BUILDING U.S. CAPABILITIES IN FLAT PANEL DISPLAYS

THE FLAT PANEL DISPLAY TASK FORCE

FINAL REPORT

Department of Defense

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IN
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Preface

Displays are emerging as a critical interface to the sensors and information systems that are revolutionizing the way in which conflicts will be fought. The potential importance of these advanced systems, vividly demonstrated by our military forces during Operation Desert Storm, had already been recognized: between 1989 and 1993, the U.S. Department of Defense invested approximately $300 million dollars in research and development in advanced flat panel display technology.

As our display technology investments came up for review in early 1993, it became evident that a clear path that would enable the Department to procure advanced flat panel displays for military systems remained elusive and uncertain. The continued availability of leading edge display technology for military applications posed a potential concern for the technology and industrial base supporting the national defense. I was tasked by the Administration to develop a framework for future policy decisions in this area.

I asked Dr. Kenneth Flamm, currently the Principal Deputy Assistant Secretary of Defense (Economic Security) and my special assistant for Dual Use Technology Policy, to lead this study. He assembled a highly qualified team of experts from the Departments of Commerce, Defense, Energy, and the Treasury, the Central Intelligence Agency, the Office of Science and Technology Policy, and the Office of the United States Trade Representative. This team's assessment of the technical, economic, and policy issues concluded that the Department of Defense must have early, assured, and affordable access to the most advanced display technology, and that it currently lacks such access. The analysis and recommendations contained within this report were the underpinnings of the National Flat Panel Display Initiative announced in April 1994. The process of producing this assessment was also very helpful in defining the issues, methodology, and approach for the Department's dual use technology policy, which seeks to maximize the national security benefit from commercial industrial and technological capabilities.

This report is truly a substantial and significant analytical effort, and I would like to personally acknowledge and thank the team that labored over many months to conduct this assessment. Key contributors to the study include: Andrew Gilmour, Lance Glasser, Marvin Goldstein, Mark Hartney, Heidi Hoffman, John Hill, Wayne Hofer, Kent Hughes, Chuck Kimzey, Jay Mandelbaum, Daniel Petonito, Matt Rohde, Wendy Silberman, David Slobodin, Donald Stein, Karen Swasey, David Tarbell, Mark Thompson, Dick Urban, Richard Van Atta and David Warlick. Also, the assistance of Dan McMahon, Paul Halpern, Tom Meeker, Dan McMorrow, and Teresa Dillard in producing this report is greatly appreciated.

John M. Deutch

Deputy Secretary of Defense

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A. TECHNOLOGY AND NATIONAL SECURITY

U.S. national security demands that United States military forces have guaranteed, cost-effective access to the world's best technology. The traditional approach for the U.S. government to meet defense technology requirements would be to use the Department of Defense (DoD) budget to conduct R&D, then procure from specialized defense suppliers, and through this build necessary production capabilities. In the past, when DoD requirements constituted a significant portion of high technology markets, this approach was often successful. DoD demand was then sufficient to sustain both the technology and production base at the leading edge, though with the penalty of higher costs than might have been obtained by purchasing commercial products. But today, with the declining DoD budget, demand levels, and resources, this approach is both unaffordable and ineffective.

Such a specialized approach is unaffordable because it does not take advantage of the economies of scale that come from high volume commercial production. Moreover, it is ineffective because it is unlikely that a defense-unique industry could keep pace in important areas with the rapid technological innovation driven by a highly dynamic commercial sector.

DoD is entering a new era in which it will increasingly rely on commercial components and technologies to meet defense requirements. Maintaining the technological superiority of defense forces will therefore necessarily require that commercial industry be able to supply products using leading edge technologies at competitive, affordable prices. Thus, a new goal for DoD R&D must be to ensure that the key elements of the domestic commercial technology base that are critical for national security remain at the leading edge.

The Clinton Administration has developed a new technology strategy that promises to deal effectively with these major changes affecting our national and economic security in the 1990s. That strategy includes the dual use technology vision outlined by Secretary of Defense William Perry and Deputy Secretary of Defense John Deutch. At the heart of this vision are two key principles:

- To reduce costs, and accelerate the introduction of new technologies into defense systems, DoD must make use of components, technologies and subsystems developed by commercial industry, wherever possible, and develop defense unique products only where necessary.
- To capitalize on this acquisition strategy, DoD's R&D efforts must focus on critical dual use technologies and capabilities that will continue to be advanced through industry's efforts to remain competitive in commercial markets. Thus, even where the military applications are specialized or unique, the underlying technologies will be sustainable through commercial forces.

B. IMPLEMENTING A DUAL USE INITIATIVE

Any initiative under the dual use strategy, rather than maintaining defense-unique producers, seeks to foster the creation of a viable domestic industry that is competitive in global markets and able to meet defense requirements drawing on the commercial technology base. This dual use strategy may call for initial government investments, but these investments will mean substantially lower future outlays as DoD acquires its products at much lower cost from commercial suppliers and relies on a healthy, dynamic, domestic commercial industry to carry the weight of future R&D investments at the leading edge.

To be successful, new initiatives must be guided by six overriding principles:

- The initiative must be of sufficient scope and duration to attract significant industry participation.
- Industry must be willing to share in the costs of the initiative. The extent of industry willingness to bear such costs is one of the most important measures of the initiative's value.
- The initiative should be based on principles of competition among firms and technologies. Central to this principle is the notion that the initiative will go forward only if industry responds with acceptable proposals and plays a lead role in determining the technologies to pursue.
- Given the international nature of modern, high-technology industries and the emphasis on achieving leading-edge capabilities, DoD programs should have the flexibility to consider participation by foreign-owned entities that satisfy program objectives.
- The initiative should be consistent with other government policy objectives. In particular, given the leading role of the United States in supporting an open international trading system and the benefits that such a system has for our economic security, the initiative should be consistent with U.S. obligations under the General Agreement on Tariffs and Trade and the World Trade Organization.
- The initiative must be subject to sunset provisions and include clear measures of success to force and guide decisions about the continuing necessity of the initiative over the medium- to long-term.

C. FLAT PANEL DISPLAYS AND U.S. NATIONAL SECURITY

A defense-critical set of information display technologies grouped under the label of flat panel displays today presents DoD and the nation with just the set of choices for which the dual use strategy was created. Flat panel displays (FPDs)—millimeters deep, weighing well under a pound, rugged enough for avionics, and completely portable—are currently poised to enable a vast new range of commercial and military applications of information technology. Demand for FPDs throughout the world will grow explosively for the foreseeable future. The lowest credible estimate projects a twofold growth in the $6.5 billion 1993 FPD market by the turn of the century. More optimistic estimates are forecasting growth of three to six times today's market by the year 2000, reaching from $20 billion to $40 billion. The largest producer today projects a $9 billion market by 1996 in just liquid crystal displays, the most popular current technology.

Demand is overwhelmingly driven by a proliferating array of commercial products. Computer displays, primarily for portable personal computers, are the largest single commercial market. Indeed, today's laptop computers were primarily enabled by the flat panel display. In addition to the computer market, there are a broad range of other commercial applications including vehicle displays (aviation cockpits, automobile dashboards and navigation displays), personal digital assistants, video telephones, medical systems, and high definition, full motion video (including HDTV).

Although FPD applications are being driven by the commercial market, FPDs are becoming increasingly important for meeting military requirements. As Desert Storm demonstrated in a dramatic and compelling fashion, our armed services are rapidly moving into an era in which information is the primary currency used to secure both tactical and strategic military advantage, save lives, and reduce material losses. A virtual torrent of digital data—from myriad air, sea, ground surveillance systems, orbiting space sensors, specialized remote probes, intelligence sources, digital mapping databases, and a proliferating array of new sources—will have to be fused together and presented to a combatant in ways that permit fast and effective real-time responses on the front line. The outcomes of future conflicts will be increasingly decided by the quality and effectiveness of the information resources utilized by our forces.

Visual displays are the primary interface between those making time-critical military decisions and their information resources, showing both information gathered by sophisticated sensors and text and graphical data required for optimal mission performance. Current display systems are available in a limited range of sizes, consume too much power, are too heavy, and are limited by ruggedness and reliability considerations. A variety of different sized flat panel displays—from wall-sized command and control displays, down to small head-mounted displays for the individual soldier—are urgently needed for systems that must be lightweight, low power, economical, and have resolutions that match both the human eye and our most sophisticated sensors. Sensors, intelligence fusion systems, command and control systems, and fire control systems will be constrained by the availability and performance of their display interfaces.

An example of a military display need is the presentation and manipulation of map data. The only revolution to date in military use of maps has been the introduction of acetate overlays and grease pencils—nothing else has changed. Our forces now require portable map-size displays that can be annotated with electronic overlays and transmitted to remote locations to enable a common view of the battlefield, permitting the receipt of satellite imagery, reference to a map, and access to information databases linked to every set of reference coordinates. Because the areas of interest and operations on the battlefield are increasing, larger displays with better resolution are needed. DoD does not now have this capability, and the flow and display of such information limits the tempo of military operations today.

While the military can tap into commercial display technology and products, the range of military needs is not and will not be fully supported without customization for military users. Our military must have displays that operate in the desert and the Arctic, that are available in a range of sizes and capabilities suited to particular military requirements (rugged, wide viewing angle, sunlight readable, night vision, and other synthetic environments) that are portable, and that have pixel formats and resolutions matched to our sensors. Also, as display systems evolve, the military will incorporate display drivers, frame buffers, and image and signal processing on the display. With the greater integration of information processing into the display, DoD's suppliers will require early access to the display design and manufacturing process. Finally, our forces must have early access to the most advanced systems, in prototype form, in order to work out the strategy, tactics, and integration with command and control systems that will optimize their use when introduced onto the battlefield.

Military applications—including cockpit displays for aircraft and surface vehicles, command and control centers, high resolution intelligence data visualization, and portable computer and communications systems—embedded in systems currently in the DoD procurement pipeline (excluding computers) will generate a demand for about 15,000 displays annually over the years 1995-1999. In the future, helmet-mounted displays will also be a significant defense application. Over the years 2000-2009, DoD conservatively projects a demand rising to over 25,000 displays per year (again excluding computers). Over the 2010-2019 period, demand will jump even farther, to perhaps, 90,000 displays annually. Such military requirements, however, are likely to remain less than 5 percent of the U.S. display market. **But these military requirements for flat panel displays are critical to national security.**

In short, to gain a vital edge on the information-driven, digital battlefield of the future, DoD must have access to

- sources of leading edge display technology willing to address the customized requirements of military use;
- the most advanced display technology even before it has been introduced into widespread commercial use.

State-of-the-art technical and industrial FPD capabilities must be readily available to our military to address these requirements.

D. THE U.S. FLAT PANEL DISPLAY INDUSTRY TODAY

Today, U.S. industry has developed world class display technologies in the laboratory (to a significant degree, the result of recent investments by DoD's Advanced Research Projects Agency—ARPA), but has virtually no capabilities for volume production serving mainstream markets. **Without domestic volume production, the existing U.S. technology base is in jeopardy, and the rationale for continuing Federal investments in the area would be unclear.**

The U.S. flat panel display industry is a player in only very limited segments of the world market. Barring a substantial change in the status quo, **U.S. industry will continue to be of only marginal significance in the future.** A small number of Japanese firms dominate the world flat panel industry with over 90 percent of global production across all FPD technologies. In the predominant technology in the world market, liquid crystal displays (LCDs), a handful of Japanese producers account for about 95 percent of the world market. U.S. firms have greater presence in other technologies, specifically electroluminescent and plasma displays, but these are niche markets. Overall, U.S. firms have 3 percent of the global FPD market.

In particular, U.S. display producers have been unable to penetrate the dominant market for FPDs, notebook computers. The U.S. does not have a single supplier to this market. Not surprisingly, the lack of a substantial FPD industry goes hand in hand with a weak infrastructure of material, component, and equipment suppliers. This lack of a supplier base is particularly important in this industry, since materials and capital equipment drive the current FPD cost structure.

The relatively small size of the domestic industry, by necessity, generates modest prospects for success on the industry's current trajectory. The largest U.S. FPD producer had 1993 sales of less than $50 million, in sharp contrast with the market leader, a diversified Japanese electronics firm with corporate sales in excess of $13 billion. While individual companies can be very successful in serving even small markets (and there are U.S. companies doing so), a globally competitive industry contesting mainstream markets is unlikely to emerge from a niche or incremental strategy.

Despite the current market position of U.S. industry, important opportunities nonetheless exist. U.S. firms currently are demonstrating laboratory prototypes employing today's dominant flat panel display technology, active matrix LCD, that are considerably superior to any product yet shown anywhere in the world. In other emerging technologies—field emission displays, for example, and microscopic digital mirrors—U.S. companies are at the very forefront in R&D efforts. Many firms believe that displays may prove to be a key discriminating component for information products. With the greater integration of computer processing functions onto the display itself, many analysts also predict that it will be increasingly necessary to have close linkage between the design and production of the display and the end-products that use them. These factors, combined with continuing explosive growth in the display market, and ongoing indications from U.S. users of displays (who account for the bulk of global demand for FPDs) that they would actively support the establishment of alternative domestic sources for FPDs, have led some U.S. companies to seriously consider their possible entry into this market. These firms, however, are faced with obstacles which must be overcome, if a dual use industrial capability addressing defense needs is to be established.

E. OBSTACLES TO U.S. ENTRY INTO GLOBAL FPD MARKET

U.S. firms face major obstacles to entering high volume display production. They face major technical and manufacturing uncertainties: factory cost models show that small differences in technical, input requirement, and market pricing parameters generate huge swings in what otherwise might seem to be an acceptable rate of return on investments. High entry costs for a volume production facility (ranging up to $400 million, sunk into highly specialized plant and equipment), in a $4 billion industry whose precise future growth trajectory is uncertain, pose another major barrier to entry. Furthermore, plant costs are only the tip of the financial iceberg for serious entry into the business: equally formidable investments in marketing, distribution, and service infrastructure, and continuing follow-on technology expenditures will be required to keep pace in an extremely dynamic business environment.

Fear of foreign actions creates other obstacles: FPD consumers worry about possible reprisals from their established suppliers when considering link-ups to potential U.S. suppliers. Foreign government support or other forms of intervention on behalf of their producers raise strategic concerns for U.S. producers considering entry (i.e., American firms contesting this market must worry about facing alone foreign competitors backed implicitly or explicitly by the full resources mobilized by their national governments). Finally, the inability to obtain needed components, materials, and equipment (with the best possible pricing and delivery times) from foreign producers linked to their overseas competitors is another common concern for potential American entrants.

When the major Japanese players in this industry made large investments in the LCD business in the 1980s, they enjoyed a significant capital cost advantage relative to American firms in a highly capital intensive business. That advantage may have disappeared, but, as "second movers," U.S. firms face some significant disadvantages in entering the industry today. A lack of experience in volume production means their manufacturing costs will be well above those of their Japanese competitors, since costs fall sharply in this industry along a learning curve (i.e., average costs fall with cumulative experience in production). Lack of a domestic infrastructure in materials and equipment is another potentially critical disadvantage: cost models suggest that materials currently constitute about 39 percent of manufacturing cost, and capital equipment another 33 percent in the active matrix FPD business. Clearly, access to the best and most technically advanced materials and capital equipment, at the best possible price, will be critical to competitive success.

F. RATIONALE FOR ACTION

U.S. national security requirements will not be met by current domestic or foreign suppliers. The world's dominant supplier and technology leader (with approximately 55% market share for mainstream active matrix LCD displays) has stated to U.S. DoD officials that it will not directly supply technology or products to the U.S. military, or make customized display products for military use available to U.S. defense contractors. Negative foreign private sector attitudes toward working with DoD are compounded by ambiguities in foreign government controls on the export of technologies tailored for military end use.

This means that **DoD cannot currently rely on the existing overseas supply base to furnish customized or specialized products or capabilities that will be required to support future DoD needs, or to provide leading edge technology to DoD before it is in widespread commercial use.** Thus, for this critical defense technology, the high degree of geographic concentration of this industry, coupled with the unwillingness of foreign suppliers to serve DoD needs, and the extremely limited volume production in the United States, raise concerns about early and assured access to both the supply of display products and to leading edge FPD technology.

The concentration of FPD production in a few firms which also compete with U.S. computer, telecommunications, and consumer electronics firms, raises economic concerns about product and technology access, and the possible exercise of monopoly power. Currently U.S. electronic systems firms are highly dependent on allocations of supply from these foreign producers. Though it has not yet materialized as a concrete problem, potential denial of access to leading edge technology clearly is considered a strategic, long term concern by many U.S. display users. These users, too, provide an important component of the broader economic infrastructure serving defense needs.

The same concern is more immediately apparent within the domestic display industry, where there are worries that foreign producers have competitive advantages in access to components, materials, and equipment. There have been complaints of restrictions, and other uncompetitive practices in the supply and pricing of FPD components, materials and equipment.

Economic security may also be affected by ripple effects on industries for which FPDs are a key component. Technological spillovers may be significant: a robust domestic FPD industry is viewed by many industry experts to be linked to the future competitiveness of the information processing, telecommunications, and other electronic systems industries. Furthermore, many of the processes and equipment used in flat panel manufacture are based on technology used in semiconductor production, and significant synergies between the two sectors might be exploited by equipment and material manufacturers. If, as is expected, the entire design of important new products is embedded in electronics actually integrated into the display itself, sensitive design information for new products might have to be transferred to potential foreign competitors if no domestic supply base exists. With greater integration of electronics onto displays this dependency may increasingly impair the competitive position of U.S. electronics firms, and the overall health of a sector increasingly vital to DoD. **In the future such externalities may become increasingly significant.**

Moreover, a wide range of currently unimagined and unforeseen new applications may be enabled by this technology. Both national and economic security rationales, therefore, suggest that the social return from federal investments in this area are likely to vastly exceed the private return to any individual investor.

