity:	200 SCCM	
		Cost:		
		Material:	BCL3 or CL2	
		Quantity:	500 SCCM	
		Cost:		
		Material:	Oxygen	Recycled 2X
		Quantity:	.2 LPM	
		Cost:		
		Material:	Hydrogen	
		Quantity:	.10 LPM	
		Cost:		
		Material:	Nitrogen	
		Quantity:	.3 CFM	
		Cost:		



	Atmospheric Emissions	Solid Wastes	Water Borne Wastes
Material:	Acid Exhaust		Solvent Drain
Quantity:	300 CFM		.1 GPM
Cost:			
Material:	Solvent Exhaust		
Quantity:	54 CFM		
Cost:			

AIR EMISSIONS		
Insulator	**Semiconductor**	**Metals**
SiCl4	SiCl4	TaCl3
CF3	CF3	BCl2
CF2	CF2	BCl3
CFOx	CF4	
NF3	CHF3	
	O2	
	HCL	

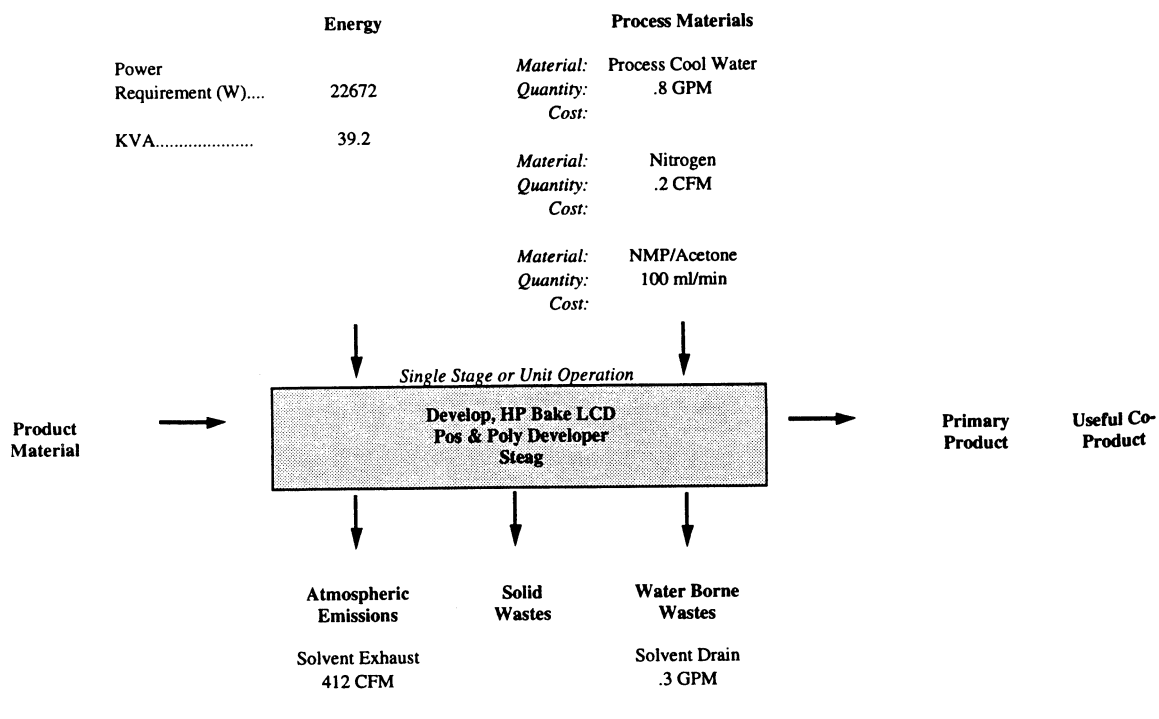
Metrics

E/mm2
CFC or PFC gas emissions mm2 or unit time

Insulator	Semiconductor	Metal
SiN/mm2	a-Si/mm2	Ta/mm2
CF4/mm2	CF2Cl2/mm2	BCL3/mm2

MATERIALS AND ENERGY ACCOUNTING

Process Stage: Solvent Cleaner/Safe Strip (75)(460)



Metrics

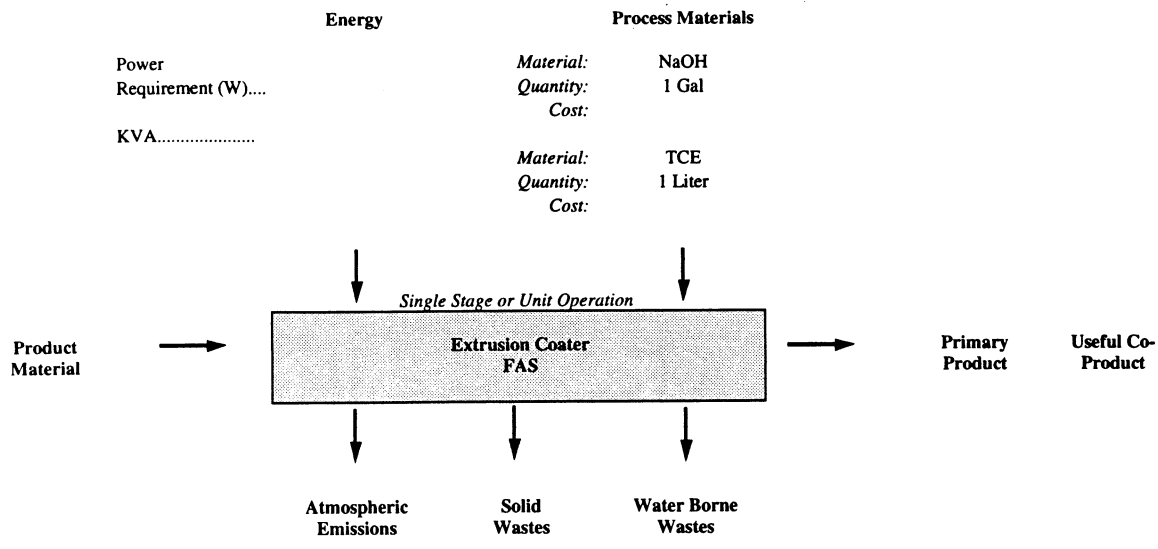
Sovent Exh/mm2

NMP-Acetone/mm2

E/mm2

MATERIALS AND ENERGY ACCOUNTING

Process Stage: Solvent Fume Hood & 8'LF Solvent Fume



Material:
Quantity:
Cost:

Metrics

E/mm2

a-Si/mm2

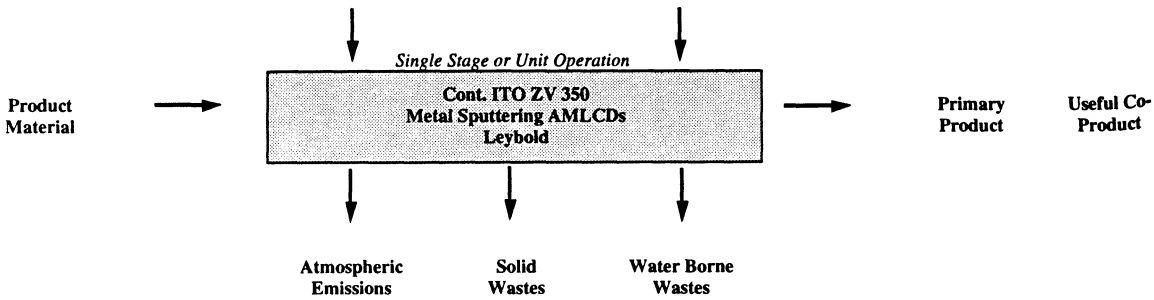
Solvent exhaust/mm2

Acid Exhaust/mm2

MATERIALS AND ENERGY ACCOUNTING

Process Stage: ITO Sputterer,VER (21)

	Energy		Process Materials
Power Requirement (W)....	34000	*Material:*	Process Cool Water
		Quantity:	10 GPM
		Cost:	
KVA.....	58.8		
		Material:	Argon
		Quantity:	.2 LPM
		Cost:	
		Material:	Oxygen
		Quantity:	.5 LPM
		Cost:	
		Material:	Nitrogen
		Quantity:	1 CFM
		Cost:	



Material:	Mo		Solvent Exhaust	
Quantity:			80 CFM	
Cost:				

Metrics

E/mm2

a-Si/mm2

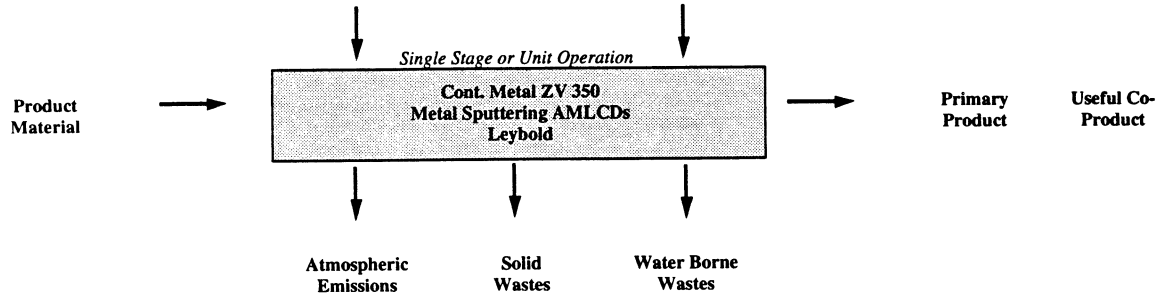
Solvent exhaust/mm2

Acid Exhaust/mm2

MATERIALS AND ENERGY ACCOUNTING

Process Stage: Metal Sputterer,VER (8)

	Energy		Process Materials
Power Requirement (W)....	64000	*Material:*	Process Cool Water
		Quantity:	34 GPM
		Cost:	
KVA.....	110.7		
		Material:	Argon
		Quantity:	.4 LPM
		Cost:	
		Material:	Oxygen
		Quantity:	.5 LPM
		Cost:	
		Material:	Nitrogen
		Quantity:	1.7 CFM
		Cost:	



Material:	Mo	Solvent Exhaust	
Quantity:		80 CFM	
Cost:			

Metrics

E/mm2

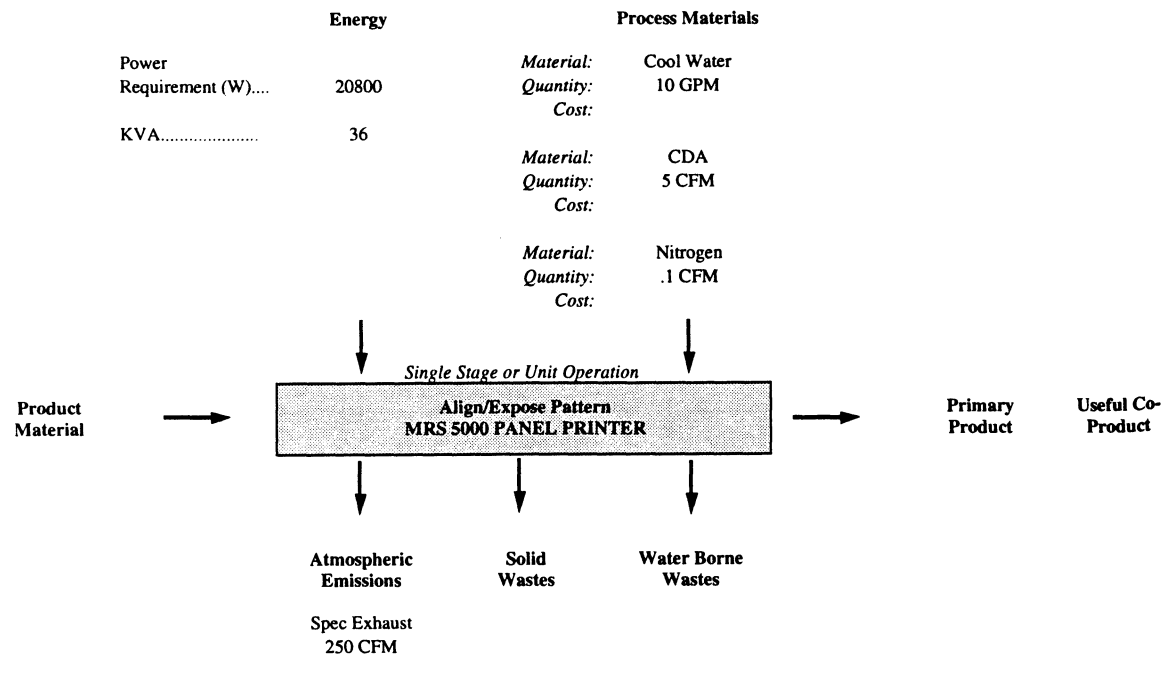
a-Si/mm2

Solvent exhaust/mm2

Acid Exhaust/mm2

MATERIALS AND ENERGY ACCOUNTING

Process Stage: Colory Poly or Active/Stepper-Sticher (37)



Metrics

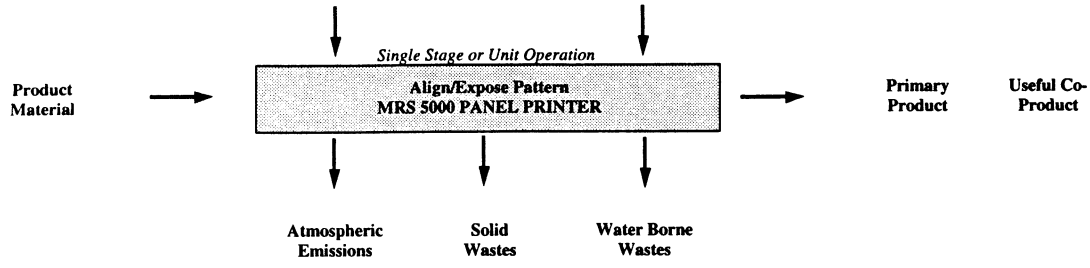
Process Water/mm2 Substrate

E/mm2 Substrate

MATERIALS AND ENERGY ACCOUNTING

Process Stage: Colory Poly or Active/Stepper-Sticher (37)

	Energy		Process Materials
Power Requirement (W)....	20800	*Material:*	Cool Water
		Quantity:	10 GPM
KVA.....	36	*Cost:*	
		Material:	CDA
		Quantity:	5 CFM
		Cost:	
		Material:	Nitrogen
		Quantity:	.1 CFM
		Cost:	
		Material:	
		Quantity:	
		Cost:	
		Material:	
		Quantity:	
		Cost:	