It is the conclusion of this study that defense technology needs cannot be met effectively through niche military suppliers. Even success in meeting defense-specific applications would not be assured by such suppliers, particularly over time, as it is unlikely that military-unique vendors could sustain themselves without very large and continuing DoD R&D funding. Moreover, the military-unique approach would not provide DoD the benefits of a dual use strategy—continued technology leadership sustained by ongoing innovation driven by the commercial mainstream, and affordability, through integration into a high volume commercial production base. With the predominantly commercial demand for FPDs, military needs for FPDs would best be met through a dual use technology strategy. That is, the DoD (and other mission agencies) should look to a healthy domestic commercial sector for the capabilities to meet its critical requirements rather than utilizing the traditional defense model of financing both technology and production using a dedicated supplier base.

G. A NATIONAL FLAT PANEL DISPLAY INITIATIVE

To meet the identified defense technology and production needs for FPDs through a dual use strategy, a set of recommended actions has been formulated as the National Flat Panel Display Initiative to

- Support U.S. FPD research and development
- Build national expertise in high volume process technology
- Encourage U. S. development of industrial capabilities in flat panel display production available to defense through focused R&D incentives
- Foster market development.

As outlined above, U.S. requirements for a domestic FPD production base stem from both the uncertainties of meeting FPD demand for military and commercial applications, as well as the need to ensure that other segments of the electronics industry are able to capture the positive externalities that derive from experience in volume production of FPDs. Thus, both consumers and producers in the U.S. have an interest in seeing the development of a competitive domestic production capability.

This study judges that penetration of 15 percent of the world market (up from the current 3 percent) is both an achievable near-term goal and an appropriate point at which to consider whether a government flat panel display program should be redefined, reduced, or terminated. This level of market share is probably sufficient to nurture and sustain the critical mass of U.S. infrastructure suppliers needed for the long term success of the U.S. FPD industry, to permit industry to exploit continued government R&D investments in advanced display technology, and to satisfy DoD needs at acceptable costs. This level of market share is also judged to be a point at which momentum should be strong enough for continued success. The year 2000 is a realistic target date for achieving this goal through an initiative encompassing the elements described below.

1. SUPPORT FPD RESEARCH AND DEVELOPMENT

In recent years the U.S. government has typically spent about $100 million annually on FPD R&D, with ARPA, the Department of Commerce (DOC), and the Department of Energy (DOE) taking leading roles. These efforts have focused largely on product technology, with lesser emphasis on process technology. They have addressed issues of basic science and technology as well as applications in specific product development. As a result of these efforts, U.S. companies are at the leading edge in understanding the functioning and design of FPDs of all types and technologies. However, U.S. industry lags considerably behind the leading edge in its understanding of the manufacturing processes and controls necessary to produce FPDs in high volumes at sustainable yield rates.

Under the National Flat Panel Display Initiative, the U.S. government will not only continue to fund R&D that pushes the leading edge in product technology, but also will seek opportunities to direct resources toward promising work in the area of process and manufacturing technology. Specifically, research objectives should continue in the areas of lower cost displays, increased display performance and functionality, manufacturing processes, and "intelligent displays" which integrate additional capabilities into the display unit.

While U.S. industry continues in its current nascent state, it is important to support the ARPA and DOE R&D programs with adequate levels of funding. For ARPA, the core R&D and infrastructure program should be about $70 million per year. ARPA should continue to develop a diverse portfolio of technologies and encourage innovative new approaches. The ARPA research program should also support longer range, particularly risky research areas, consistent with the overall ARPA mission. A balance of product and process technology should be nurtured to assure that new product developments can be moved quickly and cost effectively to the market. This program would also continue to support consortia efforts within the industry which create domestic infrastructure of equipment, component, and materials suppliers and to encourage synergy and the pooling of technological and financial resources.

For DOE, the level of support recommended is $10-20 million per year, covering both research and technology transfer efforts. DOE should increase funding for the DOE national laboratories in cost-shared programs which support accelerated display development, consistent with its mission. As part of the National Flat Panel Display Initiative, DOE should establish an explicit outreach program to pursue actively the transfer of laboratory technology useful to flat panel display production to industry. To enable a coordinated government program, it is suggested that interagency coordination be established to clearly link each agency's R&D efforts to the overall goal of this program.

2. BUILD NATIONAL EXPERTISE IN HIGH VOLUME PROCESS TECHNOLOGY

Since there are currently no high volume producers of flat panel displays in the U.S., the knowledge base does not exist to manufacture most flat panel products in high volume at competitive prices. Accomplishing the goals of this FPD initiative requires high volume production. Therefore, it is imperative for industry to gain this knowledge, and that such knowledge be widely available to reduce the considerable risks and uncertainties faced by start-ups, thereby encouraging new entrants.

Under a congressionally-mandated program, DoD has already supported the establishment of a low volume AMLCD manufacturing plant to satisfy near term military needs. Further DoD support for manufacturing test beds that develop and demonstrate production processes and produce displays in pilot quantities, can contribute to development of a sound foundation of knowledge necessary for future establishment of competitive high volume manufacturing capabilities. Additional support for such a test bed, with government cost-sharing of up to $50 million, is a sound and productive investment.

To be truly successful, the participants in a government-funded manufacturing test bed program must be willing to disseminate the knowledge gained about production processes for flat panel displays to U.S. suppliers and industry. In addition, the FPD manufacturing test bed program should engage in an active outreach program to assure that continuing technology transfer takes place to encourage potential U.S. entrants.

The timing of this manufacturing test bed is critical. The National FPD Initiative seeks to encourage decisions by the private sector to establish high volume FPD manufacturing plants in the U.S. These high volume plants, in turn, are absolutely dependent upon adequate process technology and infrastructure development which this test bed program will support. The test bed is an important element in reducing the uncertainty and the costs facing potential entrants in this arena.

3. ENCOURAGE U.S. INDUSTRY INVESTMENT IN FLAT PANEL DISPLAY PRODUCTION THROUGH FOCUSED R&D INCENTIVES

Under current conditions, risks are simply too great for industry to make the large scale investments required to build U.S. high volume FPD factories. Although some companies have considered plans for high volume production, no concrete investment for such a facility has been made to date.

To encourage such investment, the government should be prepared to make competitive awards for next generation research and development to companies demonstrating firm commitments to volume manufacturing. Through a series of sequential competitions, selected companies committed to new investments in volume production facilities for current generation products would be eligible to receive R&D support for follow-on technology development for next generation products and manufacturing processes, commensurate with the level of commitment demonstrated to volume production. Each of these competitions would be neutral with respect to technology, open to any flat panel display technology to which a firm is willing to commit resources. Important considerations in assessing proposals would include a commitment to invest in volume production, the quality of the technical proposal for follow-on R&D, and the degree of firms' commitment to match government R&D support. This R&D support would be distributed over a five year period and be subject to pre-negotiated goals and standards as well as appropriate oversight. The total program size would be scaled around follow-on technology support for as many as four world class, volume production facilities, to be established over the next five years.

The linkage of R&D funding to a commitment to produce is not an uncommon DoD practice. For example, in funding military aircraft R&D DoD is concerned with not just the technical quality of the proposed research, but also with the credibility and commitment of the proposer to move the results into production. For FPDs the situation requires analogous credibility and commitment to produce; otherwise, there would be no point in sustaining R&D efforts in this area.

These R&D funds would be used to conduct precompetitive research and development on future generations of FPD products and manufacturing processes. Firms would be expected, at a minimum, to match any government R&D support for this effort. This R&D incentive program would be aimed at supporting the long term ongoing investment in technology required to develop new products and processes that meet both government and commercial needs, by firms that commit to producing FPDs with current generation product and process technology. The follow-on R&D incentives associated with manufacturing facility commitments should have management controls built in to ensure that R&D investments are appropriately focused. Decisions to continue with subsequent competitions would be contingent on a determination of need and the success of prior efforts. Numerous "exit ramps" should be designed into this initiative to facilitate termination of individual projects, or the entire program, if warranted.

4. FOSTER MARKET DEVELOPMENT

a. Internal Market Development—Consolidation of the Government Market

Although small relative to world-wide demand, the U.S. government will be a very large buyer, in absolute terms, of products utilizing flat panel displays for general purpose applications—laptop computers, personal computers, and workstations. To contribute to the establishment of a U.S. flat panel industry, the Federal government should consolidate its buying program for general purpose displays.

Through the authority of a National Economic Council (NEC) directive, an Executive Agent should be appointed to manage a program to consolidate the acquisition of general purpose displays involving all agencies of the Executive Branch. The Executive Agent, in consultation with the General Services Administration, as appropriate, will support the agencies in: (1) assessing their needs for systems using flat panel displays over the next five years; (2) providing technical assistance in designing acquisition programs to take advantage of the best technology which satisfies those needs; (3) providing industry with the resulting market demand data; (4) developing and suggesting an overall government purchasing strategy that will maximize lot sizes for buys; (5) coordinating agency purchases. In addition, the Federal Government should provide funding and develop purchasing incentives which promote the use of domestically produced flat panel displays for national security applications, in a manner consistent with international agreements.

b. Internal Market Development—Stimulation of Demand

A second task directed by the NEC to the Executive Agent should be the convening of an interagency working group to explore the potential of flat panel display technology to meet future government needs. The working group would be tasked to identify applications and specify products, not currently in mass production, that could serve two purposes: (1) improve agency performance through insertion of leading edge technology, and (2) drive market demand for new products that could provide a large and specific target for a developing U.S. flat panel industry.

The possibilities that have been discussed include portable electronic blackboards, low energy computers, portable video conferencing, high resolution imagery and data display, and other applications involving the utilization of the emerging National Information Infrastructure. The Agent would report its conclusions and recommendations to the NEC for further action.

c. External Market Development—International Trade

Export Promotion—As part of its existing export promotion effort, DOC should include an aggressive program for products of the U.S. FPD industry and its supporting industries.

Market Access—Under the leadership of the U.S. Trade Representative, an effort should be made to assure access to foreign FPD markets.

Rationalizing Tariffs—The DOC should conduct an analysis of the current U.S. tariffs on products related to flat panel display production and develop recommendations on altering those policies that impede the development of domestic manufacturing of flat panel displays. Current tariffs on FPD components may have the effect of driving manufacturing activity overseas that might otherwise be based onshore. The DOC should fully cooperate with the effort of the FPD industry to use Foreign Trade Zone procedures in order to facilitate full onshore production.

Access to Foreign Dual Use Technology—The DoD is currently working to facilitate access by U.S. suppliers to foreign dual use technologies of potential value in DoD applications in exchange for foreign access to U.S. military systems technology. Such an effort is already underway with our Japanese allies in a new DoD policy known as "Technology for Technology." The U.S. government may wish to consider flat panel displays as a potential candidate technology area for this program.

Assessing Global Competition—Under the leadership of the U.S. Trade Representative and DOC, with the participation of DoD, DOE, Department of the Treasury (Customs), Department of Justice, and other government agencies, an interagency program to assess competitive behavior in world flat panel display markets should be established. The objective of the analysis would be to quickly identify technology, pricing and availability trends that could potentially affect the success of U.S. FPD programs. Practices this program should seek to detect include price discrimination, predatory pricing, denial of products, inability to gain expected access to export markets, restricted access to technology, and other changes in market behavior that may reflect significant departures from competitive norms in world markets.

5. *MANAGEMENT AND EVALUATION*

a. Program Management

To maintain a broad-based, national perspective, the overall strategic oversight of the program should be performed by the NEC. It is crucial that the program does not degenerate into a collection of effectively independent actions. Day-to-day management of the program should be conducted by individual agencies with periodic review and coordination through the NEC.

b. Program Evaluation

In support of its role to provide strategic oversight, the NEC should establish continuing oversight and review of the FPD program. The process should seek a balance of inputs from government, business, and academic perspectives, and a rigorous independent review. The review process should evaluate progress toward the stated goals and recommend to the NEC that the program be modified, terminated, or continued.

H. FLAT PANEL DISPLAYS WITHIN DOD'S DUAL USE TECHNOLOGY STRATEGY

The National Flat Panel Display Initiative recommended here represents a major new dual use initiative organized through DoD, and reflects the Clinton Administration's new technology strategy. Flat panel displays are by no means the only technology area in which the new dual use strategy is appropriate, but they are a good choice for a first effort designed to implement this strategy. Many recent technology assessments include flat panel display technology among the handful of critical technologies that offer a promise of substantial payoffs in terms of both national security and economic benefits. Furthermore, after five years of substantial investments by the DoD in technology and infrastructure, the domestic industry is at the threshold of achieving critical mass. A set of decisions is needed to encourage the promising first results from these technical investments to take root as a stable, reliable industrial asset, serving both DoD and commercial markets.

The proposals laid out in this initiative reflect judgments on a number of key issues that will be faced more broadly, in other contexts, as the DoD dual use technology vision is implemented:

- DoD is, and will remain, only a small part of the overall market for flat panel displays. Nonetheless, DoD has critical requirements for flat panel display technologies that are sufficiently important to motivate investments in the creation of future capabilities.
- DoD will certainly do **something** to diminish current uncertainties over its access to leading edge display capabilities. The choice is not so much **whether** something will be done, as **what**: a traditional policy of support for a defense-unique, captive industrial base, or a strategy aimed instead at investing in the creation of dual use capabilities permitting DoD needs to be served by a competitive commercial supplier base. The latter strategy will be more effective, and at a considerably lower cost over the medium and long run.

The actual measures proposed above contain a number of important features that are certain to have broader, canonical application to future initiatives in other technology areas:

- A great emphasis is put on policies that create and maintain **competition**: among both technologies and firms. The benefits and disciplines of market forces should be harnessed to encourage efficient and effective choices whenever possible.
- Policies are suggested that work not only on the supply side of the market, through creation of new technologies, but also pay attention to demand, in both domestic and foreign markets. Such an **integrated program** will also focus on government leveraging its role as a user of technology in leading edge applications, and using its resources to pry open maximum access to global markets for U.S. producers.
- The measures outlined above are an **interagency initiative**. A variety of Federal agencies will be working together, on a single common agenda, to achieve a level of effort and focus that would be impossible for any single agency working in isolation. The problems cross agency boundaries; so, too, will the Clinton Administration's responses.

CHAPTER II: FLAT PANEL DISPLAY TECHNOLOGY

The technologies that display digital information via a lightweight, small, and flat package—flat panel displays (FPDs)—have made dramatic improvements over the last 25 years. In addition to making incremental improvements in existing technologies, firms are constantly researching and developing new technologies that offer the potential for breakthroughs that provide better quality images at lower cost. This chapter presents a snapshot of the three major existing display technologies—liquid crystal, electroluminescent, and plasma—and a potential breakthrough technology—field emission.

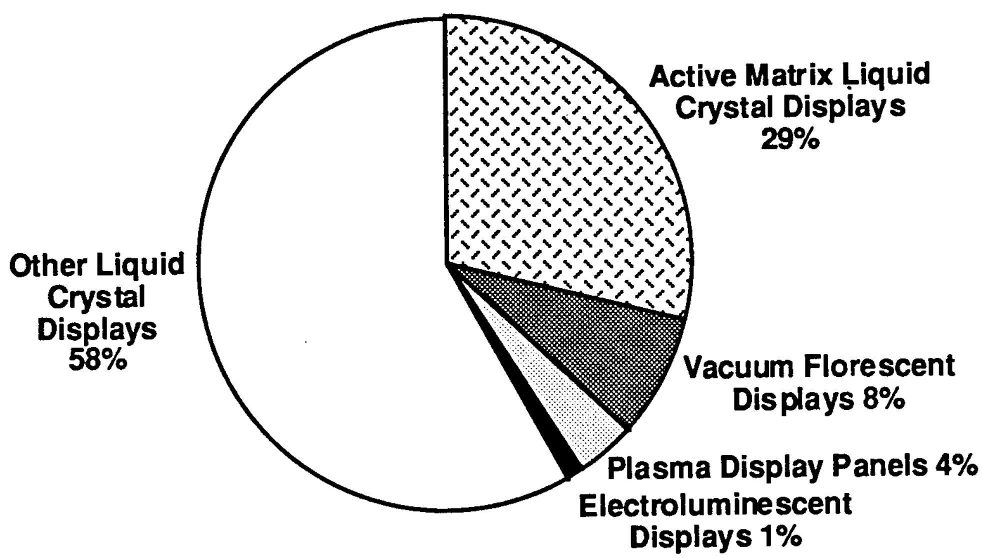
A. DISPLAY TECHNOLOGIES

FPDs are thin, flat electronic devices used for displaying alphanumeric information, graphics, and images. FPDs have increased in performance and capability dramatically over the past decade, so that the most advanced FPDs now are capable of displaying full-color, high definition images at full video rates. A number of different technologies are used for making FPDs. These technical approaches have different characteristics, with differing strengths and weaknesses.

Figure 2-1 shows the current market shares by technology. Table 2-1 summarizes information on the different technologies. Each of the technologies is described in the sections below.

FIGURE 2-1

1993 GLOBAL FPD MARKET SHARE BY TECHNOLOGY



Market Value $6.5 Billion

Source: Stanford Resources Inc.