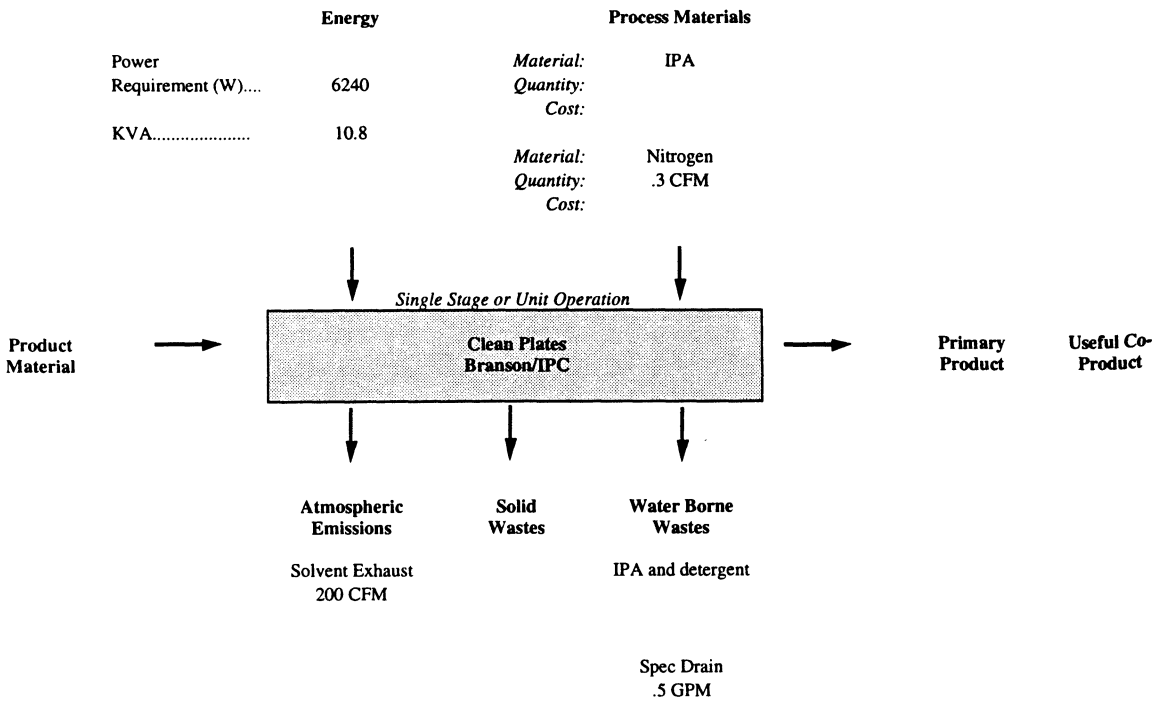


Material:	Spec Exhaust		
Quantity:	250 CFM		
Cost:			
Material:			
Quantity:			
Cost:			
Material:			
Quantity:			
Cost:			
Material:			
Quantity:			
Cost:			
Material:			
Quantity:			
Cost:			
Material:			
Quantity:			
Cost:			

Metrics

MATERIALS AND ENERGY ACCOUNTING

Process Stage: Ultrasonic Clean (975)



Metrics

E/mm2

a-Si/mm2

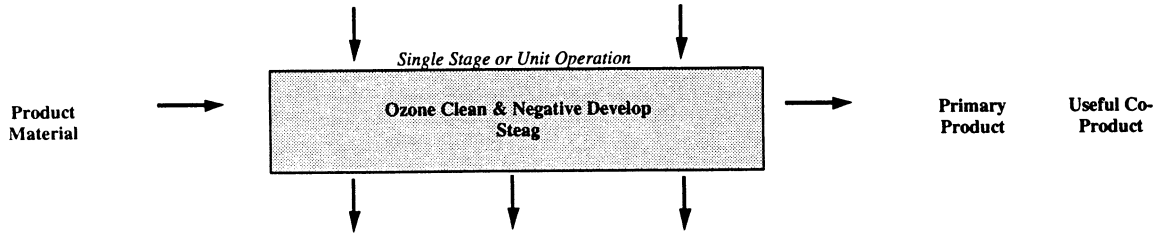
Solvent exhaust/mm2

Acid Exhaust/mm2

MATERIALS AND ENERGY ACCOUNTING

Process Stage: UV Ozone Clean (83)(82)(975)(997)(99)()

Energy		Process Materials	
Power Requirement (W)....	40560	*Material:*	4 EXH:2x4.6.1x3
		Quantity:	6.3 in
		Cost:	
KVA.....	70.2		
		Material:	Alkaline Dev
		Quantity:	50ml/min
		Cost:	
		Material:	Process Cool Water
		Quantity:	.8GPM
		Cost:	
		Material:	DI-C
		Quantity	.2 GPM
		Cost:	
		Material:	Nitrogen
		Quantity:	.5 CFM
		Cost:	



Atmospheric Emissions		Solid Wastes	Water Borne Wastes	
Material:	Solvent Exhaust		Acid Drain	
Quantity:	430 CFM		.2 GPM	
Cost:				

Metrics

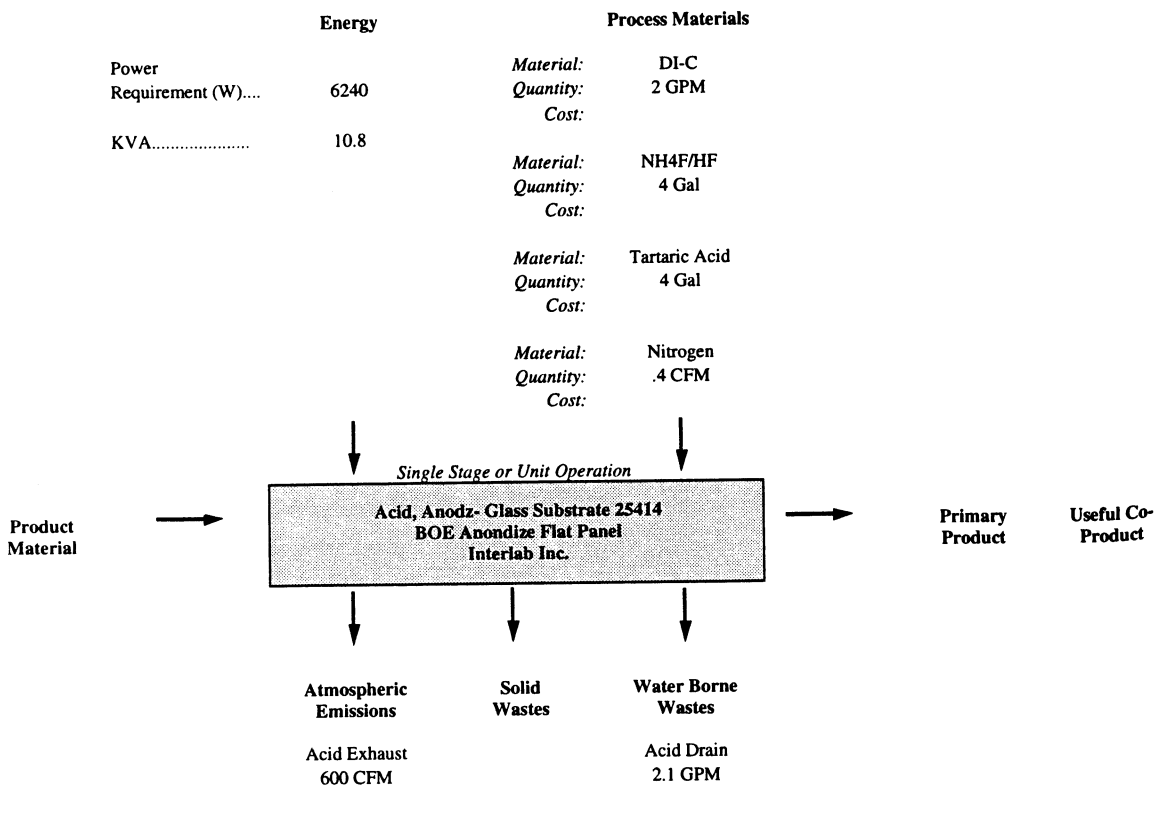
Alkaline/mm2

Solvent Exh/mm2

DI/mm2

MATERIALS AND ENERGY ACCOUNTING

Process Stage: Wet Process/Wet Bench (80)



Metrics

E/mm2

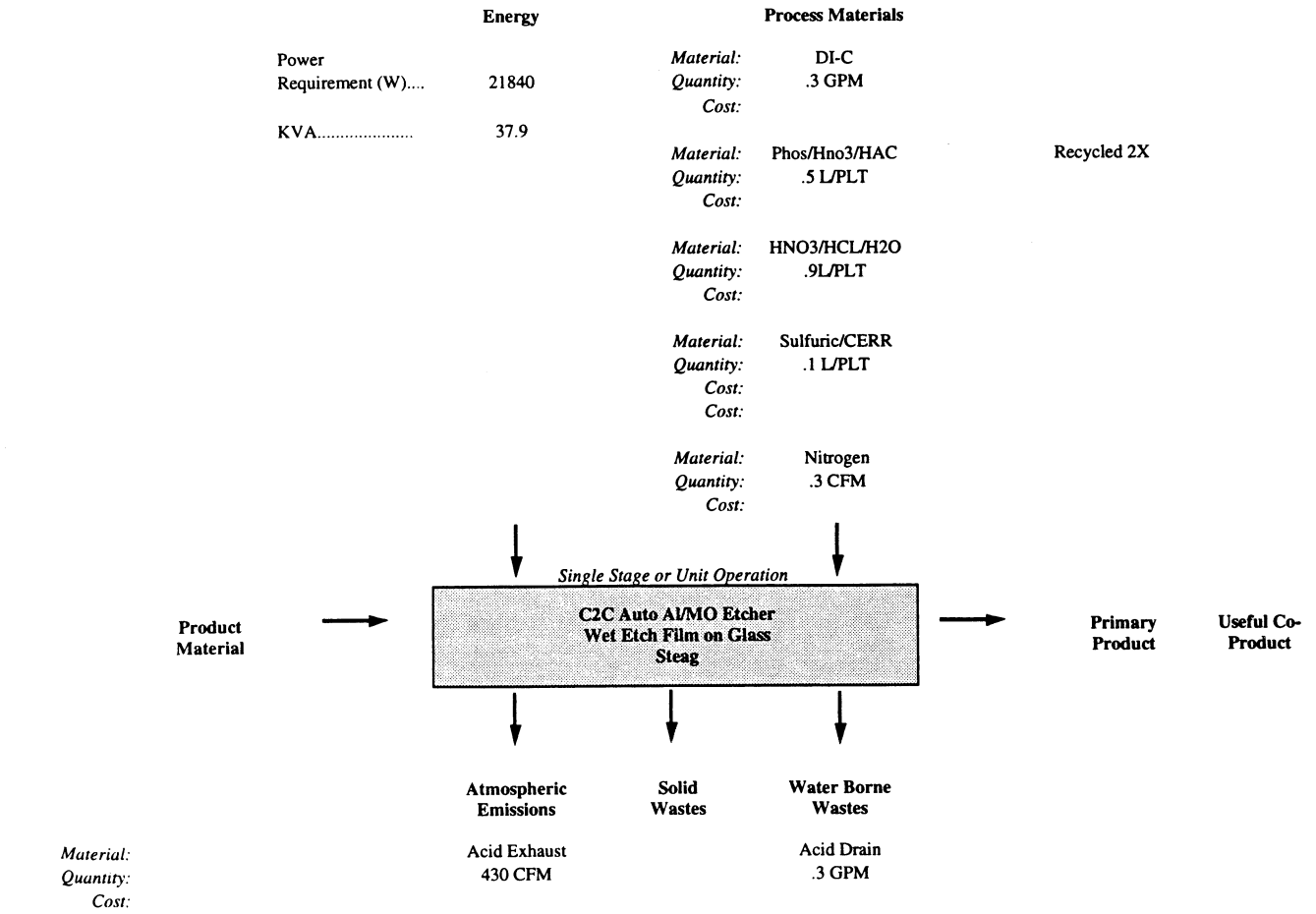
Tartaric and NH4F/HF per cycle, min, SB

Acid exhaust/mm2

DI/mm2

MATERIALS AND ENERGY ACCOUNTING

Process Stage: Wet Process/Wet Etcher (81)



Metrics

E/mm2

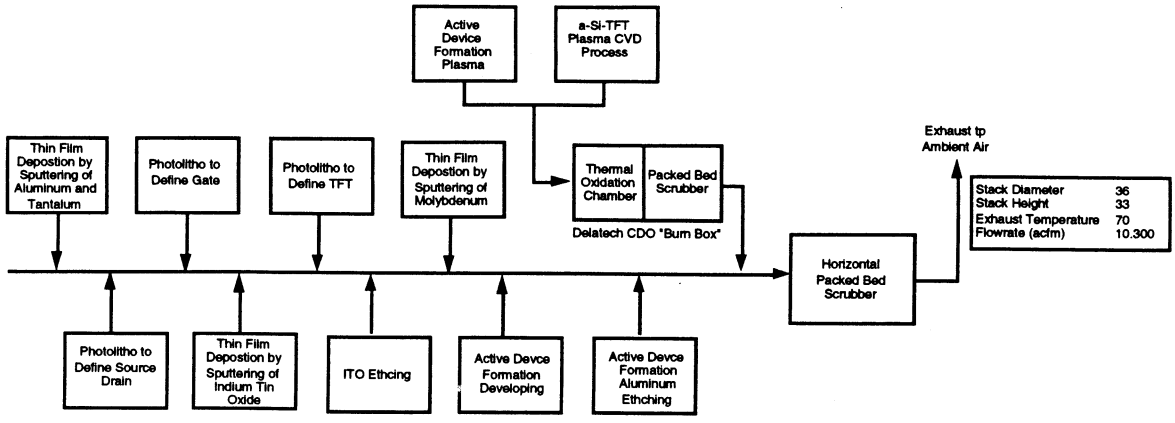
HNO3, Phos, HAC, HCL, Sulfuric per min, cycle, SB