TABLE 2-1
FLAT PANEL DISPLAY TECHNOLOGIES*

Technology	Companies	Type/Status	Max. Size	Manufacturing	Strengths	Weaknesses
LIQUID CRYSTAL DISPLAYS (LCD)						
a-Si TFT LCD	~ 15 Japan 3 U.S. (OIS, Xerox, IBM)	Active/ Manufacturing	17" Sharp	Infrastructure in place; difficult to manufacture; yields of 30-60%	Excellent color, resolution; market penetration	Expensive; power-hungry backlight; not scalable over 17"
p-Si TFT LCD	1 Japan (S-E) 2 U.S. (Xerox, DSRC)	Active/ Developing	13" Xerox	Planned for '95; Possible successor to a-Si	High resolution, saturated color	New Technology; Expensive substrate
x-Si TFT LCD	1 U.S. (Kopin)	Active/ Developing	1.5" Kopin	Uses proprietary manufacturing process	Great electron mobility; Easily integrated drivers	Expensive
"FLC" Ferro-Electric LCD	1 Japan (Canon) 1 Europe (EMI)	Passive/ Developing	15" Canon	Canon started manufacturing in 1993	Scalable to large sizes; good viewing angle	Expensive; limited gray-scale
TN LCD	~ 20 Japan ~6 U.S. many Asian	Passive/ Manufacturing	10.5"	Several large facilities for small sizes	Low-cost; easily manufactured	Limited viewing angle; slow; not scalable
Active-Addressing (AA) STN	1 U.S. (Motif)	Passive/ Manufacturing	6"	Ramping up as of 1/94	High resolution; video rate; wide viewing angle	Not scalable; new tech; complex drivers
STN LCD incl. FSTN, TSTN, others	~20 Japan ~6 U.S. ~15 Asian	Passive/ Manufacturing	11"	Many large facilities	Excellent $/performance ratio;	Slow; dull colors; limited viewing angle; backlight
"MIM" Metal-Insulator-Metal	2 Japan (Seiko-Epson, Stanley)	Passive/ Manufacturing	10" S-E	For computers & videophones	$/performance ratio	Slow; cross-talk; flicker
ELECTROLUMINESCENT DISPLAYS (ELD)						
ELDs	1 Japan (Sharp) 1 U.S. (Planar)	ELD/ Manufacturing	19" Planar	Three volume facilities	Bright; low power; easy	Not fully saturated colors
PLASMA DISPLAY PANELS (PDP)						
PDPs for computers	~5 Japan 3 U.S.	PDP/ Manufacturing	19" Plasmaco	Several large Facilities	Bright; multi-colored; scalable	High voltage; limited gray scale
PDPs for televisions	~6 Japan 2 U.S.	PDP/ Developing	45" NHK	No proven process	Scalable	Power hungry; high voltage
FIELD EMISSION DISPLAYS (FED)						
FEDs	~4 U.S. ~6 non-U.S.	FED/ Prototype	9" CNET	Planned for late 1994.	Believed to be scalable	New technology
Source: U.S. Department of Commerce						

* Assessment by Department of Commerce based on review of literature and industry discussions. Does not include all FPD technologies, particularly those in R&D stage or just moving into product development.

Liquid Crystal Displays (LCDs)

Liquid crystal displays (LCDs) contain transparent organic polymers that respond to an applied voltage. To form the display, manufacturers deposit a polarizing film on the outer surfaces of two ultra-flat glass or quartz substrates with a matrix of transparent indium tin oxide (ITO) electrodes on the inner surfaces of these substrates. With micron-sized spacers holding the two substrates apart, the sandwich is joined together. The substrates are cut into one or more displays, depending on the original size of the substrates (from 12" to 22" square);

the outer edges of each display are sealed with a gasket; the interior air is evacuated; and the void is injected with liquid crystals.

The polarizers on the front and back of the display are oriented 90° from one another. With this orientation no light can pass through, unless the polarization of the light is altered. Liquid crystals are a means for changing the polarization. When no voltage is applied liquid crystals can be aligned in twisted (90°) or supertwisted (270°) configurations. With these configurations the polarity of light is rotated allowing the light to pass through the front polarizer, thus illuminating the viewing surface. When a voltage is applied, the liquid crystals align to the electric field created, the polarity of the incoming light does not change, and the viewing surface appears dark.

All LCDs must have a source of reflected or back lighting. This source is usually a metal halide, cold cathode, fluorescent, or halogen bulb placed behind the back plate. Since the light must pass through polarizers, glass, liquid crystals, filters, and electrodes, the light source must be of sufficient wattage to allow for the desired brightness of the display. Typically, the internal complexity of the display blocks over 95 percent of the original light from ever exiting on the viewer's side. As a result, the generation of unseen light causes a major drain on a battery-operated LCD's power source.

Some LCD systems perform much better than others. The greater twist angle of supertwisted nematic (STN) liquid crystals allows a much higher contrast ratio (light to dark) and faster response than conventional twisted nematic (TN) crystals. For color displays each visible pixel must consist of three adjoining cells, one with a red filter, one with a blue filter, and one with a green filter, to achieve the red-green-blue (RGB) color standard. While color decreases the resolution of the display, color adds information to the display, particularly for desktop publishing and scientific applications.

Passive Matrix Displays—Passive matrix LCDs (PMLCDs) are the most common flat panel display. They have been used as segmented (non-programmable) displays in watches and calculators since the early 1970s. PMLCDs have closely-spaced, transparent, horizontal metal electrodes on one glass plate and vertical electrodes on the other plate. Voltages on these row and column electrodes combine at a cross point to turn on the pixel at that point.

PMLCDs are relatively easy to fabricate, but the driving circuits needed to address each pixel are quite complex. Because of the addressing scheme and the response time of the liquid crystals, passive matrix displays are relatively slow and unsuitable for greater than 30 frames-per-second video programs. The slowness increases as the display becomes larger, which has inhibited PMLCDs from sizes larger than 10" in diagonal. However, novel addressing schemes (for example, dual-scan and active-addressing) have recently demonstrated significant improvements in speed and are bringing renewed attention to PMLCDs.

Active Matrix Displays—Active matrix LCDs (AMLCDs) use metal-insulator-metal (MIM) diodes or thin film transistors (TFT) at each pixel to control the pixel's on-off state. TFTs are fabricated in a manner similar to integrated circuits, and much of the manufacturing equipment, materials, and accumulated knowledge about silicon is applicable to the fabrication process. To fabricate an AMLCD, the front transparent electrode is simply deposited over the entire glass surface and serves as a ground electrode. The rear glass is deposited with a matrix of transistors (at least one per pixel for monochrome and at least three per pixel for RGB color) and metal interconnect lines. Even with redundant transistors at each pixel, some pixels fail to operate, resulting in a quality assurance problem which has restricted economic, high-volume AMLCDs to approximately an 8"-10" range.

Most AMLCDs are built of amorphous silicon (a-Si) transistors deposited on glass substrates. Amorphous silicon has a random crystalline structure. Cadmium selenide is also used for AMLCDs, and in fact was the initial material with which active matrix displays were developed. However, the major producers of TFT displays today use silicon transistors.

Research and development using polysilicon (p-Si) and single crystal silicon (x-Si) is underway. Polysilicon is composed of micro-crystalline regions, which give transistors more rapid response than those made with a-Si. Single crystal silicon, with all molecules oriented as a single crystal, can produce even faster transistors. However, such performance is gained with relatively costly materials and production processes.

Polysilicon and single crystal silicon processes require temperatures higher than conventional glass can withstand, so expensive quartz substrates must be used instead of glass plates. Because of the associated manufacturing costs, most displays typically are made with a-Si. Although manufacturers are building high-quality displays with p-Si today, the search continues for high-melting-point glass and low-temperature transistors as a means to make the manufacturing costs acceptable to consumers. Single crystal silicon is limited to relatively small displays for use in very high quality head-mounted and virtual reality displays, although both p-Si and x-Si can be also used as light valves for projection displays.

TFT liquid crystal production technology has been characterized by industry analysts as having gone through four stages based on complexity, panel size, and throughput.[1] "Zero-generation" lines are essentially converted solar cell or semiconductor lines, which generally produce small to medium panels, or larger panels for personal computers with one panel per substrate. "First-generation" facilities are production plants designed and equipped specifically for TFT LCDs, capable of producing two to four panels per substrate. Most major high-volume display makers have zero-or first-generation plants at this time. Leading TFT producers are now bringing on-line "second-generation" plants, specifically designed for 10" displays with four panels per substrate, doubling the productivity of the preceding generation. This productivity is achieved by using larger glass substrates, standardization of the substrates, and process automation with improved manufacturing equipment. "Third generation" plants are now being planned which will use still larger substrates to achieve six display panels per substrate.

Electroluminescent Displays (ELDs)

Electroluminescent displays are classified as emissive displays because, rather than acting as a light switch like LCDs, they generate their own light. The light generating material is a phosphor which is sandwiched between the front and back electrodes. The passive and active matrix addressing schemes are similar to those described for liquid crystal displays. ELDs have a high luminous efficiency and consume very little power. They will likely continue to gain popularity as incremental improvements in phosphors are made.

Principal uses of monochrome electroluminescent displays today include military applications, financial and ATM machines, and industrial displays for medical, process control, test, and analytical equipment. There is very little ELD usage in computers and consumer electronics, applications which account for approximately two-thirds of the total FPD market today. Efficient color capability and the availability of low-cost driver circuits would likely

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1 Wakabayashi, Hideki. *Liquid Crystal Displays: Heading Toward Becoming a ¥1 Trillion Industry.* Tokyo, Nomura Research Institute (NRI), Shoken Chosa Report No. 93-99. September 8, 1993. 1-49. (Cited below as Nomura.)

increase market share. The fundamental problem in producing full color ELDs has been the identification, synthesis, and production of phosphors with high brightness and good chromaticities (saturation), particularly for blue colors. Phosphors require a relatively high voltage for activation, on the order of 150-200 volts, and require annealing temperatures above the melting point of glass. Active matrix addressed ELDs also require high-voltage transistors at each pixel to activate the phosphors.

Plasma Display Panels (PDPs)

The largest FPDs available are plasma display panels. PDPs consist of front and back substrates with phosphors deposited on the inside of the front plates. These displays have cells that operate similarly to a plasma or fluorescent lamp: the discharging of an inert gas between the glass plates of each cell generates light. Depending upon the type of gas used, various colors can be generated. In a monochrome display the light from the gas discharge is that which is seen on the display. However, to obtain a multicolor display, phosphors are required. The plasma panel uses a gas discharge at each pixel to generate ultraviolet radiation that excites the particular phosphor that is located at each pixel.

Despite an inherently lower cost to manufacture, plasma display panels (PDPs) have relatively high power consumption, high operating voltage, and low color brightness in comparison to LCDs. If these deficiencies can be addressed successfully, plasma technology has potential for a larger market share, particularly in applications requiring large-area, high-resolution displays such as High Definition Television (HDTV). A 30" full color plasma display was demonstrated early in 1994. Much of the demand today for plasma displays is in the business and commercial, industrial equipment, and military markets. They compete with ELDs for use in ticketing machines and financial terminals and with vacuum florescent displays (VFDs) for process control equipment and medical instruments.

Field Emission Displays (FEDs)

Field emission displays are solid-state vacuum displays that operate similarly to cathode ray tubes (CRTs). While a promising technology, all FED efforts are in the R&D stage, with firms just now showing prototypes. They are based on cold emission of electrons from a matrix array of metal or semiconductor microtips. Microtips are small, sharp cones that serve as cathodes. Hundreds or thousands of small microtips are used for one pixel, giving the FED extraordinary redundancy and reliability. Also being explored are cathodes using a thin film of diamonds as the emitter. An anode voltage of a few hundred volts causes a field emission of electrons to be moderately accelerated from the cathode through a grid structure toward the anode. These electrons activate phosphors at the anode and produce light. There are about a dozen companies worldwide that are working on methods to obtain better microtip fabrication uniformity, alternative emitter techniques, more cost effective standoff approaches, lower anode voltages, better vacuum sealing techniques, and more efficient phosphors for FEDs.

Other Technologies

The four technologies described above are the dominant approaches for current and future displays for high-information-content applications, such as video or information processing. Other technologies exist, such as light emitting diodes (LEDs) and vacuum florescent displays (VFDs), which have significant markets today in relatively low-information-content applications. LEDs were an early competitor, but now are primarily used in large-sized displays where relatively simple information is shown, such as advertising. LEDs are not expected to be used for advanced information applications. Similarly, VFDs serve niche markets—primarily instrumentation, and small consumer displays, but are not being considered for use in high growth applications, such as computers, telecommunications, and consumer video products.

A broad range of other technologies are also emerging, such as electrophoretic and polychromatic displays, and digital mirrors, that offer the potential for a variety of applications. Digital mirror projection displays have already been demonstrated and are a possible contender for large-sized applications. Polychromatic displays are being introduced in flexible displays for commercial use. Electrophoretic concepts are in the exploratory stage.

B. SUMMARY

Over the past thirty years FPDs have evolved from small monochrome devices for simple output, such as digital alphanumeric readings for watches and calculators, to today's advanced FPDs which can show high definition, full color, full motion video images, and which are scalable in size from goggle-sized to wall-mounted applications. The dominant technology today is liquid crystal, with AMLCD now emerging as the most rapidly growing segment due to its popularity in notebook computers. AMLCD is still a maturing technology, having first been sold in portable computers in 1990, with color AMLCDs entering the market in 1992. Beyond current amorphous silicon AMLCDs, some firms are pursuing development of polysilicon and single crystal silicon AMLCDs, which, if successful, would make on-display integration of electronics achievable. Several other avenues for improving LCD technology are also in development, such as ferroelectric AMLCDs, and actively-addressed PMLCDs.

For displaying computer graphics and information at the standard video speed of 30 frames per second, AMLCD is currently the leading contender. AMLCDs avoid the complex logic circuits of PMLCDs. With a transistor at each pixel, a new image requires only a refreshed transistor. Achieving image speeds faster than the current video standard will depend on improvements in the rate that the liquid crystals can untwist and the rate that the transistors can change states. Sizes larger than about 12" will depend on new generations of manufacturing equipment that permit use of larger substrates and that detect and correct bad pixels during the manufacturing process.

An array of other technologies exist for making flat panel displays. Several of these are emissive—they generate their own light source. In contrast, LCDs require a separate backlight for illumination. Plasma, electroluminescent (EL), and field emission are all emissive display technologies. Plasma and EL have been on the market for several years, but are only now achieving some of the key performance characteristics that have made LCDs so attractive for high volume applications. For certain applications where ruggedness, brightness, wide field of view, and low cost are a premium, EL and plasma have been able to carve market niches. These display technologies, as they evolve, may have significant advantages over LCDs for scalability to very large format displays, such as wall-mounted HDTV. FEDs, using dense arrays of miniature cathode emitters, currently are in prototype. FEDs have prospects of providing lower cost, scalable, high definition solutions, but will not be entering high volume production for at least two years.

FPD technology is still very open for major new developments. The current dominant technical approach, LCD, is hampered by complexity and characteristics that appear to be barriers to substantial cost reduction and to the technology's efficient application to certain product areas, such as very large displays. Alternative technologies are being aggressively pursued with prospects both of supplanting LCDs in current markets, such as laptop computers, due to significantly reduced costs, and of better meeting the cost and technical performance requirements for emerging markets. On the other hand, with huge sunk investments in production facilities, a vast community of well-supported researchers working in the technology, and a rich base of experience in both product and process development, LCDs will offer formidable competition to these challengers.

CHAPTER III: FLAT PANEL DISPLAY DEMAND

Flat panel display demand is largely for commercial applications. The military applications market constitutes less than one percent of total worldwide FPD volume today. Both markets are expected to experience dramatic growth well into the 21st century, although the military demand is expected to remain a very small part of total worldwide demand. The computer is the single biggest demand driver today and will likely continue to be so into the foreseeable future. In addition, as the price and capability of FPDs improve, markets that are foreseeable but not present today, such as automotive and high definition television, are expected to emerge as may many other unforeseen markets. Flat panel displays will become pervasive with the worldwide advance into the information age.

A. COMMERCIAL FPD MARKET DEMAND

The global flat panel display market in 1993 was $6.5 billion. Conservative estimates of demand for FPDs foresee a doubling of the market by the turn of the century. Other sources project markets growing from $20 billion to $40 billion by that time.[1] Even these numbers may be conservative—Sharp, the largest producer, projects the LCD market alone to exceed $9 billion in 1996. Despite this wide variation in estimates, there is consistent evidence and broad agreement that the growth in the market for FPDs will be explosive throughout the 1990s.

Display applications demanding graphics, color, portability, and compactness are driving the current worldwide demand for the most advanced high-information-content FPDs, while substantial markets still exist for products with lower information content. Table 3-1 provides some insight into the potential breadth and market size of both categories of FPD applications as seen by Japanese industry sources.

Demand by Application

Today, the major application for high-information FPDs is the portable computer. There are also significant industrial, business, consumer, and transportation applications. Figures 3-1 and 3-3 show the distribution of worldwide demand in 1993 for high-information-content FPDs by type of application, based on Stanford Resources Inc. and Sharp Corporation data, respectively. Computer applications, primarily for laptop PCs, dominated the market with more than 61 percent of the demand. Figures 3-2 and 3-4 forecast the distribution by application for the year 2000 using Stanford Resources Inc. flat panel data and for 1996 using Sharp Corporation LCD data. In the Sharp-provided data, the portable information tool and vehicle navigation categories show dramatic increases in demand.