Acid exhaust/mm2

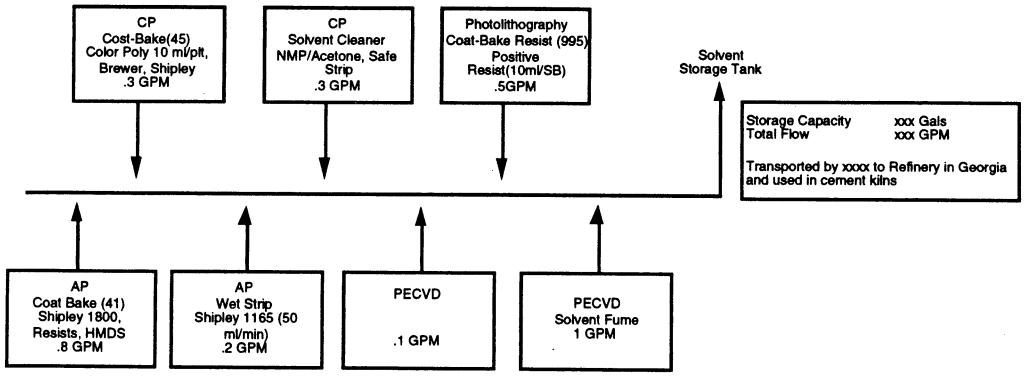
DI/mm2

APPENDIX C: PILOT DEMONSTRATION FACILITY SYSTEMS

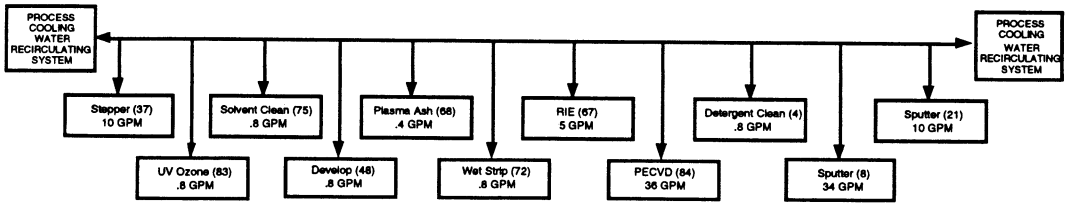
GENERAL EXHAUST SYSTEM



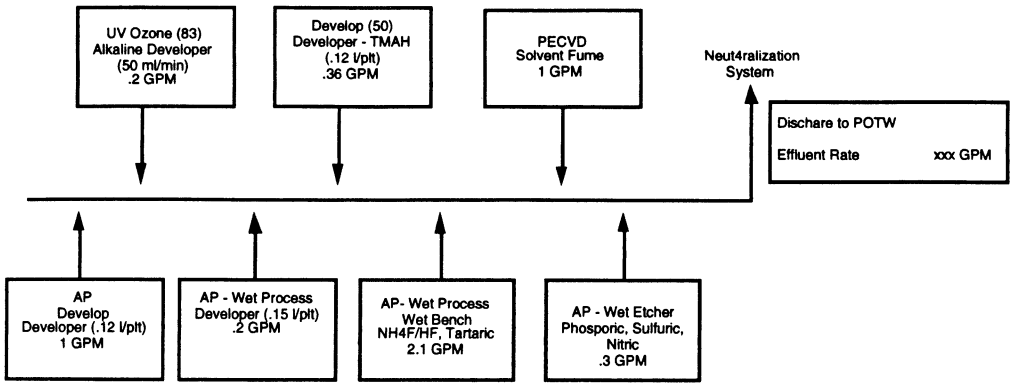
LIQUID SOLVENT DISPOSAL



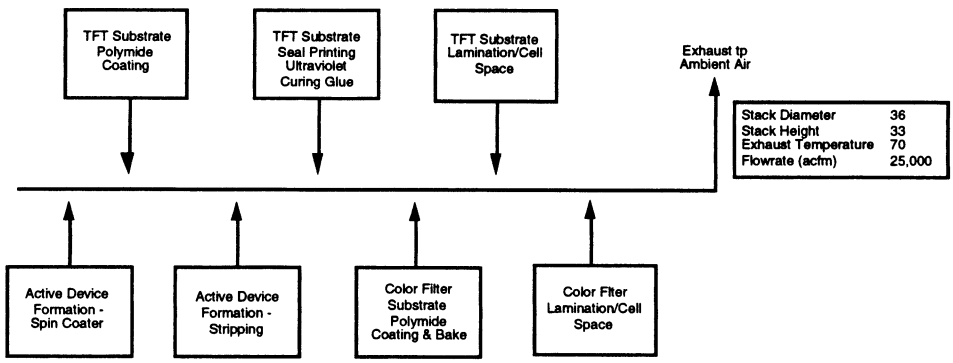
PROCESS COOLING WATER



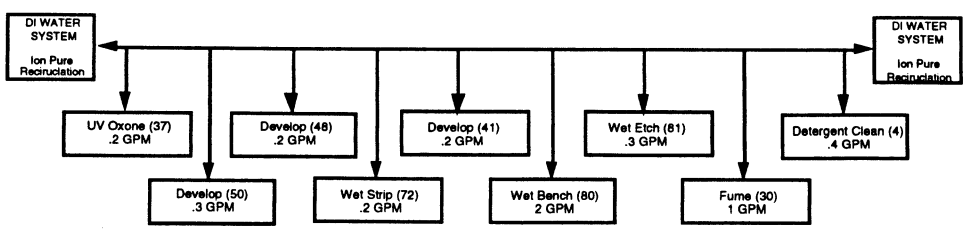
ACID DRAIN - NEUTRALIZATIN SYSTEM



SOLVENT EXHAUST SYSTEM



DI WATER USE



APPENDIX D: ENVIRONMENTAL METRICS

ENVIRONMENTAL METRICS

Assumptions

Power Factor	0.0017
Load Factor	0.3
BtU/KwH	3412.13
S/KwH	0.0862
S/BtU Gas	0.000002
S/BtU Oil	0.000004
KwH/MJ	3.6
J/KwH	3600000
Hours of Operation	5040
Number of displays/Year	40000
DI Water Conversion Factor	1.7
G/LB	453.592
S/cu.ft. Gas	
S/gal Oil	S0.53

Fuel Required to Generate 1 KwH

Natural Gas	10.54	cu ft.
Fuel Oil	0.07	gal
Coal	0.99	lb
Uranium	0.0000109	lb
Hydro	3414	BtU/KwH

BtU of Fuel Consumed for Gen. and Del.

per KwH	10712	BtU
Gas	1159	BtU/cu ft
Oil	174400	BtU/gal
Line Loss	1.037	

Industrial Heating

	Precombustion	Comb BtU per	Toal BtU
Nat Gas (cu.ft)	125	1,034	1,159
Resid Oil (Gal)	25,700	148,700	174,400
Coal	284	10,470	
Nuclear	78,990,000	983,850,000	
Hydro			
Other			

Percent of Composite	Pre BtU Cons/Comp KwH	Heat BtU Cons/Comp KwH
0.09	123.32	1020.09
0.04	75.02	434.06
0.56	156.10	5754.81
0.2056	177.02	2204.85
0.0998	0.00	0.00
0.0038	0.00	0.00
	551.12	9762.11

Emissions per KwH	National Avg	Fuel	Gas	
NOx/KwH		2.5	1.9	2.1
SO2/KwH		5.8	5.4	0
CO2/KwH		1.5	2	1.3

Chiller Operation

% Oil	0.50
% Gas	0.50

LIFE CYCLE ENERGY ANALYSIS: MANUFACTURING VS. USE PHASE

PRELIMINARY

ENERGY CONSUMPTION: MANUFACTURING

	KwH (1)	KwH/Display	BtU (3)	Cost (2)(4)	BtU/Display
Equipment	3,170,664	79	10,818,717,754	$273,311	270.468
HVAC	1,987,947		6,783,134,400	$20,369	167,763
TOTAL	**5,158,611**	**79**	**17,601,852,154**	**$293,681**	**438,231**

(1) KwH required to run equipment

(2) Cost per KwH based on average rate monthly rates inlcuding peaks for industrial uses of $.0862/KwH. Source Data Quest Service for Detroit Edison

(3) Equipment BtU demand derived from KwH; HVAC Btu demand given in OIS Utilities Matrix

(4) Assumed 50% usage of oil and gas. BtU cost for oil and gas based on Feb '96 gas price $.5295/gal; heating oil price Feb '96 $2.445/MMBtU. Source NYTimes

Fuel Consumed for HVAC System

	Gas (cu. ft.)	Fuel Oil (gal)
Combustion During Man	3,280,046	22,808
HVAC BtU	3,391,567,200	3,391,567,200
Cost (1)	$8,292.38	$12,076.90

(1) Assumed 50% usage of oil and gas. BtU cost for oil and gas based on Feb '96 gas price $.5295/gal; heating oil price Feb '96 $2.445/MMBtU. Source NYTimes

Electricity consumed for manufacturing; natural gas and fuel oil consumed on-site; and Use phase energy consumed:
The total primary energy consumed can be caluclated using efficiency factors for electricity generation and precombustion energy for natural gas and fuel oil. For example, 1 KwH requires 10,712BtU of primary energy.

	Primary (4)	Manufacturing-Use (5)	Primary/Display	Man. or Use/Display	
Equipment-Electricity (1)	33,964,152,768	10,818,717,754	849,103.82	270,467.94	BtU
HVAC-gas (2)	3,803,165,161	3,391,567,200	95,079.13	84,789.18	BtU
HVAC-oil (3)	3,973,820,220	3,391,567,200	99,345.51	84,789.18	BtU
Sub Total	41,741,138,149	17,601,852,154	1,043,528	440,046	
Display Use (65 Watt) (6)	278,512,000,000	88,715,380,000	6,962,800.00	2,217,884.50	BtU
TOTAL	361,994,276,298	123,919,084,309	9,049,857	3,097,977	

(1) BtU of Fuel Consumed per KwH is 10,712 based on national grid.

(2) Primary energy based on ratio of total energy:combustion energy or 1.155/1.030

(3) Primary energy based on ratio of total energy:combustion energy or 175.4/149.7

(4) Includes required to produce electricity for manufacturing operations

(5) Energy produced on-site for HVAC

(6) Assumes 40,000 displays manufactured and operated for 10,000 hrs with electricity from a national grid [See Energy Consumption: Use]

ENERGY CONSUMPTION: USE

Power (Watts)	12	15	20	65	230
Useful Life (Hrs.): MTBF of 10000	10,000	10,000	10,000	10,000	10,000
Energy (KWH)/Display	120	150	200	650	2,300
BtU/Display	409,456	511,820	682,426	2,217,885	7,847,899
KwH/40,000 Displays	4,800,000	6,000,000	8,000,000	26,000,000	92,000,000
BtU/40,000 Displays	16,378,224,000	20,472,780,000	27,297,040,000	88,715,380,000	313,915,960,000
Primary energy associated with Use					
Use Phase					
Primary associated with use/display (1)	1,285,440	1,606,800	2,142,400	6,962,800	24,637,600
40,000 Displays @ 10,000 hrs. MTBF	51,417,600,000	64,272,000,000	85,696,000,000	278,512,000,000	985,504,000,000

(1) Assumes use of national power grid

LIFE CYCLE ENERGY ANALYSIS: MANUFACTURING VS. USE PHASE

FIGURE I: Energy Consumption for Manufacturing and Use

Use phase assumes production of 40,000 displays with a useful life of 10,000 hrs

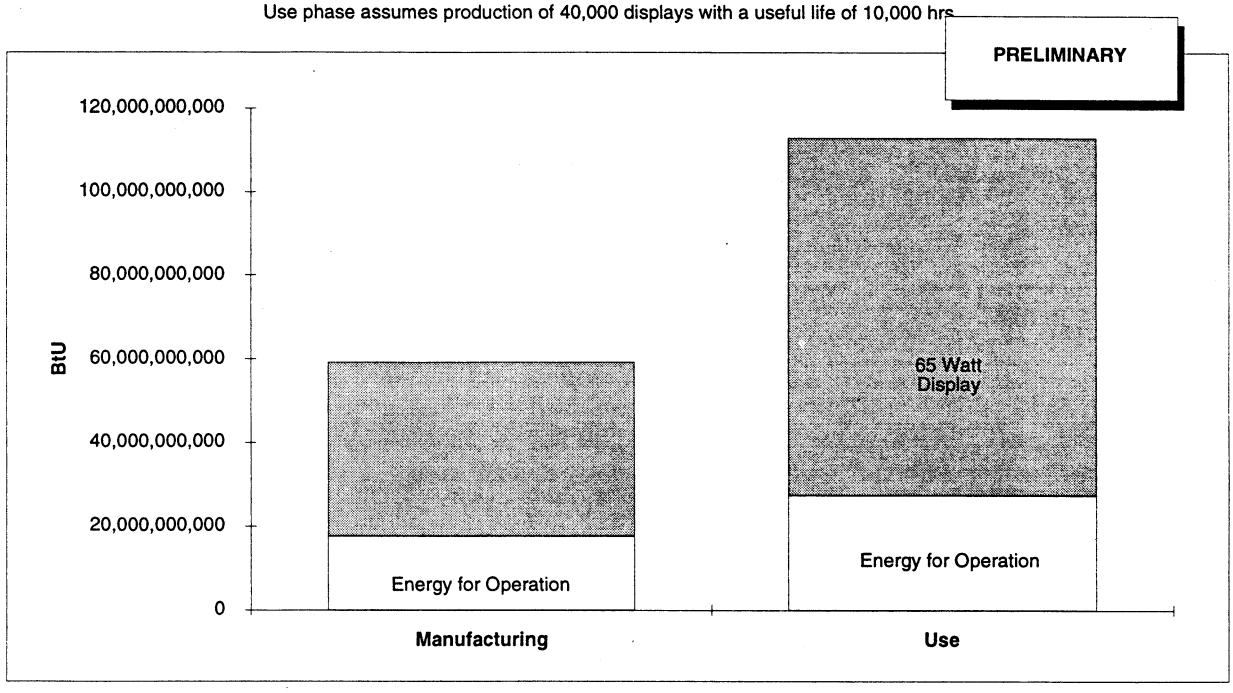
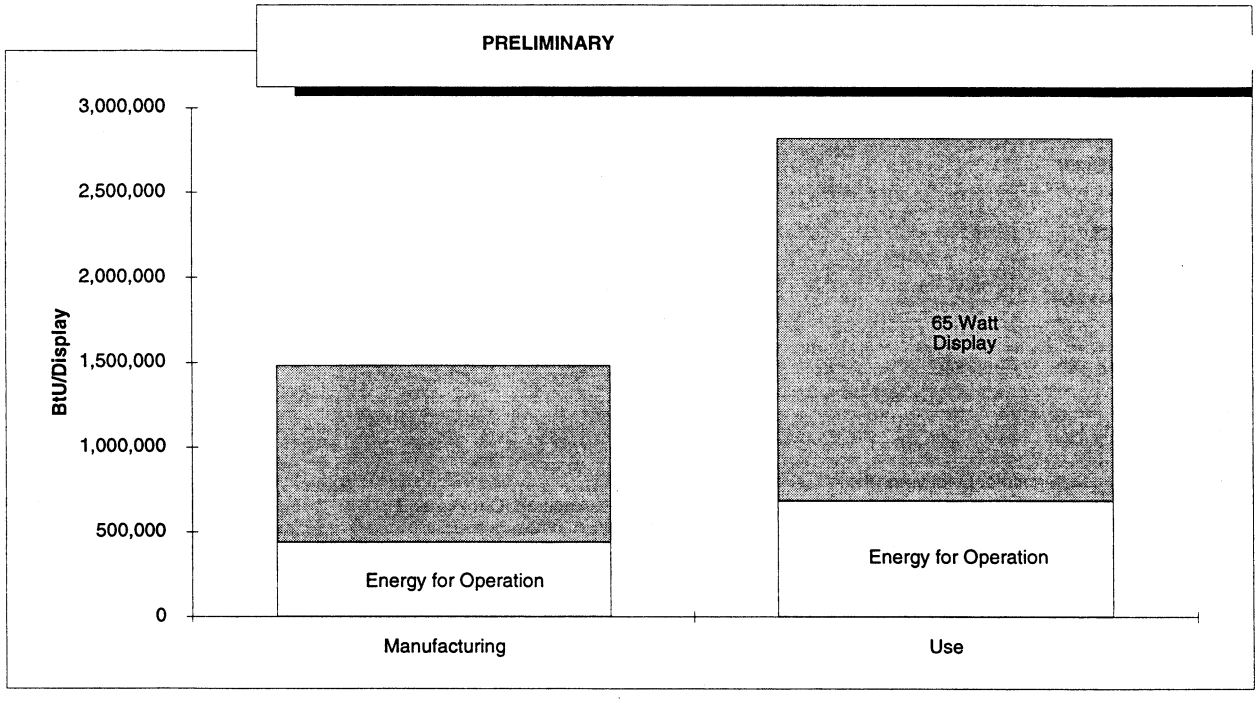


FIGURE II: Energy Consumption BtU/Display

Use phase assumes production of 40,000 displays with a useful life of 10,000 hrs.



LIFE CYCLE ENERGY ANALYSIS: MANUFACTURING VS. USE PHASE

FIGURE III: MANUFACTURING AND USE PHASE BtU/DISPLAY

Displays the BtU/Display for the operation of equipment, HVAC, and the use of the display over 40,000 hrs assuming a 65 W unit

This chart does not include primary energy

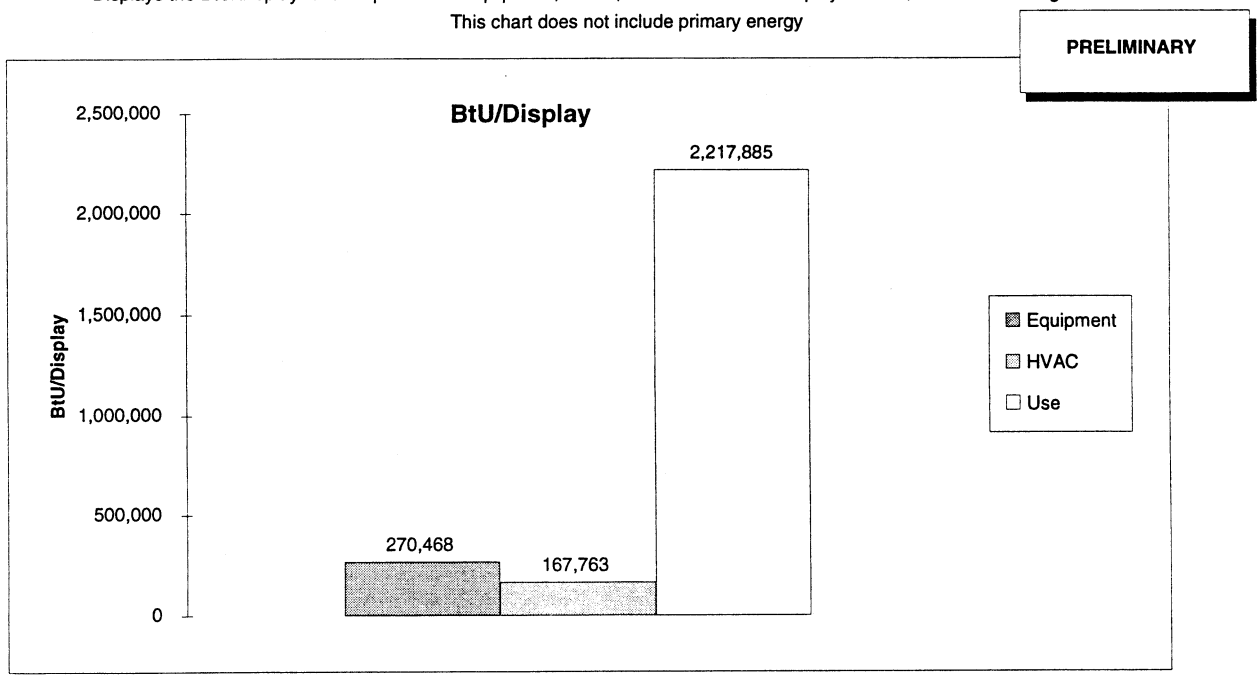
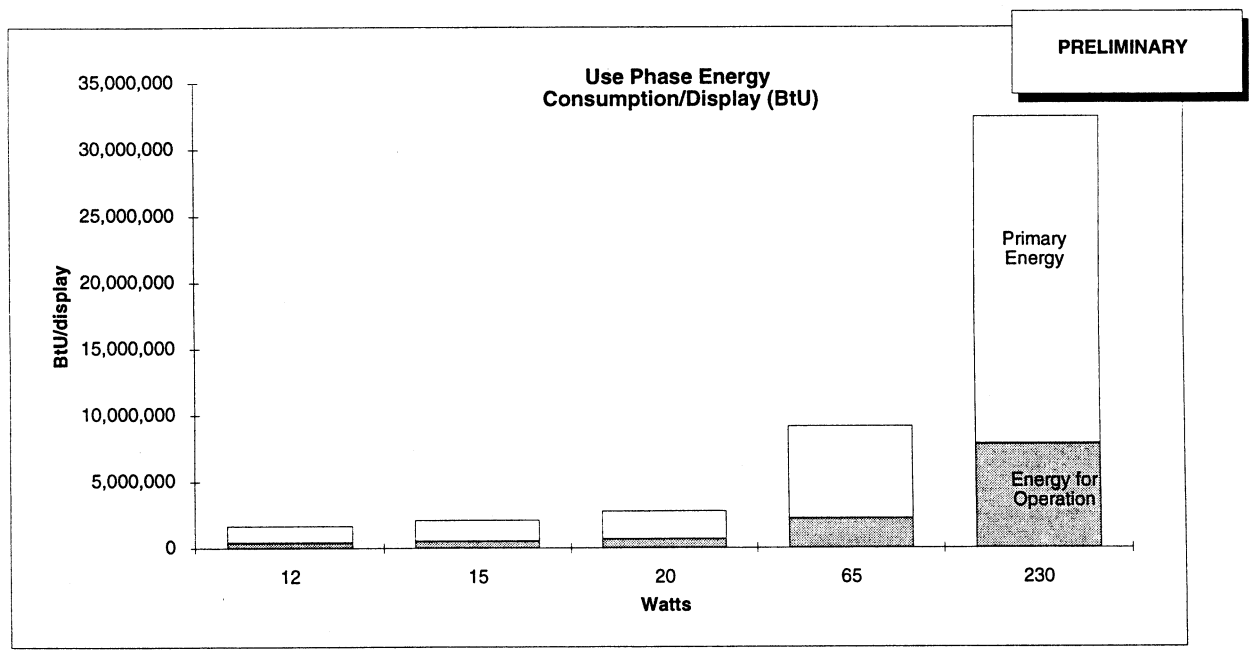


FIGURE IV: BtU/DISPLAY FOR VARYING DISPLAY POWER REQUIREMENTS

Figures do not include primary energy

BtU/Display for use phase assumes 40,000 displays operating for 10,000 hrs.



PROCESS ANALYSIS: DISTRIBUTION OF ENERGY LOADS: MANUFACTURING VS. USE PHASE

FIGURE V: HVAC ENERGY REQUIRED FOR PRODUCTION AREAS

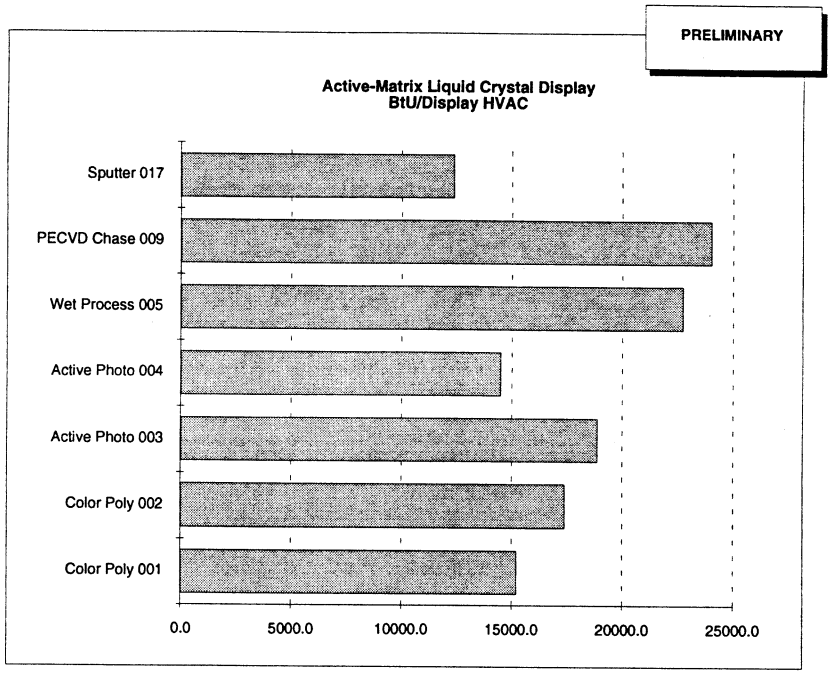
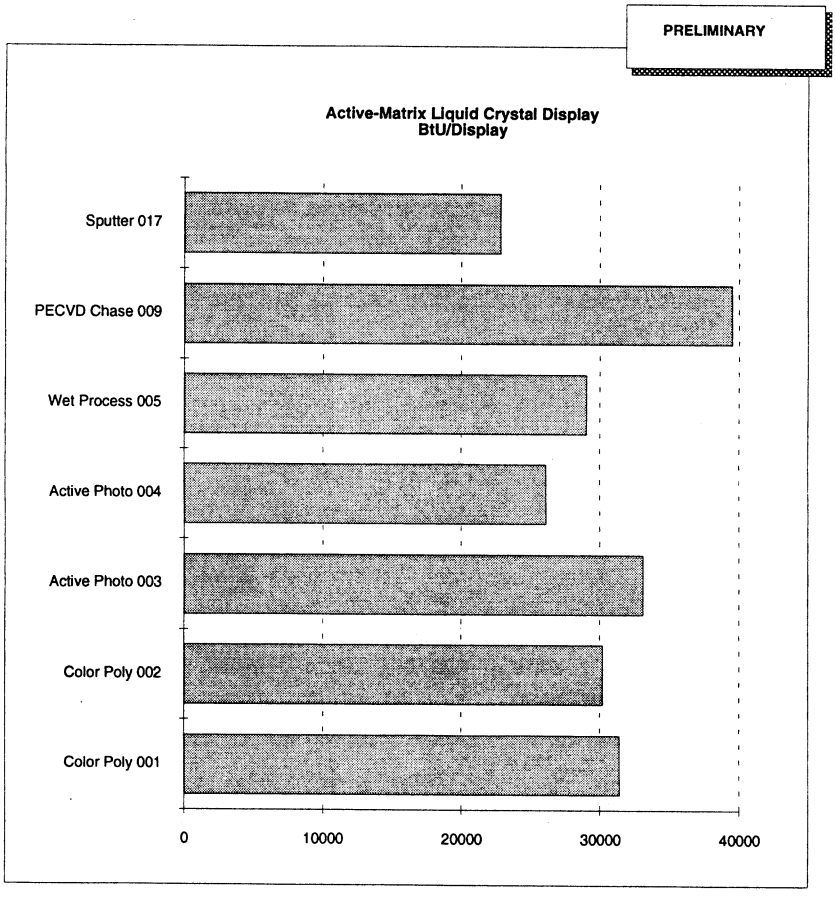