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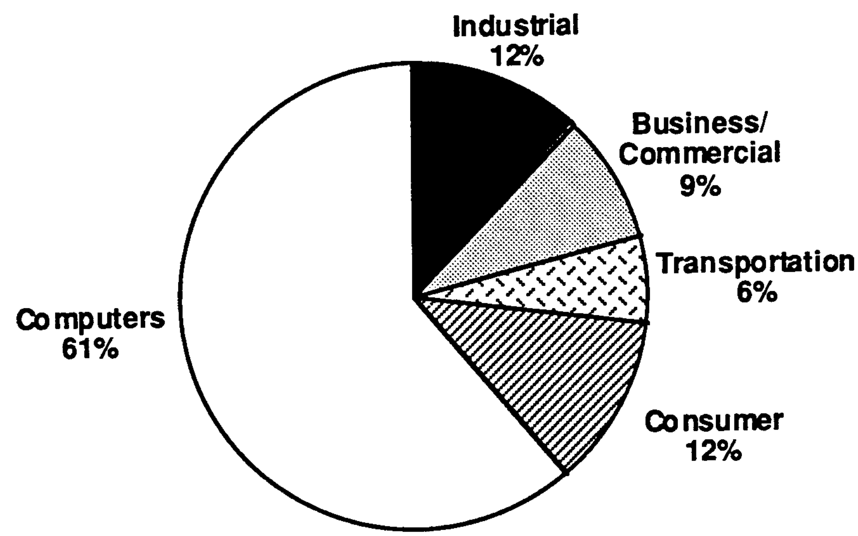
1 The exploding growth of the FPD markets has been a difficult one for market analysts to predict—in one widely read market assessment, the estimates for the year 2000 increase by 50% between the 1993 and the 1994 reports. The larger market estimates are from a variety of Japanese sources: for example T. Kawanishi, Toshiba Corporation, "Flat Panel Display Forum," presentation to AEA/Electronic Buyers News Conference, San Jose, California, May 2, 1994, and H. Mizuno, Matsushita Electric Industrial Co., Ltd., "Keynote Speech: Electronic Displays in the Era of Multi-Media," *Electronic Display Forum Proceedings*, Kanagawa, Japan, April 6, 1994.

TABLE 3-1 POTENTIAL WORLDWIDE DEMAND FOR FPDs BY APPLICATION					
Product Category	Product Name	Market Size			
		Units in 1,000's		Values in ¥100,000's	
		1992	2000	1992	2000
	CD Radio-Cassette	45,710	40,640	¥ 384,000	¥ 409,600
	DCC	100	10,840	8,000	205,000
	Stereo Set	25,600	31,000	217,600	217,000
Audio	TV-Portable	1,470	4,000	32,650	84,000
	TV-Stationary	84,000	105,000	3,360,000	4,410,000
&	TV-Projector	860	2,000	322,500	750,000
	TV-Projection	500	670	115,500	125,000
Video	TV-Wall	.1	30	29	3,000
	Video Deck	41,100	55,000	1,435,000	1,650,000
	HeadPhone Stereo	42,100	31,890	185,600	120,300
	CD Player-Portable	6,660	6,440	87,900	69,700
Field Automation	CD/ATM Equipment *	70.05	96.5	128,659	143,000
Machinery	Remote Control	20	600	14,000	120,000
& Instruments	Electron Microscope	1.7	2	26,000	30,000
	Stop Watch	3,000	3,000	7,500	7,500
Personal Assistance	Electronic Note Pad	3,000	10,000	40,000	250,000
Devices	Calculator	141,000	141,000	163,000	163,000
	Wrist Watch	360,000	250,000	220,000	150,000
Office	Fax	5,878	7,850	480,000	538,000
Automation	Overhead Projector	60	160	30,000	50,000
and	PC Desktop	20,000	50,000	4,000,000	1,000,000
Business	PC Portable	4,400	16,000	1,000,000	3,500,000
Equipment	TV Phone	0	1,200	0	240,000
	Workstation *	115	500	3,400	9,300
	Handy Terminal	500	130	75,000	160,000
	Printer	15,000	30,000	850,000	1,350,000
	Pager/Pocket Bell	8,900	20,000	129,375	175,000
	White Board	60	150	7,000	13,000
	Word Processor *	2,410	3,281	359,000	579,000
	Portable Telephone	6,000	17,000	420,000	730,000
	Electronic Display	5	1,000	1,000	100,000
	Electronic Filing System	12	400	73,000	200,000
	Telephone	80,000	300,000	700,000	3,000,000
Home Appliances	Iron *	55,000	60,000	23,000	45,000
	Air Conditioner	16,680	25,000	1,649,000	2,042,000
	Rice Cooker	9,709	10,606	145,635	159,090
	Dryer *	720	1,200	28,000	84,000
	Fan *	67,000	74,000	26,318	30,000
	Washer *	52,970	60,000	220,000	350,000
	Vacuum Cleaner	95,000	110,000	1,700,000	2,090,000
	Electric Cooking Equip.	150,000	230,000	1,100,000	1,700,000
	Electronic Range	9,000	12,000	45,000	56,000
	Freezer/Refrigerator *	4,400	4,600	380,000	430,000
Leisure	CD-Interactive	100	10,000	2,000	600,000
Total		1,359,110	1,737,275	¥ 20,194,666	¥ 34,137,490
* Represents only the number in the Japanese market.					
Source: Electronic Display Industry's Vision for Year 2000: Japan, 5/7/93. Translated by SEAM International.					

FIGURE 3-1

FLAT PANEL DISPLAY DEMAND
1993 Global Market Share By Application

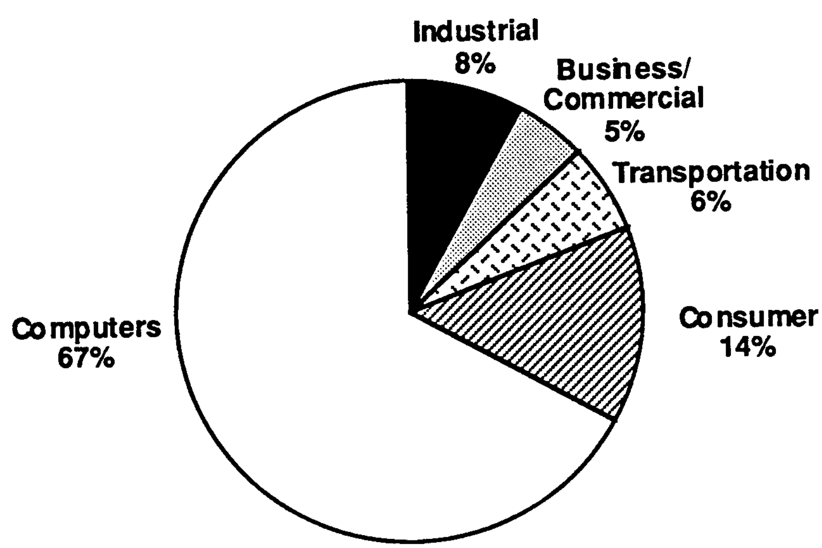


% Total Dollar Demand

Source: Stanford Resources Inc.

FIGURE 3-2

FLAT PANEL DISPLAY DEMAND
Year 2000 Projected Global Market Share By Application

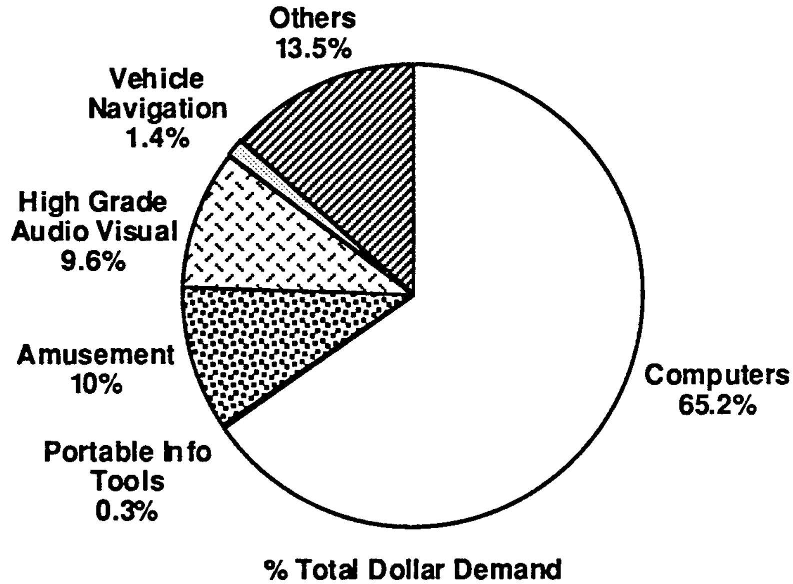


% Total Dollar Demand

Source: Stanford Resources Inc.

FIGURE 3-3

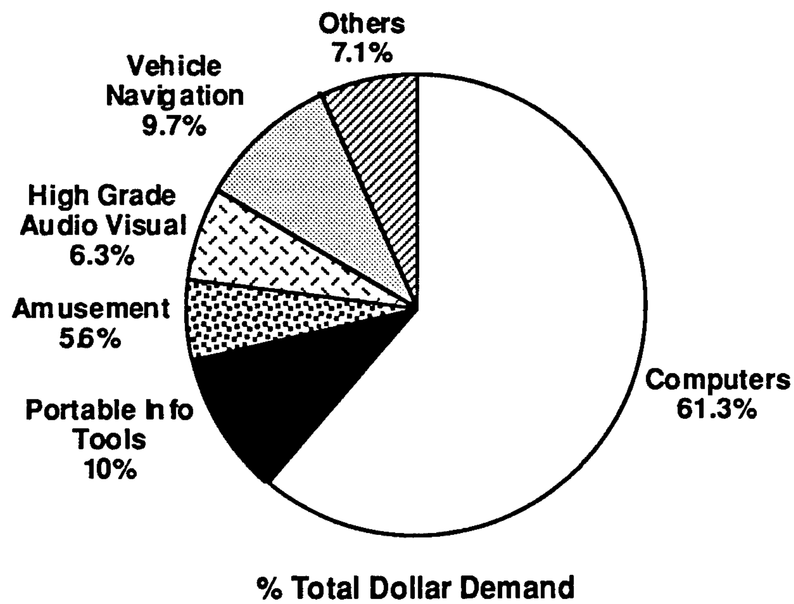
LCD FLAT PANEL DISPLAY DEMAND
1993 Global Market Share By Application



Source: Sharp Corporation

FIGURE 3-4

LCD FLAT PANEL DISPLAY DEMAND
1996 Projected Global Market Share By Application



Source: Sharp Corporation

Computer Demand—Computers are expected to continue to account for well over half of FPD demand through the end of this century. Because of their compactness and light weight, FPDs are particularly useful in portable computers, which will likely continue to constitute the single largest portion of the computer-based FPD demand. For workstations, the bulky 16"-20" CRTs of today will most likely be replaced with FPDs as soon as the performance-to-price ratio of FPDs approaches that of CRTs.[2]

Portable computers include both pen and keyboard types of laptops, notebooks, and palmtops. Portables first came to market using monochrome PDP technology. Subsequently, PMLCD technology became the standard technology for monochrome portable displays. By 1991, about 92 percent of monochrome portables used PMLCD technology, while PDP technology held only 6 percent of the monochrome portables market. In 1990, monochrome AMLCDs entered the portables market when Apple Computer introduced its first portable Macintosh, a precursor to the later PowerBook series.

In recent years, the market for color portables has exhibited strong growth with AMLCDs leading the way. Shipments of color portable computers are projected to grow from roughly 4 million units in 1993 to over 15 million units by the end of the century with AMLCDs holding the largest share (see Tables 3-1 and 4-4). The first color portables using AMLCD technology came to market in 1992. Color PMLCD technology has also progressed rapidly.

Consumer Demand—Consumer applications include televisions, games, compact disc readers, organizers, video cassette recorders, and camcorders. By 1996, AMLCDs are expected to have almost the entire market for 2"-6" TVs. The applications that will have the largest number of units in the consumer category during the 1990s include organizers, memo devices, and translators. Underscoring the demand for portability, all hand-held displays, such as games, camcorders, and pocket TVs, are currently showing double-digit growth.

Video telecommunications, an application which transcends both consumer and business markets, is now only in its infancy. Simple displays are now available for telephone systems to show such data as the caller's telephone number. Telecommunication systems which show the video image of the caller along with carrying the caller's voice are now in development. Telephone companies have been experimenting with video transmission and believe that FPDs may be a key technology for future video telephony.

Another consumer market that is just now emerging is high definition television (HDTV). Large size, high definition systems are being developed using a variety of technologies—including plasma and electroluminescent direct view, and projection systems using AMLCD or digital mirrors. Flat panel technologies have major advantages over conventional CRTs when the size of the viewing area becomes large. Prototypes of FPD-based television systems are now being shown, but it is too early to tell how soon this market will develop.

Transportation Demand—Display applications in the transportation segment of the market include both instrumentation and entertainment. Explosive growth in FPD demand is projected in transportation equipment, as the automotive and airline industries begin to offer FPDs on digital dashboards and individual passenger displays, respectively. Dashboard technology is expected to shift soon from vacuum florescent displays (VFDs) toward LCDs.

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2 T. Kawanishi at Toshiba has estimated that performance advantages will lead to a 20 percent penetration of the PC-workstation market even when the price of an AMLCD screen of similar size is three times that of a CRT. Should AMLCD prices fall to twice that of CRTs, Toshiba estimates a 70 percent penetration. The key advantages of the LCD FPDs cited by Kawanishi are power consumption, portability, and lack of radiation. Kawanishi, op.cit.

In a trend that will accelerate, many existing commercial aircraft have already retrofitted FPDs into their cockpits and most new aircraft are being designed and built with them. For example, the Boeing 777 and the military F-22 include AMLCD avionics. On the entertainment front, FPDs have been in first-class sections of aircraft and trains since 1989. Forecasts for aircraft applications include a small display at every seat. For trains, the National Railroad Passenger Corporation of the U.S. (AMTRAK) plans to install video systems starting in 1994.

Business & Commercial Equipment Demand—The category of business and commercial equipment includes devices such as telephones, office equipment, financial terminals, and ticketing machines. Large-screen displays include public information messages, scrolling news displays, and color stadium-type displays. Multifunction telephones and central switching systems could have a very rapid growth from 26,000 units in 1992 to over 350,000 units in 2000. Financial terminals, cash registers, automatic teller machines (ATMs), ticketing machines, projector plates, and copiers have traditionally used special purpose CRT terminals or low-information-content LEDs, but most suppliers of this equipment are looking to expand their user-interface and will take advantage of low-priced FPDs.

Industrial Equipment Demand—Typical industrial equipment applications include test equipment such as oscilloscopes where ELDs have the high end of the market and multiplexed LCDs and small PDPs have the low end. Analytical equipment includes expensive laboratory and industrial tools such as mass spectrometers that can easily support the added expense of FPDs for increased data output. Magnetic resonance, tomography, and ultrasound systems usually employ computed color schemes, and will likely become market drivers for color FPDs. Radiology, on the other hand, demands high gray-scale capabilities and ultra-fine resolution making it a likely driver for the high end of monochrome displays. Hand-held and factory floor data collection devices for utility meter reading, inventory control, route management, materials control, and auto rental tracking generally show 16 characters by 4 lines, with a 5x7 dot-matrix character; these devices are being used widely, but still face battery life limitations.

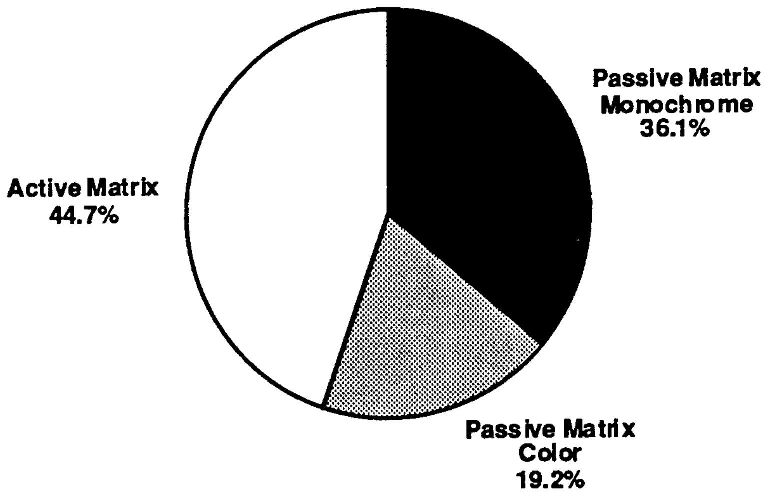
Demand by Technology

Each FPD technology excels at certain screen sizes and applications. Presently, AMLCDs are best for portable computers and perhaps for desktop computers. The demand for PMLCDs in consumer applications should continue to withstand the better, but more costly AMLCDs for applications that do not need to display full-motion video. The continual improvements by manufacturers in the speeds and addressing methods of passive-matrix displays should make PMLCDs an attractive compromise between price and performance for consumers. In early 1994, dual-scan notebook computers retailed for approximately $500 more than monochrome notebooks, and active-matrix notebooks retailed for approximately $1,000 more than dual-scan notebooks. Figures 3-5 and 3-6 show the relative share of the liquid crystal display market for AMLCD and passive (color and monochrome) for 1993 and that projected for 1996.

Technologies such as ferroelectric LCDs, PDPs, ELDs, and FEDs will provide displays for sizes larger than AMLCDs. PDPs or ELDs may enable direct view 40"-60" wall TVs. Advances in projection-based FPDs are also contenders for this market. The best replacement technology for the 19"-30" CRTs used in desk-top publishing, computer-assisted design and manufacturing, and airborne surveillance remains uncertain. A projection of total worldwide demand by technology for the year 2000 for high-information-content displays is shown in Figure 3-7.

FIGURE 3-5

LIQUID CRYSTAL FLAT PANEL DISPLAY DEMAND
1993 Global Market Share By Technology

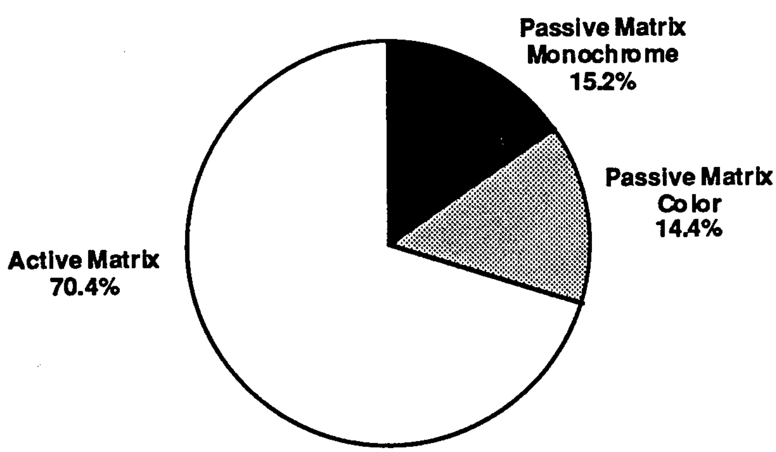


% LCD Total Dollar Demand

* Japanese Fiscal Year Data
Source: Sharp Corporation

FIGURE 3-6

LIQUID CRYSTAL FLAT PANEL DISPLAY DEMAND
1996 Projected Global Market Share By Technology

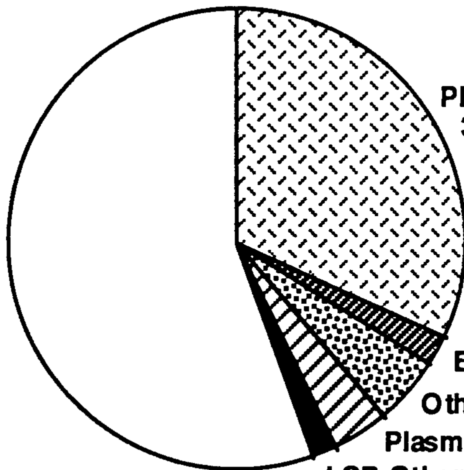


% LCD Total Dollar Demand

* Japanese Fiscal Year Data
Source: Sharp Corporation

FIGURE 3-7

FLAT PANEL DISPLAY DEMAND
Year 2000 Projected Global Market Share
For All Technologies



% Total Dollar Demand

Source: Stanford Resources Inc.

B. THE MILITARY MARKET

Military requirements today and those foreseen for the future differ significantly from those of the Cold War period. The world security environment is unpredictable, unstable, and volatile. The battlefield of the future will be characterized by increased lethality, speed, and depth. The criterion for success will be to win swiftly with minimum casualties. This changing global security environment places great emphasis on technical capabilities to provide superior battlefield information and improved situational awareness.

A remarkable demonstration was seen during Desert Storm. One of the unsung heroes was a prototype system called JSTARS, an airborne ground-surveillance system that fed imaging data to field commanders, enabling them to pinpoint the precise location of the Iraqi opposition with great detail.

The battlefield of the future will be dominated by sensors of many kinds that collect enormous quantities of information and feed it to combatants in real time. It will be a world in which individual foot soldiers, tank drivers, and platoon leaders have personal digital displays that allow them to map out what is in front of them and coordinate an instant response. Intelligence databases distributed around the globe will be queried in real time for the latest high-resolution images of what lies before our troops.

To win the information battle U.S. military forces must be able rapidly to gather, process, disseminate, and use information effectively, and deny these capabilities to the enemy.

Displays are critical to the effective use of information. Sensors, intelligence fusion systems, command and control systems, and fire control systems all require displays. The displays for these systems are the means by which most of the data are presented to the operator. Deploying these data quickly and accurately is becoming increasingly important to contend with ever-improving threats and to utilize the full potential of our weapons, while minimizing risk of casualties to our troops.

To operate these weapons effectively—aircraft, tanks, ships, tactical missile launchers, etc.—high resolution displays with large viewing areas and color capabilities are needed to accommodate the high density of information generated by the increased data flow that will be generated during combat operations. Military displays must be able to operate in harsh tactical environments, yet be affordable. Because of space, weight, and power consumption limitations, those displays must be thin, light, and operate on low power.

Flat panel displays are not only needed for future battlefield systems, but also to update the outmoded technology of today. Current aircraft cockpits, for example, contain rows and rows of small dials. Flat panel displays make it possible to integrate all this imaging and sensor data and present it on large screens. DoD studies using simulated combat engagements show that solely as a result of having a large tactical situation display available, the combat kill-ratio for F-15 fighter pilots increased by 28 percent. Displays mounted in the helmets of tank and helicopter crews promise similar results.

DoD is also interested in flat panel displays because they are far more reliable and require far less maintenance than cathode-ray tube (CRT) displays. The mean time between failure is 10 to 100 times greater than for CRTs, which translates into significant cost savings over the life cycle of a system. In addition, flat panel displays consume less power and are much lighter and more compact. Substituting flat panel displays for CRTs could increase the number of workstations on a JSTARS aircraft, for example, by about 60 percent.

Most of these requirements can be met through commercially-derived flat panel technology. However, to acquire the required capabilities, the DoD needs access to the most advanced FPD technology. Because the development and application of display technology for military applications is likely to play such a significant role in providing mission critical battlefield information, DoD must be assured that it has access to the most advanced display know-how and production.

FPD Effect on Operator Performance

Improvement in fighter pilot performance with current FPD technology has been objectively demonstrated. This improvement was measured in an evaluation of the Panoramic Cockpit Control and Display System (PCCADS 2000) program as part of a study conducted by the USAF Wright Laboratory.

F-15 simulators were equipped with a single 10 by 10 inch color, multi-purpose display (MPD) and advanced controls including a helmet mounted display and sight (HMDS). Tests were made to measure air-to-air mission effectiveness with only the MPD, with only the HMDS, and with both. Improvements were measured against performance in a standard F-15 cockpit.

The PCCADS 2000 cockpit with the MPD, by itself, increased mission effectiveness by over 25 percent over the baseline cockpit. The HMDS used in the baseline cockpit increased mission effectiveness by a similar 21 percent. Together, the PCCADS 2000 cockpit with the HMDS provided a synergistic increase in effectiveness of 45 percent over the F-15 baseline.

FPD Technologies in Military Applications

No single existing FPD technology represents a complete solution to the broad range of military applications. Tradeoffs must be made among the various advantages and limitations of the technologies as they affect a particular application. AMLCDs are the currently preferred technology for aircraft cockpit displays due to their sunlight readability. PMLCDs are lower in cost and power requirements than AMLCDs but are more difficult to militarize. With their ability to survive in harsh environmental conditions, PDPs and ELDs are used mainly in shipboard, vehicular, and portable ground systems. Where power consumption and ruggedness are decisive factors, ELDs have an advantage over PDPs. A summary of the advantages and disadvantages of the FPD technologies for military applications is shown in Table 3-2.

TABLE 3-2
MILITARY DISPLAY TECHNOLOGIES: ADVANTAGES & DISADVANTAGES

Technology	Advantages	Disadvantages
CRT	Cost Resolution Viewing angle Available sizes Color	Limited domestic sources Depth and weight Power Lacks ruggedness and reliability
AMLCD	Depth and weight Power Rugged and reliable Sunlight readable Color	Viewing angle Sizes Limited sources for military requirements Cost
PDP (powered with alternating current)	Depth and weight Rugged and reliable Viewing angle	One domestic source Cost Not sunlight readable Power
ELD	Depth and weight Rugged and reliable Sizes Viewing angle Power	One domestic source Cost Not full-color

Source: *Military Display Report*, General Research Corporation, May 1993.

Military displays vary in size from less than one inch to more than 40 inches diagonally, as shown in Table 3-3. Military applications for FPDs include large, wall-sized displays for command and control (C^2); workstation-sized displays for command, control, communications, and intelligence (C^3I); medium-sized displays for cockpits and vehicles; small displays for hand-held devices and instruments; and miniature displays for head-mounted applications. There is growing use of displays in training and simulation applications.

TABLE 3-3 MILITARY APPLICATIONS BY DIAGONAL SIZE OF DISPLAY	
0.5" - 5"	Head-mounted displays; viewfinders; pocket systems
5" - 12"	Portable computers; instrumentation; cockpit displays
12" - 40"	Workstations; tactical information consoles; cockpit displays
40" +	C^3I; air traffic control; simulation and training
Source:	"Electronic Systems Center Military Display Initiative," Proceedings, San Antonio, TX, 9-11 February 1993.

Transitioning away from CRTs

Military electronic displays typically have used CRTs due to their low cost, commercial availability, and full-color capability. But the U.S. industrial base in color CRTs has eroded over the past decade to the point that the only U.S.-owned commercial manufacturing source of color picture tubes is Zenith Corporation. All other manufacturing sources have either moved overseas or are foreign-owned with U.S. production. For militarized color CRTs, only Tektronix produces a military product on a very limited production line. Therefore, most U.S. military display integrators use foreign-made CRTs (roughly 95 percent from Japan) in their color displays for command and control applications and ground-based systems.

There have been recent indications that constraints on the supply of military-grade CRTs has created problems. This issue was noted during Desert Storm when the U.S. dependency on foreign CRTs became critical due to the difficulty in obtaining replacement CRTs to meet operational needs. Replacements were unavailable after Matsushita (supplier for AWACS) and Mitsubishi (supplier for JSTARS) informed DoD that they would no longer be manufacturing high-volume 19" color displays, and therefore they could no longer supply this size of display to the systems contractor. Consequently, the Military Services are investigating greater use of FPD technologies based on the increasing possibilities of fitting FPDs to precise form factors.

In the past, CRTs and high voltage power supplies (HVPS) have been considered throw away items. When either component malfunctioned, maintenance personnel usually would remove and replace the component. The failed component was destroyed. This led to a CRT availability problem during Desert Storm. Increased AWACS sortie rates during Desert Storm resulted in increased usage rates and increased maintenance for both the CRT displays and the CRT HVPS. This increased usage rate led to CRT failures at a pace quicker than that associated with peacetime operations. The number of spare CRTs in supply was not adequate to replace the failed CRTs and requests for additional CRTs from the vendor resulted in the discovery that the monitor was no longer being produced. Driven by the inability to acquire new AWACS CRTs, Warner Robins Air Logistics Center (WRALC) remanufactured CRTs and repaired HVPS on an emergency basis.

One option being considered as a long term solution is replacing CRTs with FPDs because of their lower life cycle cost (LCC). The high FPD procurement cost is offset by the low maintenance costs resulting from the high mean time between failure (MTBF) and low mean time to repair (MTTR) rates. These costs are based on current prices of military-unique displays by small volume producers. Acquiring FPDs from high-volume dual use vendors should lower these costs substantially, and thus favor FPD use even more. Table 3-4 shows the results of a WRALC study on replacement of the AWACS situation display console CRT with AMLCD, TFEL and Plasma FPDs. Continuing declines in AMLCD unit costs are making AMLCDs increasingly attractive replacements for CRTs.

TABLE 3-4 AWACS SITUATIONAL DISPLAY CONSOLE REPLACEMENT				
VARIABLES	CRT	AMLCD	TFEL	AC Plasma
MTBF	150	3371	5660	11600
MTTR-Depot	36	3	3	3
Unit Cost ($K)	18	80	45	35-50
LCC ($M)	42	49	29	23-31
Source: "Electronic Systems Center Military Display Initiative," Proceedings, San Antonio, TX, 9-11 February 1993.				

Military Services

By far the largest military application of flat panel technology today is flight instruments, or cockpit displays. All developmental aircraft across the services, such as the F-22, F/A 18 E/F, and the RAH-66, contain specifications for flat panel cockpit displays, and many currently fielded aircraft are being upgraded or retrofitted with flat panels. AMLCD presently is the preferred FPD technology for use in cockpit displays, primarily due to readability, both in full sunlight and mission conditions. While current AMLCD demand is less than 1,000 units per year, the figure may grow to over 11,000 units a year by 1997, with a potential U.S. military requirement—excluding spares—for an estimated 40,000 total AMLCDs (up to 10") by 1999 as shown in Table 3-5.

TABLE 3-5 FY 1995-99 AMLCD DEMAND		
Program	Production	Service
F-22	3,608	Air Force
F/A-18E/F	609	Navy
RAH-66	10,336	Army
Transports/Bombers	5,542	Air Force, Navy, Marines
Helicopters	2,695	Air Force, Navy, Marines
Fighters	7,034	Air Force, Navy
Ground Vehicles	8,843	Army
Special Aircraft	1,151	Joint
Total Military	39,818	
Source: *Wright Laboratory, U.S. Air Force, February 1994.*		

Current Air Force Demand—Cockpit displays are a primary concern for the Air Force, but actually represent a significant application area for all three services. The Wright Laboratory Joint Cockpit Office and its predecessors, tri-service working groups on cockpit displays, have been active for more than 20 years. This office has been the focal point of much of the display coordination among the services. The cockpit represents a very severe operating environment for which AMLCDs are particularly suited, especially for panoramic information displays. AMLCDs offer color for enhancing mission effectiveness, superior contrast for sunlight readability, a wide range of environmental tolerances (ability to withstand temperature, altitude, shock, and acceleration), reduced space requirements, availability in different sizes, and reliability as a cost offset for the development of new displays.

The Air Force has issued an FPD insertion contract worth $44.3 million over five years to redesign a commercial flight control system and cockpit display for the C-130. The contract includes replacement of 1,000 CRTs with FPDs beginning in 1994. The value of the contract is expected to increase to $409 million if options are exercised, and to over $1 billion if foreign militaries also retrofit their C-141 and C-130 aircraft. The Air Force expects the flight control system and cockpit display retrofit to reduce avionics maintenance costs by a factor of 10 with a resulting reduction of overall life cycle costs.

The cockpit transition from analog avionics to FPDs requires establishing some preliminary engineering standards. The Wright Laboratory Joint Cockpit Office leads a Canadian and U.S. partnership to guide the selection, design, and development of AMLCDs for use in military cockpits. To date, the partnership has produced a "Draft Standard for Flat Panel Active Matrix Liquid Crystal Displays for U.S. Military Aircraft: Recommended Best Practice," a document that should evolve into a Flat Panel Cockpit Display Specification by late 1994.

Current Navy Demand—In addition to cockpit display retrofits in Naval aircraft, Navy display requirement are driven by the need for surface and undersea command-and-control workstations. Navy applications include sunlight-readable computer displays for surface operations; multifunction and common workstation displays with integrated communications; and shipboard and shore-based workstations and large high-resolution displays. Current shipboard CRT workstations and projection displays do not completely satisfy the needs for color, resolution, brightness, and other performance factors.

Both shipboard and submarine control rooms employing FPD workstations are being explored under the Flat Panel Attack Center R&D program. Objectives of the program include determining the impact of reductions in volume, weight, power consumption, and area configuration; identifying innovative alternatives to traditional combat system console and arrangement design; evaluating gains in operability and tactical performance; and demonstrating the advanced display technology options for undersea warfare programs. An initial set of attack-center designs have been developed, and modular, reconfigurable consoles have been built to support the current testing of plasma displays on an R&D submarine. FPDs are expected to be able to meet the naval requirement to have high resolution and wide viewing angles to serve multiple observers.

Current Army Demand—U.S. Army display technology is driven by the need for very rugged displays for field command post applications, portable infantry equipment, and armored vehicles. Display requirements for ground-based systems span the spectrum from miniature devices for helmet-mounted displays, through medium-sized flat panels for vehicular and portable applications, to high resolution large-screen displays for command posts. In performance, they range from simple monochrome devices for text and graphics to high resolution color displays for detailed mapping applications. Generally, the displays must operate in the full range of environmental conditions relating to temperature, shock, vibration, and humidity. Since many systems are battery operated, power consumption is a primary consideration. The major display technologies advocated and used for Army applications are ELDs and AC-powered PDPs.

A growing area of application in military displays is for helmet or head-mounted displays (HMDs). Currently, they are generally used in high performance Army and Marine Corps helicopter cockpits, but new uses are being envisioned in vehicles and for individual soldiers, as well as in the areas of simulation, training, maintenance, and logistics. The aviation demand for HMDs is currently being met with the use of tiny CRTs, but LCD and ELD technology applications are being studied. The potential FPD demand in this area, however, will be limited by the numbers of pilots and airframes. Currently there are plans for 5,000 CRT HMDs to be procured through FY 99. These systems are heavy, require high voltages, and have bulky optical paths. Pilots use available HMDs only in low-visibility situations where the displays' military advantages outweigh the weight, voltage, and bulk disadvantages. Pilots will not use these displays today in clear weather situations where they find their natural vision superior to electronic images. Current R&D programs focusing on developing high resolution miniature displays are intended to overcome these disadvantages. Such displays will likely be extensively employed in future aviation helmets.