FIGURE VI: EQUIPMENT ENERGY REQUIRED FOR PRODUCTION AREAS



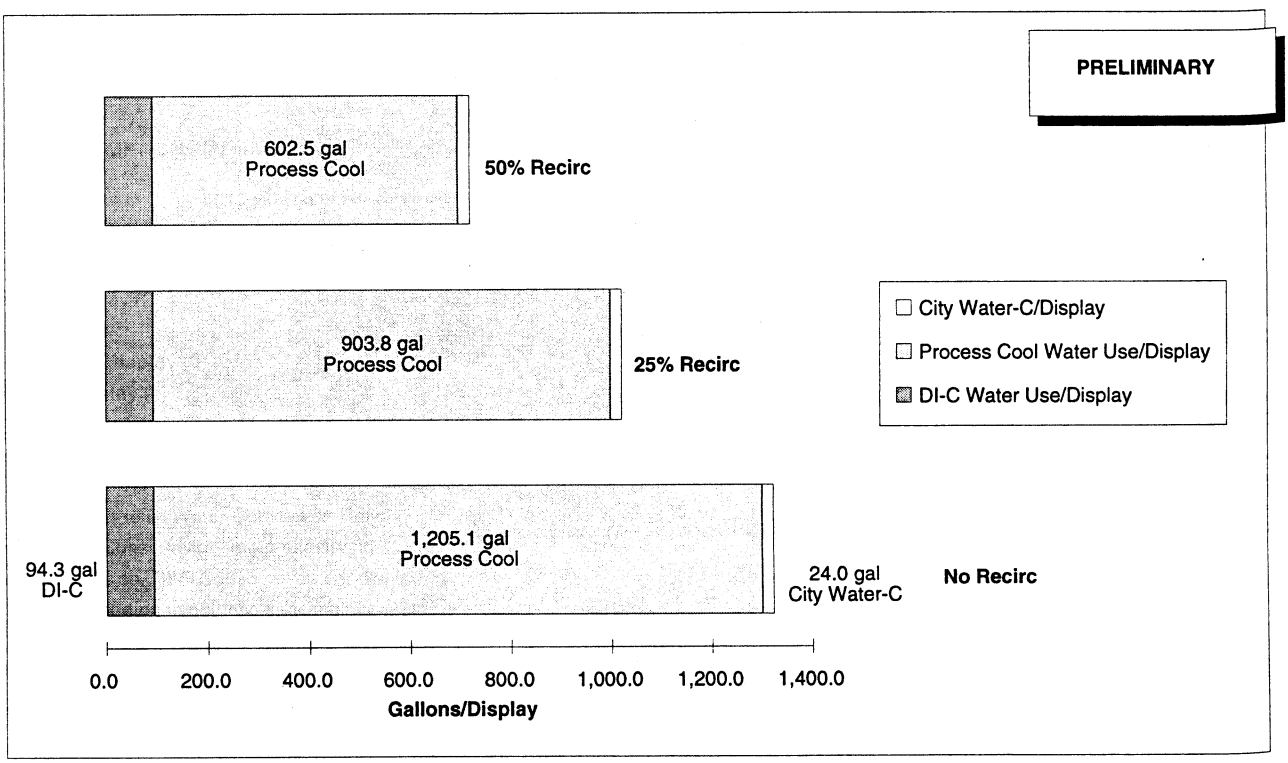
PROCESS ANALYSIS: WATER CONSUMPTION

WATER CONSUMPTION: Manufacturing

	No Recirc	25% Recirc Process Cool	50% Recirc Process Cool
Total Water Use (1)	27,244,969.9	15,194,329.9	3,143,689.9
Water Use/Display (2)	681.1	379.9	78.6
DI-C Water Use/Display (3)	94.3	94.3	94.3
Proc Water/Display (4)	1,205.1	903.8	602.5
City Water-C/Display	24.0	24.0	24.0
TOTAL	1,323.3	1,022.0	720.8

(1) 1.7 City Water to DI Water Conversion Ratio
(2) Total Water Consumption in Manufacturing
(3) Post-Conversion, DI-C Consumption per display
(4) Changes based on hypothetical recirculation rates

FIGURE VII: WATER CONSUMPTION PER DISPLAY



PROCESS ANALYSIS: AIR EMISSIONS

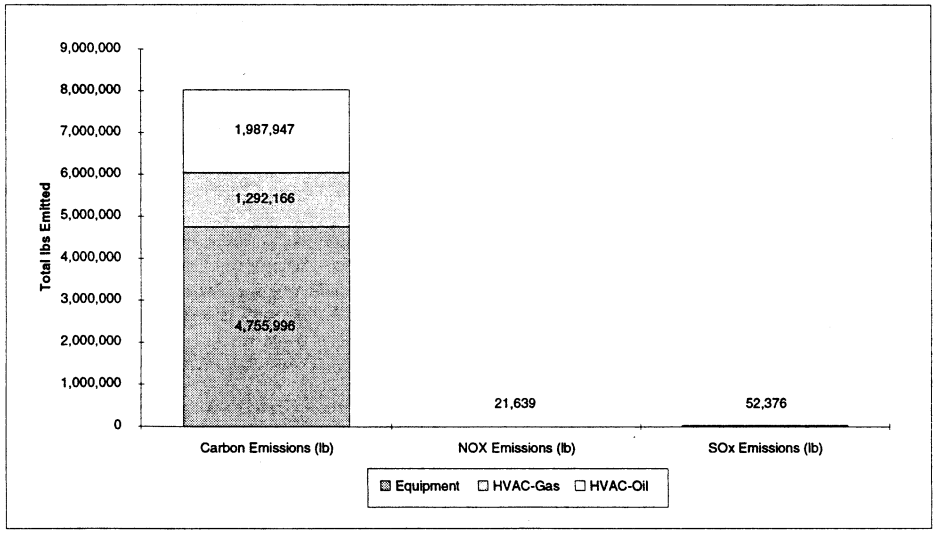
AIR EMISSIONS: Energy Related Emissions

	Equipment (1)	HVAC-GAS (2)	HVAC-OIL (2)	Eq. Em Per Display	HVAC-GAS Em Per Display	HVAC-OIL Em Per Display	TOTALS	TOTAL/ Display
Carbon Emissions (lb)	4,755,996	1,292,166	1,987,947	118.90	32.30	49.70	**6,743,943**	168.60
NOX Emissions (lb)	17,475	4,602	4,164	198.17	0.12	0.10	**21,639**	0.54
SOx Emissions (lb)	40,543	0	11,833	459.75	0.00	0.30	**52,376**	1.31

(1) Emissions based on EPA estimates for a national grid

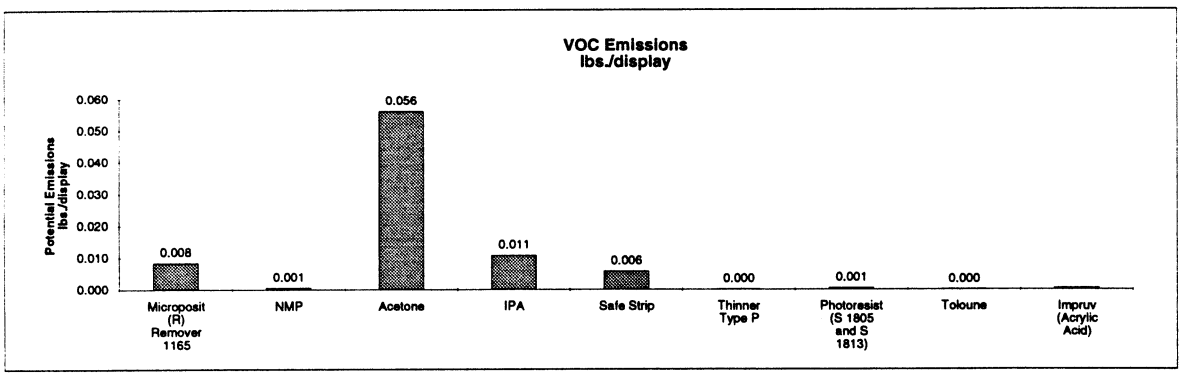
(2) Emissions based on EPA estimates for gas and oil fuel; assumes 50% usage of each to power HVAC

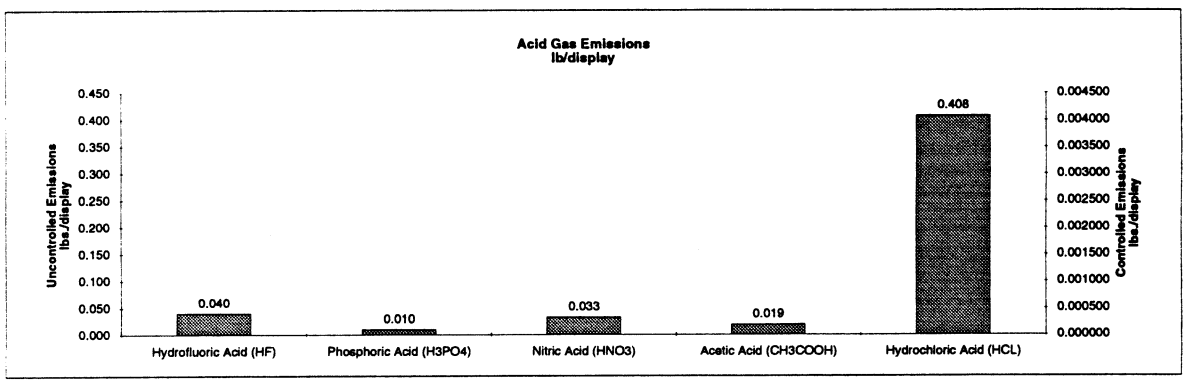
FIGURE VIII: AIR EMISSIONS FROM ENERGY CONSUMPTION DURING MANUFACTURING

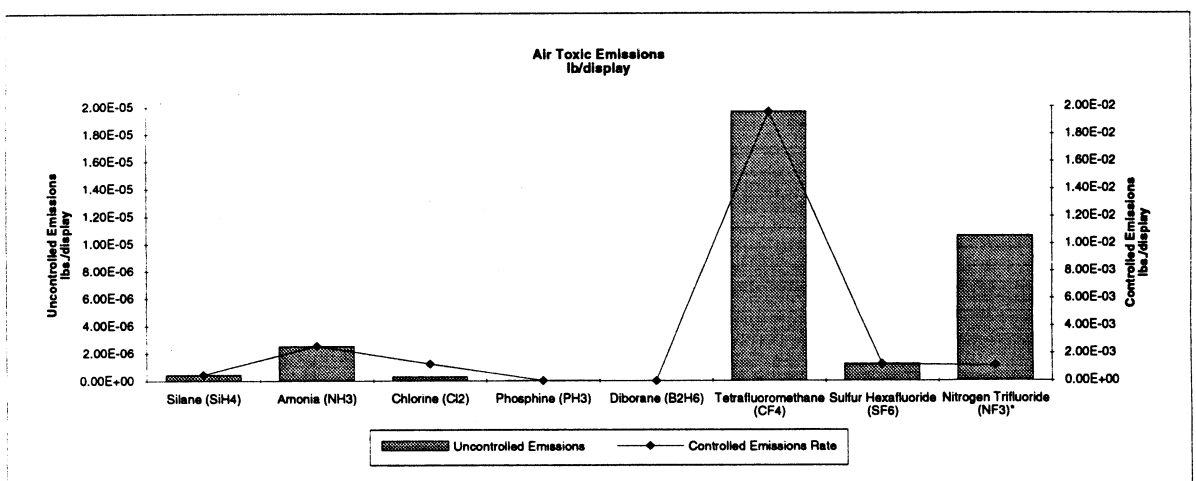


PROCESS ANALSYSIS: AIR EMISSIONS FROM MANUFACTURING

FIGURES IX, X, XI: AIR EMISSIONS







PROCESS ANALSYSIS: AIR EMISSIONS FROM MANUFACTURING

Table I: VOC Emission Rates Produced by Organic Solvents from Photolithography

Trade Name	Chemical Name	Quantitities Used (gal/hr)	Usage Rate ml/display (1)	Emission (lbs/hr) via Solvent Exhaust	Lbs. VOC/ Display (1)	Potential Emissions (lbs/hr)	Lb. VOC/ Display (1)
Microposit (R) Remover 1165	NMP	2	953.9208	N/A		0.0672	0.008
NMP	NMP	0.16	76.313664	0.012	0.002	0.0054	0.001
Acetone	Acetone	0.23	109.700892	0.35	0.044	0.4453	0.056
IPA	IPA	0.23	109.700892	0.064	0.008	0.0852	0.011
Safe Strip	PGMEA	1.16	553.274064	N/A		0.0461	0.006
Thinner Type P	PGMEA	0.02	9.539208	N/A		0.0009	0.000
Photoresist (S 1805 and S 1813)	PGMEA	0.1	47.69604	0.051	0.006	0.0044	0.001
Toloune	Toluene	0.0014	0.66774456	0.0004	0.000	0.0004	0.000
Impruv (Acrylic Acid)	PUMA	0.04	19.078416	0.004	0.001	0.004	0.001

NMP 1-methyl-2-pyrrolidinone
PGMEA Propylene glycol monomethyl ether acetate
PUMA Polyurethane methacrylate

Note: Permit provides a set of data for solvent exhaust and potential emissions. These values are shown where available.
(1) Based on 40,000 displays per year and 5020 hrs of manufacturing operations

Table II: Acid Gas Emission Rates from Photolithography and Acid Ethching

Chemical	Uncontrolled Rates (lbs/hr)	lbs/dispaly (1)	Controlled Emission Rates (lbs/hr) (2)	lbs./display (1)
Hydrofluoric Acid (HF)	0.32	0.040	0.0032	0.000403
Phosphoric Acid (H3PO4)	0.08	0.010	0.0008	0.000101
Nitric Acid (HNO3)	0.26	0.033	0.0026	0.000328
Acetic Acid (CH3COOH)	0.15	0.019	0.0015	0.000189
Hydrochloric Acid (HCL)	3.24	0.408	0.0324	0.004082

(1) Based on 40,000 displays per year and 5020 hrs of manufacturing operations
(2) All Emissions are Controlled by Packed Bed Scrubber that has a 99% Control Efficiency

Table III: Air Toxic Emissions from Photolithography and PECVD

Chemical	g/hr	g/display (1)	Uncontrolled Rates (lbs/hr)	Uncontrolled Emissions lbs/display (1)	Controlled Emission Rates (lbs/hr)	Emissions lbs/display (1)	Controlled Emission lb/yr
Silane (SiH4)	1.58	0.19908	3.47E-03	4.37E-04	3.47E-06	4.37E-07	1.75E-02
Amonia (NH3)	9.11	1.14786	2.02E-02	2.55E-03	2.01E-05	2.53E-06	1.01E-01
Chlorine (Cl2)	70.71	8.90946	9.76E-03	1.23E-03	2.37E-06	2.99E-07	1.19E-02
Phosphine (PH3)	4.43	0.55818	2.01E-04	2.53E-05	2.01E-07	2.53E-08	1.01E-03
Diborane (B2H6)	1.08	0.13608	6.51E-05	8.20E-06	6.51E-08	8.20E-09	3.28E-04
Tetrafluoromethane (CF4)	0.09	0.01134	1.56E-01	1.97E-02	1.56E-04	1.97E-05	7.86E-01
Sulfur Hexafluoride (SF6)	0.03	0.00378	9.76E-03	1.23E-03	9.76E-06	1.23E-06	4.92E-02
Nitrogen Trifluoride (NF3)*	3.80	0.47880	8.38E-03	1.06E-03	8.38E-05	1.06E-05	4.22E-01

All Emissions are Controlled by Packed Bed Scrubber that has a 99% Control Efficiency and Delatech CDO Model No. 857V-M
* Not connected to Delatech CDO
(1) Based on 40,000 displays per year and 5020 hrs of manufacturing operations
(2) GWP for 100 years. Source: SEMATECH

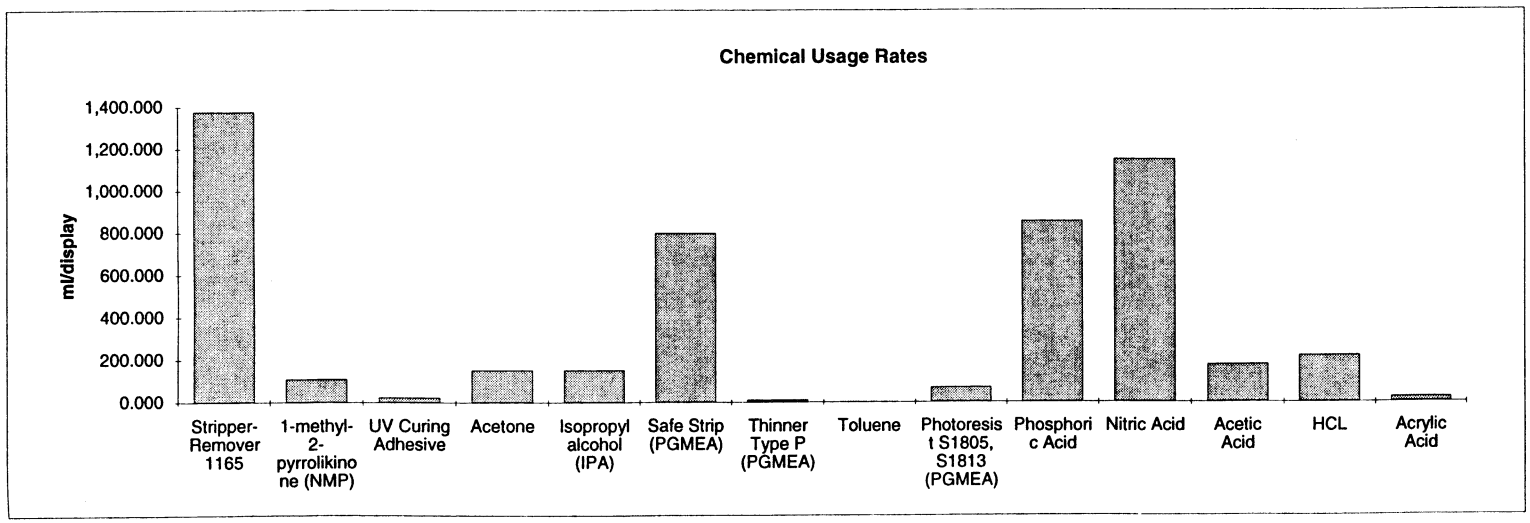
PROCESS ANALSYSIS: MATERIAL USAGE DURING MANUFACTURING

Table IV: Maximum Biweekly and Annual Material Usage Rates for the AMLCD Manufacturing Process

Chemical	Usage Rate (gals/2 wks.)	Gals/yr	Gals/hr (1)	ml/display (1)	Usage Rate (lbs/yer.)	Lbs/ substrate
Stripper-Remover 1165	560.00	14,560.000	2.889	1,377.886	124,362	3.109
1-methyl-2-pyrrolikinone (NMP)	45.00	1,170.000	0.232	110.723	10,002	0.250
UV Curing Adhesive	10.00	260.000	0.052	24.605	2,212	0.055
Acetone	63.00	1,638.000	0.325	155.012	10,740	0.269
Isopropyl alcohol (IPA)	63.00	1,638.000	0.325	155.012	10,740	0.269
Safe Strip (PGMEA)	325.00	8,450.000	1.677	799.666	67,330	1.683
Thinner Type P (PGMEA)	6.00	156.000	0.031	14.763	1,321	0.033
Toluene	0.40	10.400	0.002	0.984	75	0.002
Photoresist S1805, S1813 (PGMEA)	29.00	754.000	0.150	71.355	6,383	0.160
Phosphoric Acid	348.00	9,048.000	1.795	856.257	139,683	3.492
Nitric Acid	468.00	12,168.000	2.414	1,151.519	142,402	3.560
Acetic Acid	73.00	1,898.000	0.377	179.617	16,137	0.403
HCL	91.00	2,366.000	0.469	223.906	23,617	0.590
Acrylic Acid	10	260.000	0.052	24.605	2,201	0.055

(1) Based on 40,000 displays per year and 5020 hrs of manufacturing operations

FIGRUE XIII: CHEMICAL USAGE RATE



APPENDIX E: YIELD ANALYSIS

COLOR FILTER SUBSTRATE PREPARATION

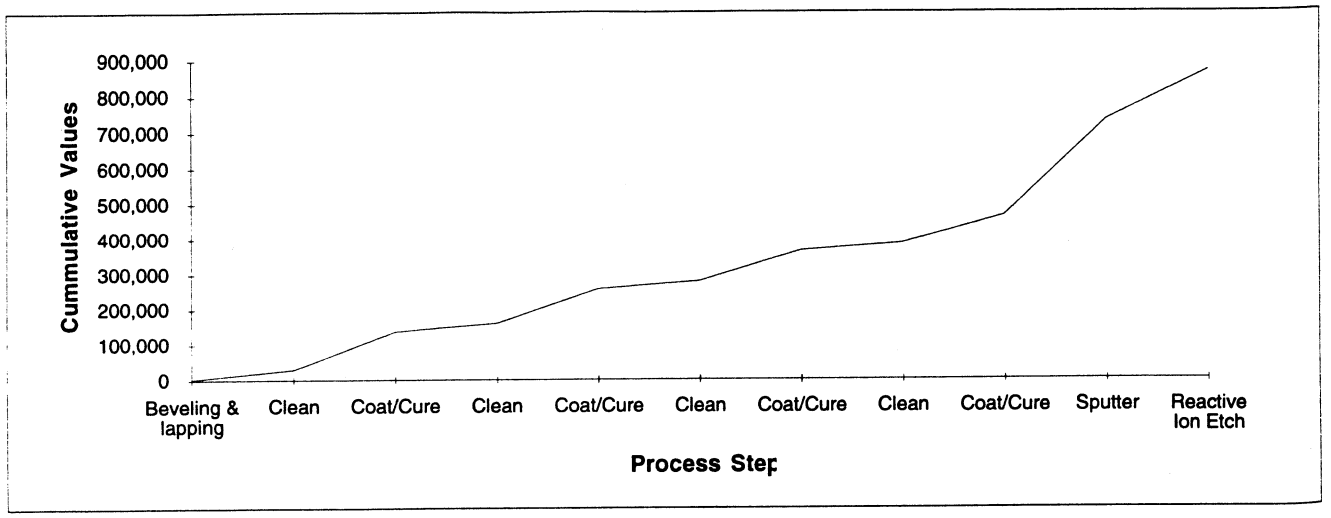
Assumptions:
Energy demand derived by dividing the total KwH demand for process by annual througput

Color Filter Yield	0.569	
Substrate Starts/Year	70,323	
Year End Substrates	40,000	
Substrates/Hour	13.95	
Substrate Configuration	4	
Dispaly Dimension	6	
Display Size	225	cm2
Coater Efficiency	0.9	
Number of Colors	4	
Hours of Operation	5040	

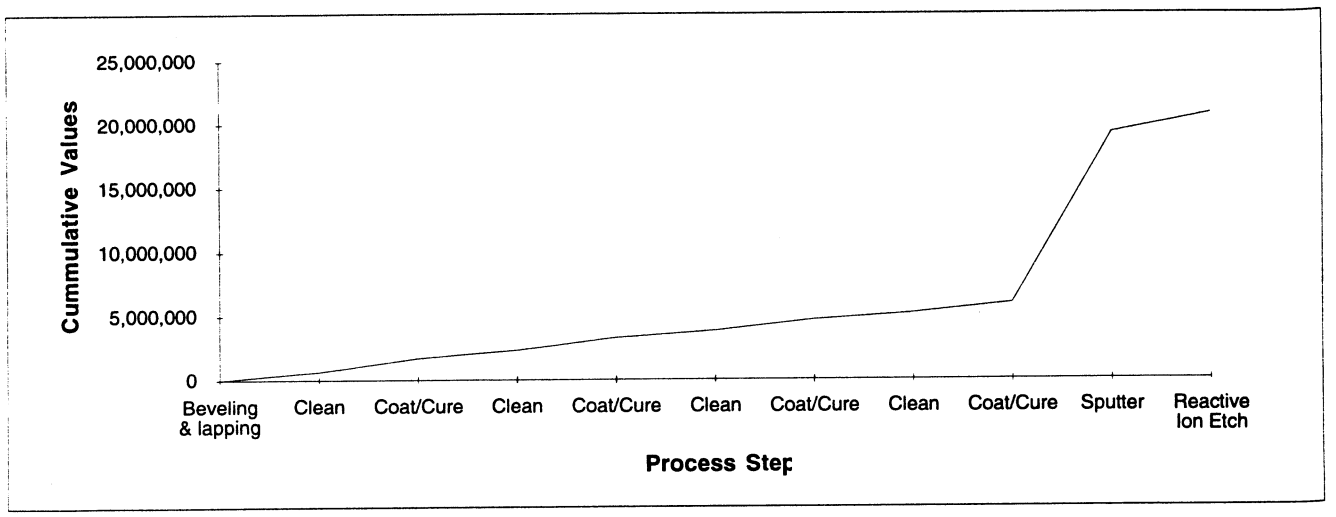
	# Substrates	Yield/Pass	Subs to Next	Energy (kWH)	Cummulative Kwh	%	All Water	Cum Water	%	DI Water	Cum DI Water	%
Beveling & lapping	70323.48	0.95	66,807	2,722	2,722	0.00	0	0	0.00	0	0	0.00
Clean	66807.30	0.95	63,467	26,542	29,264	0.03	674,862	674,862	0.03	166,788	166,788	0.23
Coat/Cure	63466.94	0.95	60,294	106,783	136,047	0.16	1,060,823	1,735,685	0.08	44,675	211,464	0.29
Clean	60293.59	0.95	57,279	23,955	160,002	0.18	609,063	2,344,747	0.11	150,526	361,990	0.50
Coat/Cure	57278.91	0.95	54,415	96,372	256,373	0.30	957,392	3,302,140	0.16	40,320	402,310	0.55
Clean	54414.97	0.95	51,694	21,619	277,992	0.32	549,679	3,851,819	0.19	135,850	538,160	0.74
Coat/Cure	51694.22	0.95	49,110	86,975	364,968	0.42	864,047	4,715,866	0.23	36,388	574,548	0.79
Clean	49109.51	0.95	46,654	19,511	384,479	0.44	496,086	5,211,951	0.25	122,605	697,153	0.96
Coat/Cure	46654.03	0.95	44,321	78,495	462,974	0.53	779,802	5,991,754	0.29	32,841	729,994	1.00
Sputter	44321.33	0.95	42,105	267,775	730,750	0.84	13,305,600	19,297,354	0.93	0	729,994	1.00
Reactive Ion Etch	42105.26	0.95	40,000	136,080	866,830	1.00	1,512,000	20,809,354	1.00	0	729,994	1.00
TOTAL				866,829.60			20,809,353.60			729,993.60		

Process Tool	Function	Energy Demand (KwH)	Water Consumption (GPM)	DI Water Consumption (GPM)		Materials	Material/ Substrate	Value Added (Accm)	Value Added (Acm/cm2)	Total (acm/cm2)
Beveling & lapping	Glass Proce:	2,722								
Total Bev Subs	70323.48									
Sub Total		**0.04**								
Clean	Cleaning	91,627	7.70	1.90	100	Detergent (ml/min)	131.1217432	0		
Conveyor Oven	Drying				0.3	IPA (g/min)	0.39336523	0		
					0.35	CO2 Ionization (200 CFM)	0.458926101	0		
Total Clean Subs	230625.37									
Sub Total		**0.40**	**10.10**	**2.50**						
Spin Coater	Overcoat	368,626	12.11	0.51	10	Color Poly (ml/sub)	2190940.975	219094.0975	3895.01	243.437886
Spin Coater	Resist Coat				1200	MIBK (ml/Min)	1656.274652	0		
Developer	Develop				50	Developer (ml/min)	69.01144382	0		
Developer	Develop				120	Developer AQ (ml/sub)	26291291.7	0		
Stacked Oven	Soft Bake									
MRS Stepper	Expose									
Conveyor Oven	Cure									
Total Coat	219094.10									
Sub Total		**1.68**	**16.71**	**0.70**						
Sputtering	ITO Deposit	267,775	44.00	0.00						
Total Sputter	44321.33									
Sub Total		**6.04**	**300.21**	**0.00**						
Reactive Ion Etch	Safe Strip	136,080	5.00	0.00	200	SF6 (SCCM)	0			
Total RIE	42105.26				200	CH4 (SCCM)	0			
Sub Total		**3.23**	**35.91**	**0.00**	50	BCL3,CL2 (SCCM)	0			
Clean	DI Water									
TOTAL		**866,829.60**	**20,809,353.60**	**729,993.60**						
Per Substrate		**11.39**	**362.93**	**3.20**						
Per Substrate [Based on 40,000 per year]		12.3263	295.9091	10.3805						