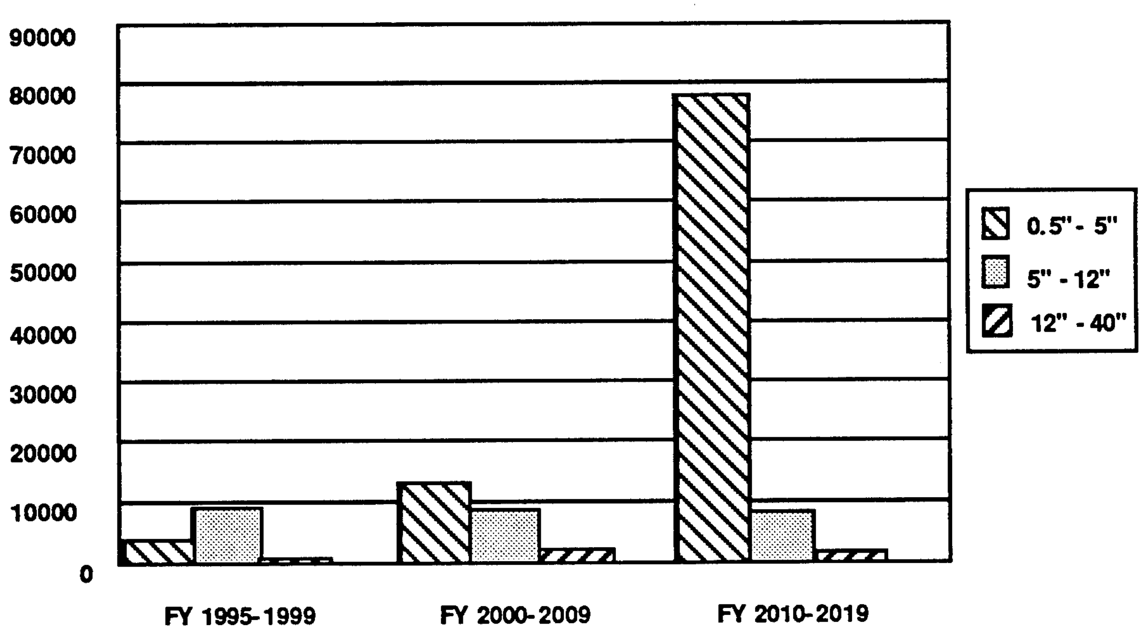
The individual soldier HMD configurations being explored include the Army's Land Warrior 21st Century program which envisions equipping dismounted infantry, engineers, and military police; and the Mounted Armored Crew Ensemble (MACE) program. These programs may lead to substantial requirements for miniature FPD procurements, but not until after FY 2000.

Defense Demand Projection—An estimate of potential DoD flat panel display demand, based on an assumption of maximum penetration of FPDs into DoD procurement for military applications, was developed for this study. Assumptions were made about the replacement of currently fielded CRTs with flat panels beginning in FY 2000 and the fielding of new systems using FPDs to develop an estimate of future demand. Laptop computers, PCs, and workstations were not included. The results are portrayed in Figure 3-8. Note that the first dataset, FY 1995-1999, represents procurements currently being planned by the Department.

FIGURE 3-8

DEFENSE FPD DEMAND PROJECTION

Average Annual Demand



The average annual demand in the 1995-1999 time frame is expected to be approximately 15,000 flat panel displays, for approximately 75,000 units in total over this time period. Between the years 2000-2009 demand is projected to increase to 25,000 flat panel displays annually, or 125,000 in total. For the years 2010-2019, flat panel display demand is projected to reach nearly 90,000 units annually. The largest demand projections are in the area of helmet mounted displays where a scenario envisioning equipping most ground soldiers with helmet mounted displays was included. This would result in a significant increase in the demand, approximately 80,000 units annually, for miniature (0.5"-5") FPDs in that time frame. This is an area of military demand which could stimulate the commercial technology market. The stringent technical requirements, including extremely high resolution, full color, sunlight readability, transparent backlighting, etc. may drive commercial R&D to satisfy this requirement. Head mounted displays are foreseen in a number of commercial and civilian applications, including medical, maintenance, civil transportation, and industrial production.

C. SUMMARY

Demand for flat panel displays is surging and the markets are just emerging. Today's market of nearly $6.5 billion foreshadows a huge market by the next decade—perhaps exceeding $20 billion. FPDs have carved out their own markets, largely distinct from those of the CRT, ranging from small sizes used for watches, calculators, and the now emerging personal digital assistants, to larger displays for portable computers, to the prospect of large monitors and televisions that would overcome the ever increasing bulkiness of CRTs. Flat panel technology will be used in new products that are created as a result of the unique technical advantages offered by FPDs. Many of these products will offer portability, such as notebook computers; ruggedness, required in displays for aircraft, automobiles, and military ground vehicles; or large formats, such as video conference systems or wall-mounted television.

These features are of great significance to the military. Upgrades in DoD weapons and information systems in the future will emphasize high-information-content displays that have full color, light weight, and low power consumption. Light weight and small size are both crucial to mobile forces, but even large-screen, C^3I displays that need to be airlifted can benefit from reductions in power consumption, weight, and volume. While operationally of great value and technologically advanced, military applications will create only very limited demand relative to the commercial market.

CHAPTER IV: FLAT PANEL DISPLAY SUPPLY AND INDUSTRY STRUCTURE

While there are over 50 firms worldwide that produce flat panel displays, three Japanese companies have nearly half of the market. Liquid crystal displays (LCDs) account for nearly 90 percent of the market. For active-matrix LCDs the top three Japanese firms have about 80 percent of the market. The United States is preeminent in only one technology—electroluminescent displays—and accounts for only three percent of the world FPD market overall. Dominance of the FPD market by a handful of Japanese companies is so extreme that the potential exercise of monopoly power is a real concern.

The investment by Japanese firms in FPDs continues to be strong, which resulted in the doubling of their production capacity from 1992 to 1994. In contrast, U.S. investment has been minuscule. Analysis of U.S. industry's small investments suggests a perception of very high risk.

A. CURRENT FPD WORLDWIDE PRODUCTION

Liquid Crystal Displays

LCDs encompassed about 87 percent of the value of FPD shipments in 1993. The two principal types of LCDs on the market today are passive matrix (PMLCDs) and active matrix (AMLCDs).

Table 4-1 summarizes 1993 LCD shipments by country of company headquarters. Japanese companies account for 92 percent of the market overall and 98 percent of the AMLCD market worldwide. Sharp Corporation is the largest Japanese producer. It now claims 55 percent of the AMLCD market.[1] NEC and DTI Corporations are the two next largest producers, with about 35 percent of worldwide AMLCD sales split between them. The three largest producers of PMLCDs are Sharp, Seiko-Epson, and Toshiba Corporations.

PMLCDs account for approximately two-thirds of the total 1993 LCD market. Large quantities of PMLCDs are low-information-content displays for wrist watches, calculators, and similar applications. Within the high-information-content PMLCD segment, 60 percent are used in portable computers and word processors. Industrial, commercial, transportation, and consumer applications split the other 40 percent.

Approximately one-third of 1993 LCD shipments were active matrix, up from one-quarter in 1992. Active matrix LCD applications are primarily in computers (both portable and workstation) and consumer goods (mostly portable TVs, VCRs, and camcorders), which account for approximately 70 and 18 percent of the market, respectively.

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1 Data for Japan's fiscal 1994 show Sharp estimating its share of the world AMLCD market at 55 percent. Using different time periods (that is, for example, calendar versus fiscal year) can give different percentage shares. For example, using U.S. calendar year 1993, instead of Japan's fiscal 1993, Sharp's market share percentage is 44 percent for AMLCD. This variation is largely attributable to firms bringing on line new production capacity at different times in this highly supply-constrained market.

TABLE 4-1
1993 LCD MARKET SHARE OF SHIPMENTS BY COUNTRY OF COMPANY HEADQUARTERS

	Active		Other		Total	
Country	Value ($M)	Share	Value ($M)	Share	Value ($M)	Share
Japan	1954	98%	3458	89%	5412	92%
Korea	7	<1%	92	3%	99	2%
U.S.	11	<1%	60	2%	71	1%
Europe	11	<1%	50	1%	61	1%
Other	11	<1%	205	5%	216	4%
Total	1994		3865		5859	

Source: Nomura Research Institute, Stanford Resources Inc.

Japanese companies have distributed their PMLCD production facilities throughout the world. 1992 data from the Japanese government (Ministry of International Trade and Industry) suggest that the share of PMLCDs manufactured in Japan was 72 percent of total Japanese companies' PMLCD production, with production outside of Japan by Japanese firms making up the remaining 28 percent. All of Japanese AMLCD production to date has been done in Japan (though small amounts of final product assembly are being located overseas).

Table 4-1 shows total worldwide LCD shipment data for over 40 companies. The data show the headquarters country for these companies and the 1993 shipment value and market share, broken down by active matrix LCDs, all other LCDs, and the total.[2] Optical Imaging Systems has the only U.S. AMLCD production facility and one percent of worldwide sales. Litton Systems in Canada also has one percent of the worldwide market. The data also show five U.S. firms in the passive display market, each under one percent of the market.

Electroluminescent Displays

As shown in Figure 4-1, Japanese and U.S. firms are the two principal ELD manufacturers. Planar Systems Inc. is the world's leading producer of ELDs; Sharp of Japan is the next largest producer.

Plasma Displays

Shipments of plasma displays are shown in Figure 4-2. Japanese companies account for 68 percent of the total sales. Fujitsu Ltd. and Matsushita Electronics Corporation of Japan are the world's largest suppliers, together accounting for more than half of the $258 million PDP display market. U.S. firms account for about 19 percent of total sales. Babcock Display Products Inc. and Photonics Technology Inc. are the two largest U.S. producers.

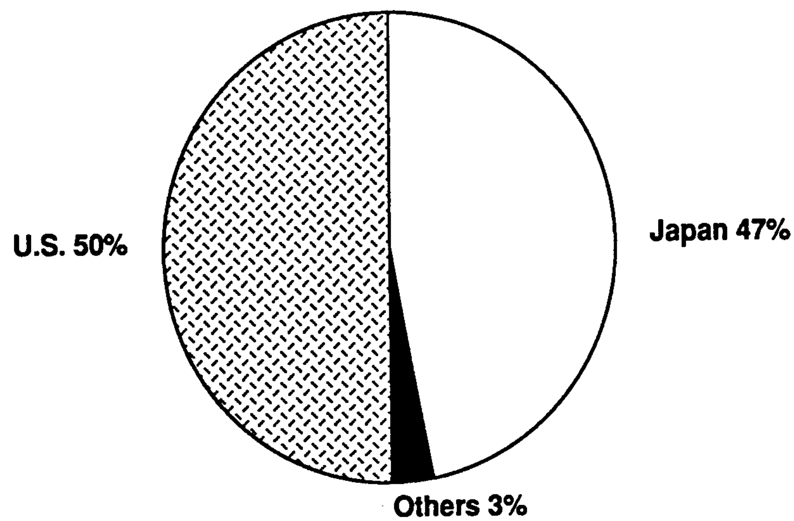
Vacuum Florescent Displays

Nearly all of the $561 million VFD market is produced by Japanese companies. Futaba, NEC, and Ise are the three principal producers.

2 The information in this table was developed from several sources. Nomura Research Institute was the source of nearly all of the data on Japanese companies. For all other firms, Stanford Resources Inc. provided the value of 1993 shipments. Subjective descriptions of the companies provided by Stanford Resources Inc. and other sources were used to allocate total LCD production between active matrix and all other. Since this data is derived from several sources, totals may not be consistent with other single sources cited in this report.

FIGURE 4-1

ELECTROLUMINESCENT — 1993 Global Market Share by Company Nationality

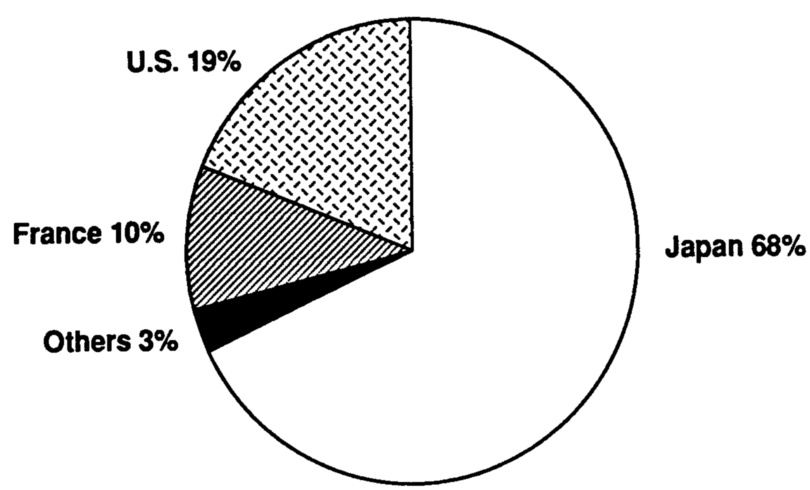


Market Value $97 Million

Source: Stanford Resources Inc.

FIGURE 4-2

PLASMA — 1993 Global Market Share by Company Nationality



Market Value $258 Million

Source: Stanford Resources Inc.

B. INCREASING WORLDWIDE PRODUCTION CAPACITY

Japanese Investment

Table 4-2 shows publicly announced data on Japanese investments in AMLCD production facilities. First generation investments, those made from 1989-1991, began producing in late 1992. Second generation investments, made from 1992-1994, should begin producing in late 1994. Table 4-3 shows similar, more recent information at the plant level.

TABLE 4-2
MAJOR JAPANESE LCD INVESTMENT & PRODUCTION
(Investment and Production in ¥100,000,000)

		1989	1990	1991	1992OP*	1992CO*	1993**	1994**	1995**
Sharp	Investment	1000 over 3 yrs			U/P	800 over 3 yrs			U/D
	Production	450	670	1150	1650	1500	2000	2500	5000
Hitachi	Investment	100	N/D	N/D	N/D	N/D	N/D		
	Production	160	250	330	330	300	N/D		
NEC	Investment	600 over 4 yrs				100-200	200	300 over 2 yrs	
	Production	-	-	100		160-200	300		1000
Toshiba & DTI	Investment	800 over 4 yrs			100	U/D	U/D	U/D	U/D
	Production	200	260	300	520	400	>500	U/D	>900
Hosiden	Investment	200 over 3 yrs			U/D	35	300 over 3 yrs		
	Production	80	100	155	250	200	300	U/D	700
Sanyo Electron	Investment	50	15	450 over 91-94				N/D	
	Production	220	260	310	350	315	320	U/P	U/P
Mitsubishi & ADI	Investment	125	-	200	U/D	0	U/D	U/D	U/D
	Production	-	-	-	U/D	-	U/D	U/D	
Matsushita	Investment	140	400 over 2 yrs		U/D	0	50-80	U/D	U/D
	Production	N/D	190	175	N/R	175	500	U/D	1000
Casio	Investment	450	55	130	380 over 2 yrs			U/D	U/D
	Production	-	200	300	400	400	500	750	1000
Seiko-Epson	Investment	284	100	100	100	100	100	U/D	U/D
	Production	N/D	600	750	1000	750-800	900	U/D	1300
Optrex	Investment	N/D	100	30	60	20	50	N/R	N/R
	Production	-	360	380	440	360	400	N/R	N/R
Kyocera	Investment	100	N/D	N/D	N/D	N/D	N/R	N/R	N/R
	Production	-	N/D	N/D	N/D	N/D	N/R	N/R	N/R
Seiko Electron	Investment	70	10-30	20	10-30	20	10-30	10-30	10-30
	Production	-	100	100	U/D	110	200	240	250
Citizen	Investment	N/R	N/D	100 over 2 yrs			200-300 beginning 1993		
	Production	-	130	150	250	250	300	350	400
Alps	Investment	115	N/D	N/D	N/D	N/D	N/D		
	Production	N/D	-	-	-	-	-		
Stanley Electric	Investment	-	5	50	5	5	35-70	U/D	U/D
	Production		120	130	175	140	210	250	300
Canon	Investment	N/D	-	-	-	150	U/D	U/D	
	Production	-	-	-	-	-	-	U/D	
Fujitsu	Investment	-	100 over 2 yrs		U/D	N/D			
	Production	N/D	N/D	N/D	N/D	N/D			

*Explanation: 1992OP = original plan; 1992CO = corrected plan; U/D = Undecided; N/D = No Disclosure; U/P = Under Planning; N/R = No Reply
** Projected

Source: *Flat Panel Display 1993*, collected and translated by SEAM International Associates

Table 4-3
Major Japanese LCD Manufacturers' Production Lines and Total Capital Investment

FIRM	1989	1990	1991	1992	1993	1994	1995	1996	1997
	YEAR								
Sharp	Zero Generation Old Tenri		1st Generation New Tenri NF1		2nd Generation New Tenri NF3		3rd Generation Mie		
NEC	0.5 Generation Old Kagoshima				2nd Generation New Kagoshima	2.5 Generation Akita (?)			
Toshiba/DTI	Zero Generation Himeji		1st Generation DTI1			2nd Generation DTI2			
Hosiden	0.5-1st Generation Old Kobe					2nd Generation New Kobe			
Hitachi Ltd.	0.5 Gneration Old Shigebara					2nd Generation (?) New Shigebara			
Sanyo Electric	Zero Generation Old Gifu				1st Generation New Gifu				
Casio					1st Generation Kochi				
Fujitsu						1st Generation (?) Yonago			
Mitsubishi Electric						1st-2nd Generation Kiko			
Matsushita Electric	Zero Generation Kadoma		0.5-1st Generation (?) Ishikawa						
Estimated Total Industry Capital Investment (In 100million Yen)	1989	1990	1991	1992	1993*	1994**	1995**	1996**	1997**
	N.A.	1,200	1,800	1,600	2,000	1,500	1,600	1,500	1,500

Source: NRI * Forecast
** Projected

It has been estimated that as a result of these investments, Japanese production capacity will double during 1994 and double again by 1996-7.

European, Other Asian, and U.S. Investments

AMLCD investments are also being made in other parts of the world. A consortium of three European companies, Philips, CNET-Sagem, and Thomson, has invested $70 million in an AMLCD plant in Eindhoven, The Netherlands. This factory will produce AMLCDs using metal-insulator-metal (MIM) technology rather than the predominant thin film transistors (TFT) technology. The MIM process for manufacturing AMLCDs is simpler than that for TFT, and thus could provide a cost advantage. Korean firms have also targeted the AMLCD market. Samsung, Hyundai, and Goldstar are all investing in AMLCD facilities. Sharp estimates that among the Korean firms, Samsung will be producing significant quantities by 1996.

In the United States, the only substantial publicly announced investment is by Optical Imaging Systems (OIS) for an AMLCD plant in Northville, Michigan. This pilot plant is in part supported by ARPA. Under the ARPA contract OIS will purchase, install, evaluate, and use its newly developed manufacturing equipment and materials. It will expand its capabilities to manufacture advanced AMLCDs, with the plant sized to start 36,000 substrate pairs per year. OIS' products will primarily be for avionics applications for the military and commercial customers.

While relatively small scale investments for pilot facilities (such as for field emission displays, actively addressed PMLCDs by MOTIF, and a color ELD line by Planar Systems) are being discussed by a number of companies, no U.S. companies are known to be actively making investments for high volume production addressing the biggest FPD markets (computer and consumer applications).

C. INDUSTRY CONCENTRATION

Herfindahl-Hirschman Index

Concentration ratios are one of the most common tools used to examine an industry's structure and, consequently, the ability of a group of companies to exercise some control over a market. The Herfindahl-Hirschman Index is calculated by summing the squares of the market shares of all firms in the industry. The higher the Herfindahl Index, the higher the potential for the exercise of market power. A Herfindahl Index below 1000 is not considered a concentrated market. Industries with a Herfindahl Index between 1000 and 1800 have some degree of concentration. If the Herfindahl Index is greater than 1800, the degree of monopoly power potentially exercised by the dominant companies is typically judged to be significant.

For 1993, the active matrix LCD industry has a Herfindahl Index of 2646—a situation where significant monopoly power could potentially be exerted. However, for the PMLCD market, the 1993 Herfindahl Index is 984, which does not indicate extensive market concentration.

N-Firm Concentration Ratio

The n-firm concentration ratio is another widely recognized measure of market concentration. This ratio is defined as the percentage of total industry sales made by the largest "n" firms. Several observations can be made from calculations for LCDs. AMLCDs are the most concentrated segment of the market. The top five firms account for more than 91 percent of the world market (up from 85 percent in 1992). The PMLCD market is significantly less concentrated: the top five firms account for approximately 68 percent of the world market.

Japan dominates in each of these market segments. For AMLCDs, the top seven firms are Japanese. In 1993, these firms accounted for 98 percent of the market (up from 95 percent in 1992). For PMLCDs, the 11 largest producers are Japanese. The total 1993 market share for these 11 companies is 87 percent. The concentration is most evident in markets experiencing rapid growth. LCD shipments in 1992 were valued at $4.3 billion. Sales in 1993 were 37 percent higher. For AMLCDs only, the growth nearly doubled—1992 sales were slightly more than $1 billion while 1993 sales were slightly less than $2 billion. The conclusion is that there is a strong concentration of AMLCD production in a few Japanese firms that could potentially create the basis for the exercise of monopoly power.

D. RISKS FOR INVESTMENT

In the late 1980s, DoD became convinced that flat panel displays were critical. Yet, despite a successful $300 million investment in pre-competitive FPD R&D by DoD's Advanced Research Projects Agency (ARPA) since 1989, obstacles to commercialization have inhibited any U.S. company from moving into high-volume display manufacturing. The expenditure of such R&D funds with limited product commercialization is a matter of concern. Even with a dynamic, promising commercial market, U.S. companies were not entering into the FPD business, except in small niche areas. Based on interviews with a number of U.S. companies, reasons for this situation emerged: significant barriers to entry.

Although the prospect of future volume orders for products may be enticing, the rate of return on investment is extremely uncertain for potential producers with no previous experience. The economics of manufacturing are such that very minor changes in technology, manufacturing processes, and market parameters can cause large swings in the rate of return. Moreover, the entry costs in FPD production are large: an active matrix LCD plant with enough capacity to compete in the volume market costs about $400 million. The overall investment will probably be two to three times that, since continuing technology investment will be needed to stay current, and a sales and distribution infrastructure will have to be established. Even large electronics, chemical, and pharmaceutical companies are reluctant to make such investments, particularly when the technology itself is in flux. In the semiconductor industry, for example, the cost of a new high volume fabrication facility now approaches a billion dollars, and many firms are turning to multinational consortia, involving such giants as Toshiba, Siemans, and IBM, to share the risks.

When the major Japanese firms in this industry entered the LCD business in the 1970s and 1980s, they enjoyed a significant cost-of-capital advantage relative to U.S. firms. While that advantage now has disappeared, U.S. companies, as "second movers," face significant disadvantages in entering the market today. A lack of experience in volume production translates into manufacturing costs well above their Japanese competitors, due to a predictable and significant learning curve associated with the fabrication process.

To gain a better understanding of industry behavior, the best available technical and cost estimates were gathered from industry and used to construct a model of an AMLCD factory, in order to assess the costs of production for AMLCDs. Appendix A contains a more detailed explanation of the model and shows some sensitivities to changes in cost and revenue. The model's data included three categories of costs applicable to the establishment and operation of a commercially competitive AMLCD facility: (1) research, development, and investment costs; (2) manufacturing costs that vary as a function of throughput including direct materials, direct labor, indirect labor, fringe benefits, overtime, telephone, warranty, supplies, and utilities; and (3) fixed operating costs that vary as a function of capacity, including rent, insurance, maintenance, and property taxes. The measure of effectiveness used in the cost model—the internal rate of return (IRR)—was calculated over one year of construction and six years of operation. In addition to costs, other factors in the model included display selling price, yield, learning curve, and capacity utilization.

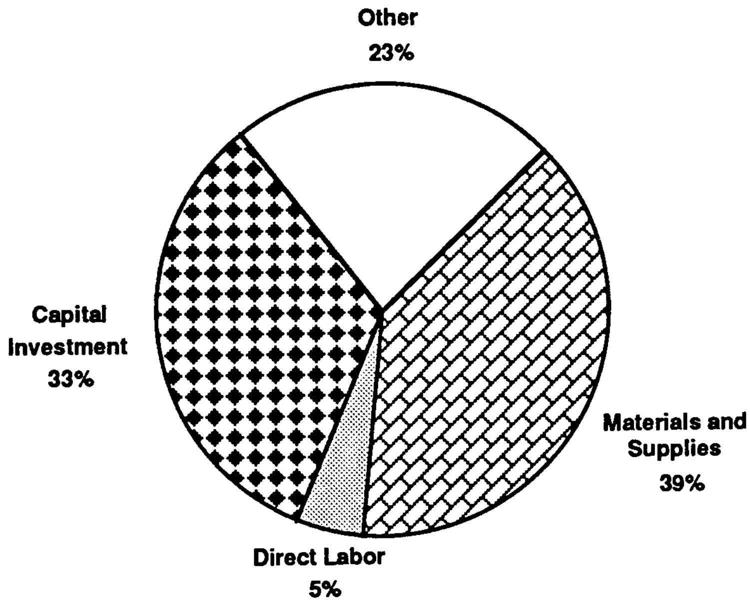
The model shows that materials and capital costs dominate the AMLCD cost structure. An illustrative five percent discount was used to compute discounted present values of the costs for operation over six years. Figure 4-3 portrays the resulting cost breakdown. Capital investment accounts for about 33 percent of the cost. This finding is not surprising given the estimated $300-400 million that a high volume facility would cost. Materials costs are roughly 39 percent of the total.

In the base case scenario, the internal rate of return (IRR) on the required investment was about 12 percent. However, an examination of the IRR shows great sensitivity to several elements in the production process, indicating that lack of hard knowledge about these factors could make investment in a high volume AMLCD factory a very high risk venture. The model results, consistent with the above cost breakdown, are highly sensitive to materials and equipment costs (with a small number of offshore sources for critical inputs), yield (where the U.S. has no experience in high volume production), and learning curve economies. Coupled with the lack of a service and distribution infrastructure and the very high total costs of entry, these factors may help to explain the lack of large scale U.S. investment.

U.S. companies also are concerned about the availability of raw materials, components, and manufacturing equipment, which together account for 60 percent to 70 percent of manufacturing costs. Access to leading-edge materials and equipment at the best price is critical. Today, that argues for locating a facility in Japan. Though we have pockets of excellence, the overall U.S. infrastructure is deficient.

FIGURE 4-3

CALCULATED AMLCD MANUFACTURING COST STRUCTURE
Factory Construction and Operation Over 7-Year Life Cycle



E. SUPPLY-DEMAND BALANCE

Despite dramatic increases in AMLCD production capacity over the last two years, many analysts have concluded that a continuing shortage of active matrix color displays is likely to persist into the forseeable future. The gap between demand and supply is likely to be filled with passive matrix color displays and monochrome displays, where significant overcapacity is likely.[3]

Data which support this conclusion are shown in Table 4-4. Current estimates are that world capacity for 8" to 10" color AMLCD production in 1997 will be about 12 million displays. A very conservative estimate of demand for color notebook PCs is about 15 million units in that year, with the residual shortage directed into passive matrix color and monochrome displays. A less conservative estimate might assume that 10 percent of desktop PCs in 1996, and 20 percent of desktops shipped in 1997 would use AMLCD displays, giving a forecast demand for color FPDs of 21 million units in 1997.[4] An optimistic estimate might add half the forecast demand for multimedia PDAs and workstations to arrive at a demand for 27 million color FPDs in 1997.

3 Nomura, Section 4.
4 See Chapter 3, footnote 2, p. III-5.

TABLE 4-4

PROJECTED SUPPLY-DEMAND BALANCE
8"-10" COLOR DISPLAYS
(10,000 PANELS)

	1991	1992	1993	1994	1995	1996	1997
1. Projected Color 8"-10" TFT Display Capacity	20	100	200	400	700	900	1200
2. Projected Desktop Computer Demand			2700	2800	2900	2950	3000
3. Projected Color Notebook Demand			400	750	950	1200	1500
4. Projected Multimedia Workstation/PDA Demand			50	200	400	800	1250
5. Very Conservative Color FPD Demand Projection (Line 3)			400	750	950	1200	1500
6. Conservative Color FPD Demand Projection (Line 5+.1 Line 2 in 1996, .2 Line 2 in 1997)			400	750	950	1495	2100
7. Optimistic Color FPD Demand Projection (Line 6+.5 Line 4 in 1996 and 1997)			400	750	950	1895	2725

Sources: Lines 1-4, Nomura, op. cit., Diagrams 10, 14.

If investments much larger than the currently projected amounts go into new AMLCD production facilities, of course, the supply-demand balance might change. But for the moment, at least, convincing evidence that larger investments may be occurring is unavailable, and suspicions that actual investments might even fall short of announced plans are strong.

F. SUMMARY

The FPD market is highly concentrated and dominated by a few large Japanese firms. In the lower end of the market, specifically PMLCDs, there has been a surge of entrants, particularly from other Asian countries. At the high end, large investments are being made by Japanese companies, dramatically increasing their production capacity. Other large firms, primarily in Asia, are also making large investments in AMLCD production. Yet, even a doubling of capacity from 1992 to 1994 has not satiated an exploding demand.

Indicators of concentration in the newly emerging AMLCD industry are now very high, as only a few firms produce in volume, and Sharp alone has over 50 percent of the market. New entrants may reduce this concentration to some extent, but since incumbent producers are also enlarging their capacities aggressively, the market is likely to remain concentrated.

Cost model analyses show that investments in this market, particularly without good information and experience, could be very risky. Expected return on investment (ROI) would be highly sensitive to experience, something that domestic firms do not have. By contrast foreign firms have learned from steadily producing displays, first for calculators and watches, and now for a variety of consumer electronic and information processing products. This risk and the very large scale of investment itself are daunting factors for any private U.S. firm challenging the world leaders in FPD manufacturing. A minimal investment in facilities would cost almost $100 million, while a high volume AMLCD facility might cost $400 million. A U.S. facility would be isolated from its competitors and from key infrastructure such as experienced workers and suppliers.

CHAPTER V: EQUIPMENT AND MATERIALS INFRASTRUCTURE

Several large U.S. companies have established strong market positions for selected FPD components, such as Corning Glass in glass substrates, and Texas Instruments in electronic display driver circuits. However, without a large FPD fabrication facility in the continental U.S., most U.S. FPD materials and equipment suppliers have moved their production offshore. Corning Glass and Texas Instruments have either built or acquired new Japanese facilities for the production of glass substrates and display drivers. Domestic manufacturers of equipment, like MRS Technologies, have little of the synergy that comes from a mutually beneficial relationship with a local fabricator, such as receiving direct feedback on how the equipment might be improved. While it is conceivable that such feedback can be obtained from foreign customers, in actuality this has been difficult and demonstrably less effective. Although this obstacle is being overcome by some U.S. producers through such means as joint ventures, success will be difficult to achieve. While U.S. materials and equipment suppliers have competitive strengths in the world market, these strengths will be hard to maintain in the absence of a substantial domestic market.

A. U.S. INFRASTRUCTURE: STRENGTHS AND WEAKNESSES

Despite the weak position of U.S. flat panel display producers, several U.S. FPD materials and equipment producers have established very strong positions in Japan. In a few key areas these U.S. firms dominate: specifically non-alkali glass, chemical vapor deposition (CVD) equipment, and in-situ inspection equipment. The most significant U.S. materials strength is in the area of non-alkali glass used in TFT LCDs. Corning Glass has approximately 80 percent of this market, with the remaining supply provided by Nippon Electric Glass (~15%) and NH Technoglass, a joint venture of Nippon Sheet Glass and HOYA (~%5). Corning currently produces this glass in the United States, but finishes it in Japan. In CVD for flat panel displays, Applied Materials has a leadership position, and has established a partnership with Komatsu in order to improve access to the Japanese market. In the expanding market for in-process testing Photon Dynamics has had success in the Japanese market. While these are significant developments, it is clear that there are a number of equipment and materials areas, such as color filters, where the U.S. base is either very weak or non-existent. Also, in the few areas of U.S. leadership there are notable overseas efforts to build alternatives, and U.S. firms feel considerable pressure to establish partnerships with Japanese firms to maintain access to the Japanese market.

Table 5-1 shows the AMLCD manufacturing process and the leading companies that supply equipment for each process, with the U.S. companies shown in italics. There are very few U.S. equipment suppliers.

U.S. Strengths—Materials

Flat Glass Substrates—Flat glass substrates for FPDs must meet demanding specifications which are challenging to today's glass manufacturers. The glass must incorporate a high degree of flatness. Tolerances vary from .1 micron for AMLCD processing to 5 microns for other FPD processes. For active matrix displays, the most popular glass is Corning's "7059" fusion-drawn glass, which dominates its market.

TABLE 5-1
AMLCD MANUFACTURING PROCESS

PROCESS	EQUIPMENT	MANUFACTURERS *U.S. Companies in Italics*
Step 1: Glass Substrate Process		
Glass substrate	glass-making	*Corning Glass*
Step 2: Color Filter Manufacturing Process		
Glass Preparation	bevelling & lapping	
Cleaning	cleaning	Shimazu (SPC Equipment), Dai Nippon Screen (DNS), Chuo Riken, Pretech
Drying	conveyor oven	DNS
Undercoating	CVD	Shimazu, Tokyo Electron, Anelva, Ulvac
Curing	conveyor oven	DNS
Color filter formation	photolithography electrodeposition	Hitachi Electron Engineering
Overcoat	spin coater	DNS, Chuo Riken, Hitachi Electron Eng.
Curing	conveyor oven	DNS
Transparent electrode	sputtering	Nichiden, Anelva, Ulvac
Step 3: Array-Making Process		
Cleaning	cleaning	SPC Equipment, DNS, Chuo Riken, Pretech
Coating	sputtering	Nichiden, Anelva, Ulvac
Sputtering	P-CVD	Shimazu, Tokyo Electron, Anelva, Ulvac, *Applied Materials*
Cleaning	cleaning	SPC Electronics, Chuo Riken, DNS
Resist coating	coater (spin)	DNS, Chuo Riken, Hitachi Electron Eng.
Pre-baking	oven (conveyer)	DNS
Exposure	stepper projection	Canon, DNS, *MRS Technology*, Nikon, Hitachi Electron Eng.
Developing	developer	Emsetech, DNS, Tokyo Electron, Chuo Riken, *Spire*
Post-baking	oven	DNS
Etching	etcher (dry/wet)	DNS, Chuo Riken, Anelva, Plasma Systems
Resist stripping	stripper (conveyer)	Tokyo Electron
Testing	testers	Tokyo Electron, Tokyo Cathode Lab, *Photon Dynamics*
Step 4: Cell-Assembly Process		
Cleaning	cleaning	Kaijo, Shibaura Eng. Works, SPC Electronics, Newrong
PI coating/baking	printer/oven	Nihon Photo Printing, Hitachi Chemistry, Denko
Aligning	rubbing	Kawaguchiko Seimitsu, Joyokogaku, Newrong, Hitachi Electron Engineering
Cleaning	cleaning	Kaijo, Shibaura Eng. Works, SPC Electronics, Newrong
Spacer spraying	spraying	Joyokohaku, Shokubai-chemistry, Nisshin Eng., Hitachi
Sealing/coating	printer/dispenser	Kawaguchiko Seimitsu, Chuo Riken, Tore Eng., Newrong, Hitachi
Assembly	laminating	Ayumi Kogyo, Kawaguchiko Seimitsu, Joyo Kogaku, Shinetsu Eng., Seiwa Kogaku Seisakusho, Chuo Seiki, Denko, Newrong
Liquid crystal injection	vacuum	Ayumi Kogyo, Osaka Shinkukiki, Kawaguchiko Seimitsu, Kyoshin Engineering, Satoh Sinku Kikai Kogyo, Joyo Kogaku Giken, Shinko Seiki, Daia Shinku
Orientation film printing	orientation and film printing	Joyo Kogaku Giken, Nittoh Denko
Testing	testing	Tabai Espec, Tokyo Cathode Labs, Tokyo Seimitsu, *Optical Specialties*
Step 5: Module Assembly Process		
Tab-IC, OLB	OLB	Iwasaki Engineering, Osaki Eng., Casio Micronics, Joyo Kogaku, Tore Engineering, Nihon Abionics, Micro Gilken
PCB Connection	manual	
Backlight Equipping	manual	
Testing	testing	Tabai Espec, Tokyo Seimitsu, Chuo Riken

Source: Published in Japanese in *SEMICONDUCTOR WEEKLY*, 4/20/93

Corning currently manufacturers, or "draws," its FPD glass in Kentucky and then sends this borosilicate glass to Japan for finishing, before delivering it to the customer. This transportation of glass around the world adds cost but no value to the thin glass sheets. To reduce the transportation cost, among other reasons, Corning is building a drawing facility in Japan. Japanese companies such as Nippon Electric Glass (NEG), Hoya, and Asahi Glass are actively trying to develop competitive products.