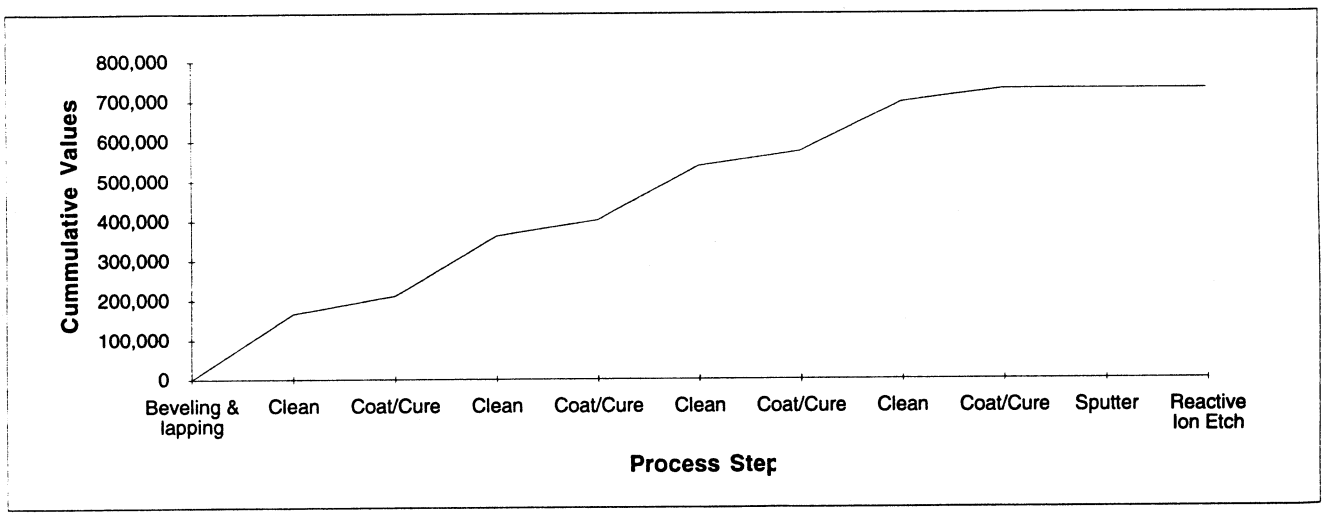
KwH

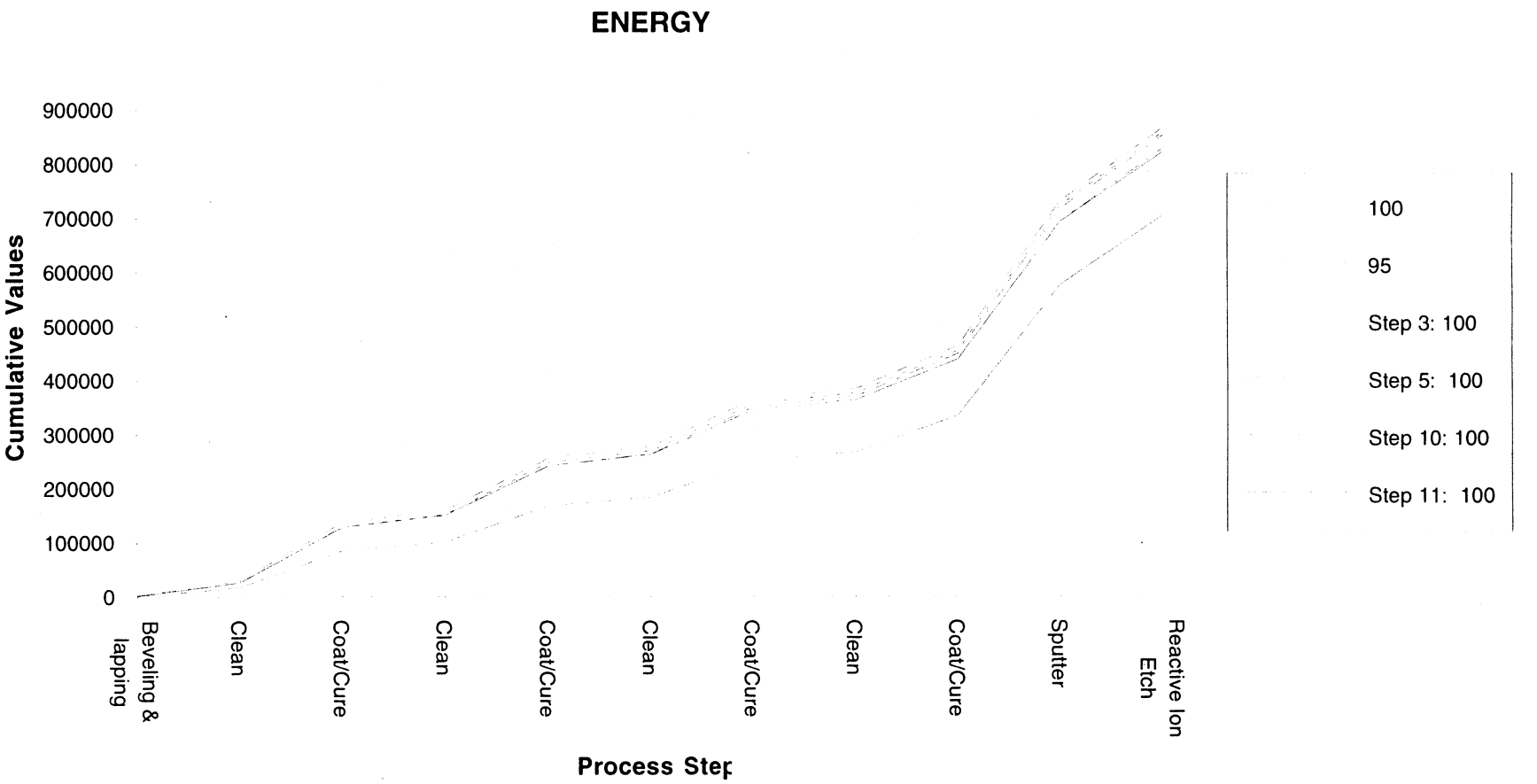


All Water



DI Water




ENERGY
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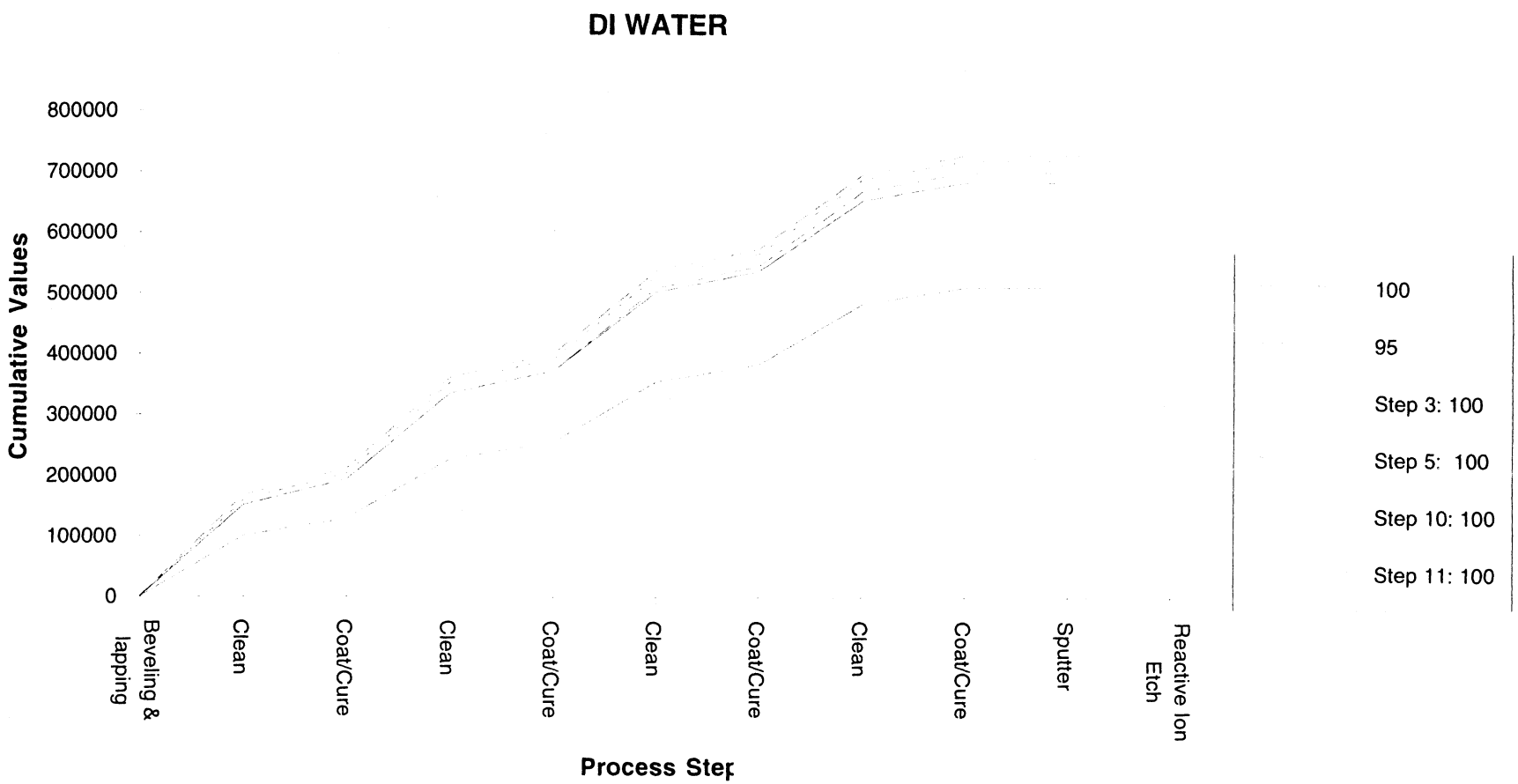
800000
700000
600000
500000
400000
300000
200000
100000
0
Cumulative Values
Beveling & lapping
Clean
Coat/Cure
Clean
Coat/Cure
Clean
Coat/Cure
Clean
Coat/Cure
Sputter
Reactive Ion Etch
Process Step
100
95
Step 3: 100
Step 5: 100
Step 10: 100
Step 11: 100


DI WATER
Cumulative Values
800000
700000
600000
500000
400000
300000
200000
100000
0
Beveling & lapping
Clean
Coat/Cure
Clean
Coat/Cure
Clean
Coat/Cure
Clean
Coat/Cure
Sputter
Reactive Ion Etch
Process Step
100
95
Step 3: 100
Step 5: 100
Step 10: 100
Step 11: 100

ACTIVE DEVICE SUBSTRATE PREPARATION

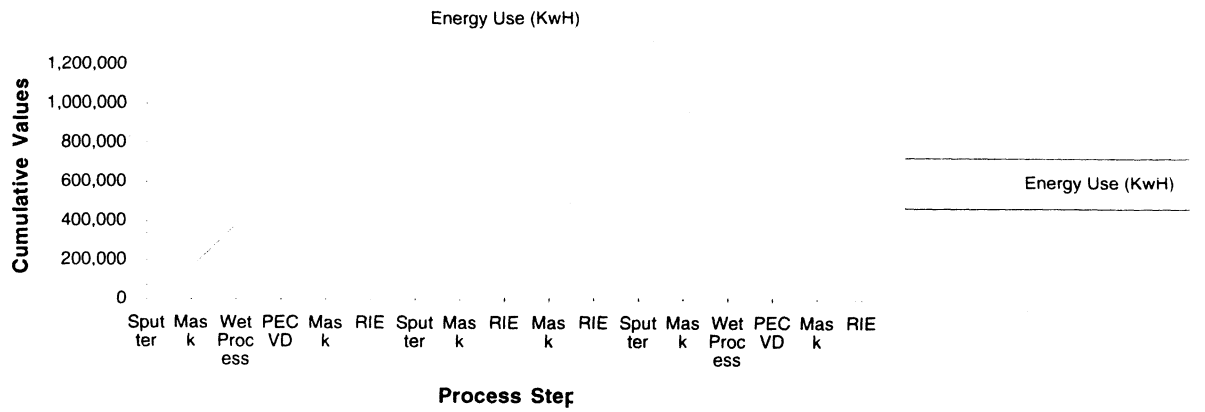
Assumptions:

Active Device Yield	0.418	Gallons/liter	3.7854
Substrates Starts/Year	95,666	Ml/gallon	3785.4
Year End Substrates	40,000		
Substrates/Hour	18.98		
Substrate Configuratio	4		
Display Dimension	6		
Display Size	225 cm2		
Hours of Operation	5040		
Sputtering Passes	3		
PECVD Passes	2		
Number of Masks	6		
Wet Process Passes	6		
RIE Passes	3		

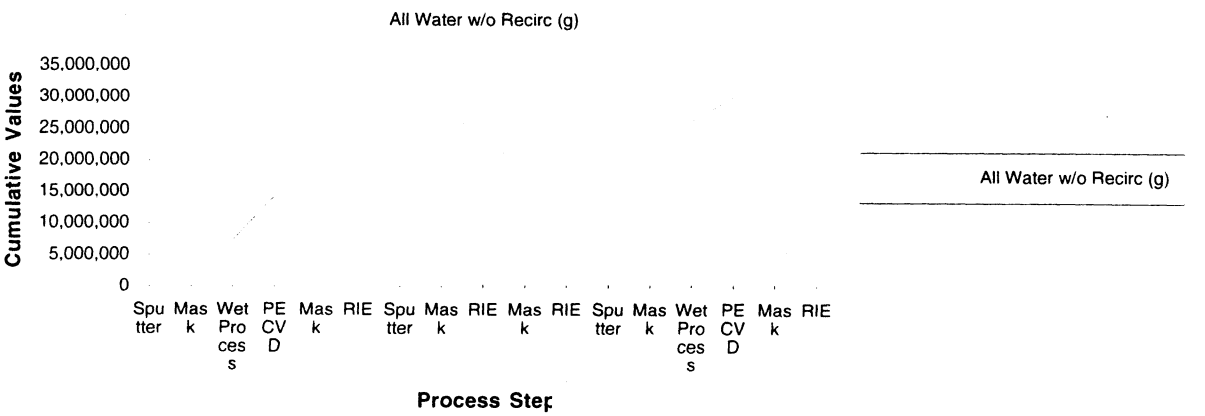
	# Substrates	Yield/Pass	Subs to Next	Energy (kWH)	Cummulative KwH	%	All Water	Cum Water	%	DI Water	Cum DI Water	%
Sputter	95666.24	0.95	90,883	72,650	72,650	0.06	4,462,709	4,462,709	0.14	0	0	0.00
Mask	90882.93	0.95	86,339	90,074	162,725	0.14	1,477,652	5,940,362	0.19	19,074	19,074	0.01
Wet Process	86338.78	0.95	82,022	217,239	379,964	0.32	1,378,611	7,318,972	0.23	838,886	857,960	0.61
PECVD	82021.84	0.95	77,921	104,090	484,053	0.40	6,939,316	14,258,289	0.46	0	857,960	0.61
Mask	77920.75	0.95	74,025	77,227	561,281	0.47	1,266,902	15,525,191	0.50	16,353	874,313	0.63
RIE	74024.71	0.95	70,323	42,526	603,806	0.50	472,506	15,997,698	0.51	0	874,313	0.63
Sputter	70323.48	0.95	66,807	53,405	657,211	0.55	3,280,501	19,278,199	0.62	0	874,313	0.63
Mask	66807.30	0.95	63,467	66,213	723,424	0.60	1,086,210	20,364,409	0.65	14,021	888,334	0.64
RIE	63466.94	0.95	60,294	36,460	759,884	0.64	405,115	20,769,524	0.67	0	888,334	0.64
Mask	60293.59	0.95	57,279	59,757	819,641	0.69	980,305	21,749,829	0.70	12,654	900,988	0.64
RIE	57278.91	0.95	54,415	32,905	852,547	0.71	365,617	22,115,446	0.71	0	900,988	0.64
Sputter	54414.97	0.95	51,694	41,323	893,870	0.75	2,538,389	24,653,835	0.79	0	900,988	0.64
Mask	51694.22	0.95	49,110	51,234	945,105	0.79	840,489	25,494,324	0.82	10,849	911,837	0.65
Wet Process	49109.51	0.95	46,654	123,566	1,068,670	0.89	784,154	26,278,478	0.84	477,159	1,388,996	0.99
PECVD	46654.03	0.95	44,321	59,206	1,127,876	0.94	3,947,084	30,225,562	0.97	0	1,388,996	0.99
Mask	44321.33	0.95	42,105	43,927	1,171,803	0.98	720,614	30,946,176	0.99	9,302	1,398,298	1.00
RIE	42105.26	0.95	40,000	24,189	1,195,992	1.00	268,762	31,214,938	1.00	0	1,398,298	1.00
TOTAL				1,195,992.00			31,214,937.60			1,398,297.60		

Process Tool	Function	Energy Demand (KwH)	All Water Consumption (GPM)	DI Water Consumption (GPM)	Materials		Material/ Substrate	Mat/cm2	Cost	Total (acm/cm2)
Cassette	Clean									
[Usage levels assumed to be part of Active Photo process summarized below]										
PECVD	TFT Deposit	163.296	36.00	0.00	25000	N2O (ml/m	58,752.27	261.12		
					1000	SiNH4	2,473.78	10.99		
					1000	NH3	2,603.98	11.57		
					200	PH3	860.03	3.82		
					8000	HF3	36,211.61	160.94		
					180000	N2	857,643.40	3,811.75		
Sub-Total: Per Substrate		***1.27***	***84.60***	***0.00***						
[Each substrate goes through PECVD. One cluster tool is devoted to active device deposition]										
Sputtering	TFT Deposit	167.378	34.00	0.00			0.00			
[Each substrate goes through Sputtering. One cluster tool is devoted to active device deposition]										
Sub-Total		***0.76***	***46.65***	***0.00***						
Wet Process	Etch Back	340.805	7.15	4.35	100	1165 (ml/min)	223.26	0.99		
[Each substrate goes through Wet Process]					15141.6	NH4,NF (mL)	5.81	0.03		
					15141.6	Tatanc (ml)	5.81	0.03		
					378.54	Sulfunc (ml)	0.15	0.00		
					50	1165 (ml/min)	111.63	0.50		
					200	CH4 (sccm)		0.00		
					500	Phos,HNO3,NAC	500.00	2.22		
Total Wet Substrates					500	Phos/NHO3,NAC	500.00	2.22		
#REF!					900	HNO3,HCL,N2O (	900.00	4.00		
Sub-Total		***2.52***	***15.97***	***9.72***						
Spin Coater	Resist Coat	388.433	21.07	0.27	12	Resist (ml/sub)	12.00	0.05		
[Part of Active Photo area]					150	Developer AQ (ml/	150.00	0.67		
					1135.62	Thinner (ml/min)	876.23	3.89		
					75708	Solvent (ml)	10.04	0.04		
UV Ozone	Clean				50	Developer (ml/min	38.58	0.17		
[Part of Active Photo area]										
Stacked Oven	Bake									
MRS Stepper	Expose									
Developer	Develop									
Stripper										
[Part of Active Photo area]										
Total Masked Substrates										
391920.12										
Sub-Total		***0.99***	***16.26***	***0.21***						
Reactive Ion Etch	Etch	136.080	5.00	0.00	200	SF6 (SCCM)	0	0		
[Each substrate goes through RIE]					200	CH4 (SCCM)	0	0		
					50	BCL3,CL2 (SCCM	0	0		
Sub-Total		***0.57***	***6.38***	***0.00***						
Oven	Bake	[Part of Active Photo area]								
TOTAL		1,195,992.00	31,214,937.60	1,398,297.60			**0**	**0**	**0**	
Per Substrate		6.11	169.86	9.93						
[Based on expected yield and process steps]										
Per Substrate		29.90	780.37	34.96						
[Based on number of on-spec product: 40,000]										

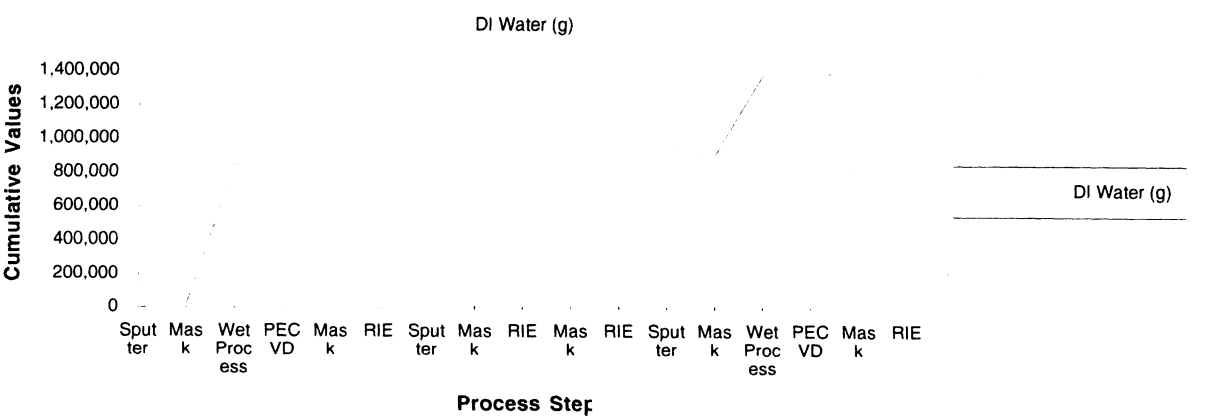
ENERGY

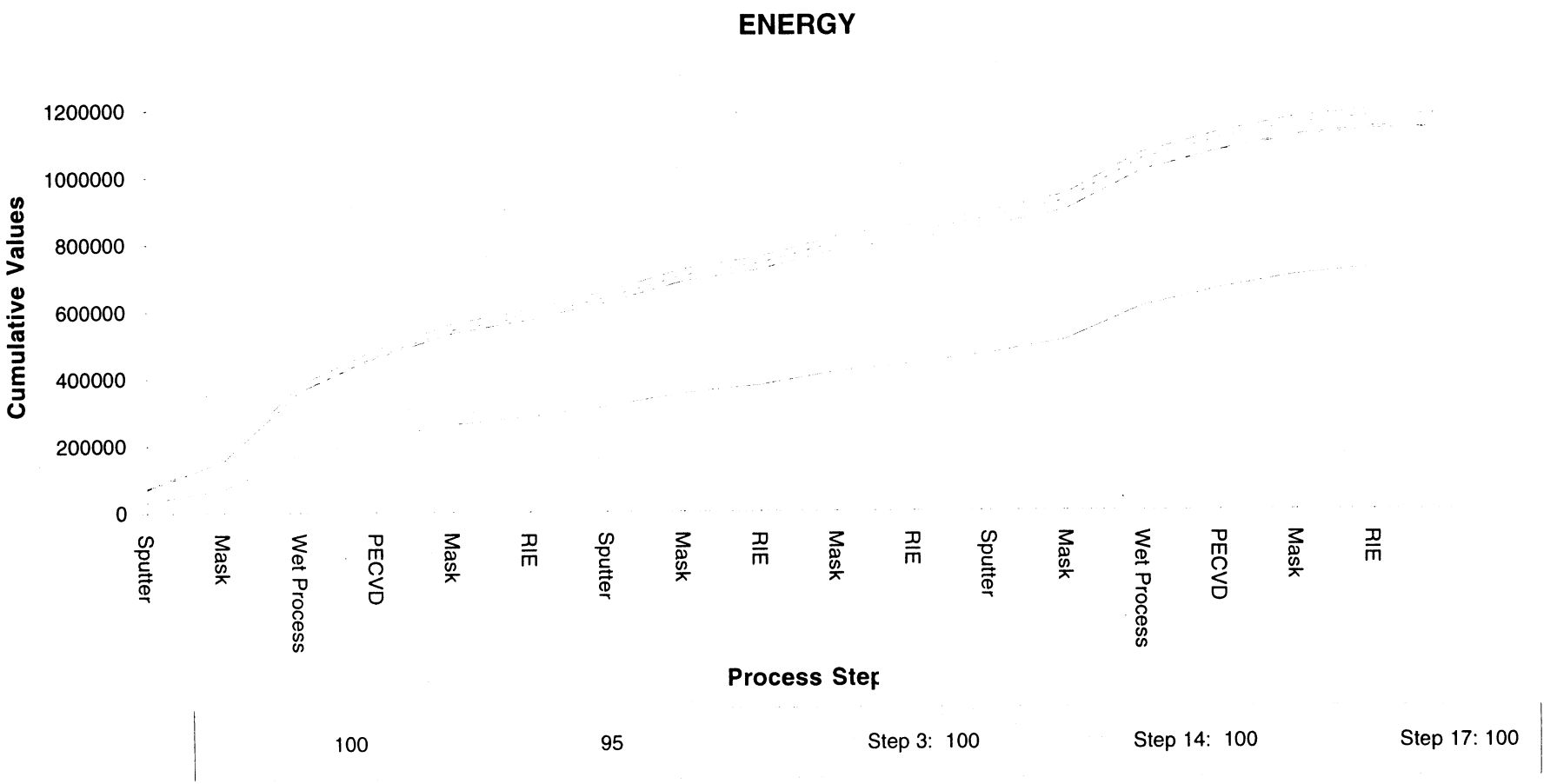


ALL WATER



DI WATER




ENERGY
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800000
600000
400000
200000
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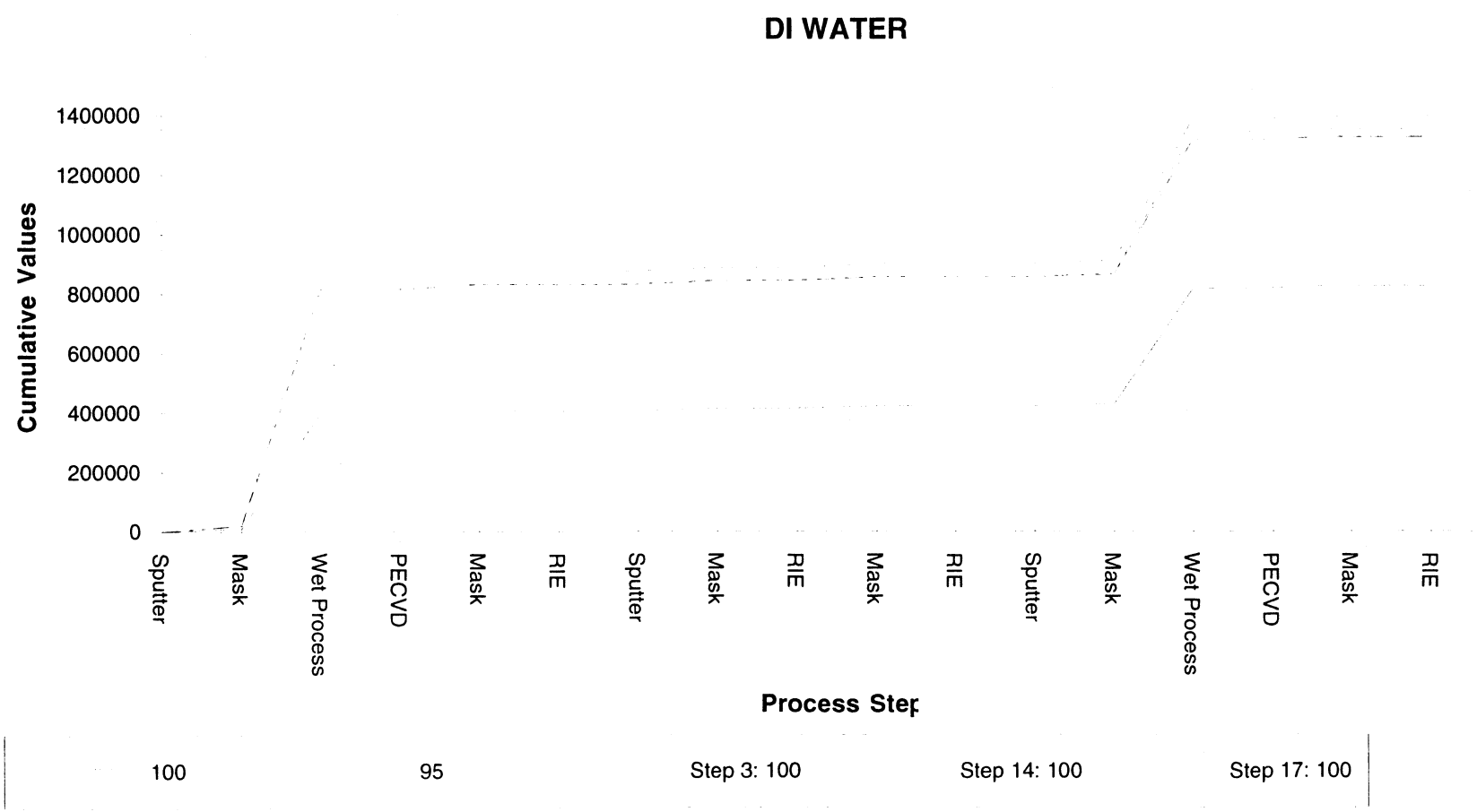
Sputter
Mask
Wet Process
PECVD
Mask
RIE
Sputter
Mask
RIE
Mask
RIE
Sputter
Mask
Wet Process
PECVD
Mask
RIE
Process Step
100
95
Step 3: 100
Step 14: 100
Step 17: 100


DI WATER
Cumulative Values
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200000
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Sputter
Mask
Wet Process
PECVD
Mask
RIE
Sputter
Mask
RIE
Mask
RIE
Sputter
Mask
Wet Process
PECVD
Mask
RIE
Process Step
100
95
Step 3: 100
Step 14: 100
Step 17: 100

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