U.S. Strengths—Equipment

Second-Generation Chemical Vapor Deposition Equipment—Applied Materials, a U.S. firm, which is a world leader with a 40 percent share of the plasma-enhanced chemical vapor deposition (PECVD) equipment market for manufacturing semiconductors, has successfully applied their expertise to FPD production. Applied Komatsu Technology (AKT), is a joint venture with Komatsu that began in June 1993. Applied is licensing the technology to the joint venture, which will not do any of its own R&D for five years. Komatsu, a diversified producer of construction equipment and industrial machinery, is interested in entering the FPD equipment market.

In-Process Test and Repair Equipment—Photon Dynamics, Inc. (PDI), Fremont, CA, is the source of some of the most competitive electrical test and repair equipment for flat panel production. Their products are particularly valuable to a young industry struggling with yields of 50-60 percent. PDI has been well received in Japan and anticipates success in the Japanese market.

Although several companies have shown interest in licensing PDI's technology, the company has resisted sharing its source code for controlling the testing and the inspection lens. PDI has a larger installed base than any other in-process tester, with 10 machines working in the Far East.

Photolithography Equipment for Large Substrates—MRS Technologies, a U.S. company that manufactures equipment used for patterning substrates for flat panel production, is one of three companies in the world competing for this business. The other two are Nikon and Canon. This technology is considered by many to be the most critical manufacturing process in the production of FPDs. MRS is a small company with products competitive in world markets; however, it has had only limited success penetrating the Japanese market.

U.S. Strengths—Technology Support Environment

Advanced Research Projects Agency (ARPA) Support

ARPA's financial support has allowed U.S. vendors to at least keep up with, if not move ahead of, Japanese equipment vendors. The largest ARPA infrastructure contract is with the U.S. Display Consortium (USDC). The consortium has been funded at an initial amount of $20M, with which it began its operations in 1993. Although during the first years of funding ARPA has agreed to cover more than 50 percent of USDC's costs, the government share is planned to decrease to 50 percent within 5 years. This group was formed to aid development of an infrastructure for U.S. FPD makers. The USDC acts as a funding mechanism for material and equipment suppliers.

The USDC's program encompasses several aspects of building an infrastructure, including the development of quality suppliers, insertion of technology into manufacturing, development of standardization and procedures, and the dissemination of information. The funding members of the USDC include AT&T, OIS, Standish Industries, Xerox, and the American Display Consortium (which is composed of Planar, Plasmaco, Electro-Plasma, Kent Digital Sign, Norden Systems, Silicon Video, Photonics, Tektronix, and Three-Five Systems). The USDC is closely allied with the North American FPD division of the Semiconductor Equipment and Materials International (SEMI), which has signed over 80 equipment vendors as members. The initial programs will focus on development of technologies common to all types of FPDs.

ARPA has also been funding individual R&D projects at equipment and materials companies for the past five years. Several are listed below to provide examples of these projects:

- Aktis -- rapid thermal processor for AMLCD manufacturing
- Applied Materials -- PECVD equipment for AMLCD manufacturing
- Aron Vecht & Assoc.-- low voltage excitable phosphors
- Brewer Science -- polyimide color filter development
- GTE -- ELD phosphors
- Kent State -- polymer dispersed liquid crystal research
- Lehigh University -- advanced materials & devices for AMLCDs
- Lighting Sciences -- backlight technology
- Micron -- FED production process
- MIT Lincoln Labs -- diamond FEDs
- MRS -- large area lithography tools
- Nitor -- laser based projection system
- OIS -- manufacturing process technology
- Photon Dynamics -- in-process test and repair equipment
- Photonics -- drivers for AC plasma displays
- Planar -- TFEL production process
- Reveo -- 3-dimensional imaging
- Sarnoff -- TFEL phosphors
- Silicon Video -- self-supported flat CRT
- Spectrum Sciences -- ion implant systems
- Spire Corp. -- TFEL by ion implantation
- Stanford University -- low temperature, AMLCD technology for display drivers
- Texas Instruments -- high-definition DMD displays
- Xerox PARC -- high-definition display technology
- XMR -- laser crystallization process

ARPA also co-funded the Phosphor Center of Excellence in 1992 in order to strengthen the domestic knowledge base in this area. ARPA judged that the U.S. phosphor research is inadequate to meet anticipated needs of almost every display technology for either direct light emitters or illumination sources. The Phosphor Technology Center of Excellence has a dual emphasis upon both technology and education. The Center consists of the University of Georgia, Georgia Tech, Pennsylvania State, Oregon State, University of Florida, David Sarnoff Research Center, and the American Display Consortium.

ARPA has focused much of its effort on developing the industry and opening channels of communications between research efforts across technologies. One of the frequently cited problems with emerging industries is that the development work is done in a vacuum with very little interaction with the final users or complementary component makers. However, once an ARPA contract is received by a company or institution, that entity must present reviews of its progress to ARPA's program managers. This type of communication has fostered developments in many aspects of FPD technology.

Semiconductor Manufacturing Equipment (SME) Industry

One of the strengths of the U.S. FPD manufacturing equipment industry is its technology and market development for the U.S. semiconductor manufacturing equipment (SME) industry. Although subject to severe foreign competition and a declining market share in the 1980s, the U.S. SME industry has continued to rebound through the 1990s—reaching 52 percent market share in 1993[1]—signaling a turnaround of this industry's ability to compete in the market.

U.S. SME companies typically invest 15 percent of sales in R&D, a much higher average than the electronics sector as a whole. The profit margins the equipment makers need to support this massive R&D effort force the price of the next generation of equipment upward, to the point that purchase of the expensive equipment is one of the financial risks of manufacturers entering the FPD industry. However, these profit margins also allow the equipment makers to advance their technology.

The SME and FPD manufacturing equipment industries have many of the same upstream suppliers and rely upon the health of much of the same infrastructure. For example, the lithographic lens maker Tropel supplies MRS, an FPD photolithography tool-maker, and Tropel also supplies the Silicon Valley Group's IC photolithographic tool. Without a domestic semiconductor company's business supporting Tropel's continuous research into lens improvements, the company could fall behind in lens technology, leaving the systems manufacturers to rely upon their foreign competitors for a critical component.

Research Universities

In the U.S., Kent State University is the site of the Liquid Crystal Institute, formed to study and understand the properties of liquid crystals. The students who graduate from the Institute are quickly hired by companies like Standish Industries, Xerox, Magnascreen, Tektronix, and Kopin. The Institute has realized a dramatic increase in interest from the private sector in recent years. Although always strong in basic liquid crystal research, the Institute now has industry partners who want to take the research forward in such areas as retardation films and alignment layers. The U.S. is equal to, if not ahead of, Japan in the area of liquid crystal research.

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[1] Semiconductor Equipment and Materials International (SEMI), April 20, 1994.

U.S. Weaknesses

Backlights (AMLCDs and PMLCDs only)—There have been many improvements in backlighting technology, many from U.S. firms. However, at the present time the industry standard is the cold cathode fluorescent lamp, supplied by Ushio, Mitsubishi Rayon, and other foreign firms. The lamp is incorporated in a diffuser to spread the light uniformly behind the liquid crystal display. The adoption of new technologies is dependent upon display manufacturers agreeing to incorporate new designs into the display modules. Japanese display makers have been reluctant to do so in the past, discouraging further attempts by others to develop superior backlighting technology.

Lack of Domestic High Volume Production—Even when U.S. vendors have been able to install their equipment in a Japanese display facility, the manufacturers tend not to provide the feedback necessary to make improvements to the equipment. Feedback is very important in this industry in order to make improvements on the spot or in the next generation of equipment. Actual process refinements are considered company trade secrets and guarded accordingly. Access to the foreign facility is restricted. Japanese equipment vendors have noted this as a reason faster progress has not been made in solving some of the manufacturing bottlenecks.

The example of one U.S. manufacturer which sold equipment in Japan is instructive. Once its technicians had installed the equipment, they were not allowed back to service or make the upgrades they had designed. The Japanese buyer insisted that for security reasons, the U.S. manufacturer send the parts and the instructions and the buyer's technicians would do the installation or replacement. The seller was not allowed to see how its equipment performed in the buyer's environment, and was therefore unable to make adjustments that may have been key to get the buyer to purchase additional equipment for the next high volume production line. Other U.S. companies have run into similar situations at other fabrication facilities.

When talking to potential customers in Japan, U.S. vendors constantly have to deal with the question of how they are going to provide good service to their customer from "the other side of the world." U.S. companies have attempted to deal with this problem by establishing subsidiaries and joint ventures, or by hiring a distributor for their products in Japan. As one CEO put it, "During the 1970s U.S. companies signed up distributors, in the 1980s they set up Tokyo offices and wholly-owned subs, and in the 1990s the focus will be on joint ventures."

Unproven Equipment—The biggest hurdle facing the U.S. equipment firms is proving their equipment can perform in a high volume manufacturing facility. With the sizable capital investments involved in FPD manufacturing (up to $400 million for a high volume facility), equipment failure is intolerable. The inability to test their equipment on a high volume manufacturing line is a barrier to market success.

Standards—Uncertainty over standards presents a barrier to commercializing new products. Individual firms have trouble assembling the resources needed to pursue developments that cover the whole range of possible contingencies, particularly when standards are just beginning to be developed. For example, a non-standard substrate size is an obvious disadvantage to a company designing equipment to penetrate the market. Japanese industry reportedly is forming domestic standards setting groups; lack of participation in those groups could be disadvantageous to U.S. companies considering entering the market. The lack of a strong domestic flat panel industry will result in a correspondingly weak influence on standards development.

Relative Size of U.S. Suppliers—Foreign distributors, agents, and partners are a necessity for U.S. firms trying to sell products in Japan. Lack of size and market strength can put U.S. firms at a disadvantage in negotiating access to foreign markets. Several Japanese distributors have attempted to leverage their position by requiring access to U.S. vendors' source code or manufacturing processes. Several U.S. equipment companies have had to contend with attempted takeovers of their technology by their Japanese partners. Local support for access to the Japanese market may also be traded for equity in the U.S. firm, which obviously provides more leverage to the foreign partner.

B. SUMMARY

The lack of domestic, high volume FPD manufacturing will not only prevent the establishment of a complete materials, components, and equipment infrastructure in the U.S., but may ultimately cause the loss of the existing FPD production base. The geographical disassociation of the U.S. suppliers from the equipment users has inhibited traditional product feedback loops essential for product improvement. If an equipment manufacturer cannot get feedback about the performance of equipment in the field, product improvements necessary to maintain competitiveness cannot be effectively accomplished. While the U.S. still has important strengths that include advanced research and related industrial capabilities, even these may be in jeopardy if substantial growth in U.S.-based flat panel production is not achieved.

CHAPTER VI: INDUSTRY STRATEGIES

This chapter presents U.S. industry's approaches to FPDs as producers and consumers. For flat panel producers, it reviews the evolution of corporate developments in FPDs, including their research and development activities, investment activities, production and market focus. For consumers of FPDs, the chapter looks at their current supply approach, future directions in demand for displays, and company plans to meet these demands.

A. DOMESTIC PRODUCTION CAPABILITIES

The demand and supply of FPDs present a highly asymmetric picture. On the demand side, as shown in Chapter III, FPDs are a key component for many existing high technology products and are projected to be increasingly important for future applications in information processing, telecommunications, and consumer products. The market for FPDs is projected to grow rapidly in all regions of the world over the next decade and beyond. Yet on the supply side of the equation, as shown in Chapter IV, production of FPDs is heavily dominated by a few suppliers located primarily in Japan. In the most advanced areas of production, specifically AMLCDs, production is concentrated in a very few firms in Japan, with minimal production in the United States, Europe, and elsewhere in Asia. This asymmetry—flat panel displays impacting a broad array of downstream high technology industries all over the globe on the one hand, and on the other hand, a supply highly concentrated in a few, mostly large, vertically integrated Japanese companies—creates a potentially difficult strategic situation for most U.S. companies, existing suppliers, would-be suppliers, and consumers.

Early U.S. Development of Display Technologies

FPDs were invented in the laboratories of large U.S. electronics manufacturers in the early 1960s. RCA, General Electric, and Westinghouse had early developments in displays based on liquid crystal technology. IBM began to explore various display technologies during this time, and focused in the 1970s on plasma display technology. These companies pursued FPDs as advanced technology in their research labs, with little near-term product interest.

For RCA, flat panel technologies were pursued as a distant future alternative to television CRTs. RCA's work in liquid crystal stemmed from the research of George Heilmeier at RCA's Sarnoff Laboratory. As early as 1968, this technology was portrayed as offering prospects of a new type of display that had the potential for a thin television screen that could be hung on the wall, as well as electronic clocks and watches with no moving parts. However, internal turmoil within RCA—and a view that LCDs were more a threat to existing business than an opportunity—prevented successful exploitation of RCA's early lead in LCDs.

Westinghouse pursued LCD technology in the late 1960s and 1970s. Dr. Peter Brody of Westinghouse invented the active matrix approach using cadmium selenide. For Westinghouse, major efforts to develop LCDs for use in the Consumer Electronics Division sparked several million dollars of research. This research resulted in demonstrations of both AMLCDs and ELDs, but Westinghouse decided not to get into the flat panel business. At this time Westinghouse's weak position in television resulted in it halting production of television and related components in the mid-1970s. With no other source of support for this research within the company and the technology at the stage of prototype production, Westinghouse had the option of either investing in an expensive and risky manufacturing effort for external sale or abandoning the effort. In 1979, Westinghouse canceled the project. Dr. Brody then went on to found Panelvision, which subsequently was acquired by Litton.

General Electric also had an extensive research program in LCDs during the 1970s. Its attempt to enter into manufacturing was overtaken by a corporate strategy to focus on "systems" rather than components. GE focused its display efforts mainly on military applications in the 1980s. Moreover, GE's divestiture of its consumer electronics group and the subsequent sale of its avionics division eliminated its internal customers for this technology.

IBM, as an integrated manufacturer of computers, has been interested in the prospect of using flat panel technologies in a wide array of business and industrial applications. Although IBM developed plasma displays during the 1970s, the company determined in 1984 that liquid crystal was the most promising technology. Based on this determination, IBM divested its plasma operation (which subsequently became Plasmaco) and searched for an LCD partner. Such a partner had to be capable of sharing both the R&D costs and the manufacturing investment. No suitable U.S. company was willing to do so. IBM then looked for an international partner and established a partnership with Toshiba of Japan.

Several other large U.S. companies that made either electronic products or components looked into the possibilities of producing liquid crystal displays during the 1970s and 1980s. These included Beckman Instruments, Fairchild, Hewlett-Packard, Motorola, Texas Instruments, and Timex. Generally these companies concluded that the requirement for large-scale investment in R&D and production facilities, coupled with marketing, sales, and distribution expenses for this new product carries too high a price. Most U.S. firms found that a sustained position in consumer electronics, which was then the main market for such displays, was untenable, given the strong competition from Japanese firms.

Consumer Displays—One reason for U.S. consumer products companies not putting greater emphasis on LCDs was the emergence of the light-emitting diode (LED) as an alternative for such applications as calculators and watches. However, the LED proved to be limited by poor power efficiency, and LEDs were unsuitable for economically increasing the size and content of information of displays in comparison to other technologies, such as LCDs and plasma.

With the larger U.S. companies exiting the FPD business, only small niche-oriented U.S. firms remained. Most of these companies had excellent technical capabilities, some of which were acquired as spin-offs from larger U.S. companies that had left the business. However, relative to the burgeoning capabilities, scale of investment, and product base of foreign competitors, particularly in Japan, these U.S. firms clearly faced competitive disadvantages.

With RCA bought by GE and then sold to Thomson (France), the main domestic proponent for developing high-information-content displays for the consumer entertainment market ceased to exist. RCA's Sarnoff Research Laboratory had gotten out of LCDs early and from 1970-1983 worked on flat CRTs. In the early 1980s, attention at Sarnoff shifted back to LCD research. RCA was exploring a joint production venture with Hitachi, but the sale of RCA to GE brought these discussions to an end. The Sarnoff Laboratory was later sold to SRI.

The main U.S. customers for smaller displays, particularly calculators, purchased displays almost entirely from foreign suppliers. In the early 1970s, Texas Instruments (TI) explored several different display options, including beam indexing CRTs, flat tube, plasma, and electroluminescent displays, but found none that it could see achieving commercial results for its consumer applications. With its emphasis on consumer applications in the early 1980s, TI looked into producing small panel LCDs, primarily for watches and calculators, but determined that insufficient internal volume existed to make production economical, and concluded it did not want to be a merchant of displays to outside customers. Hewlett-Packard, another prominent U.S. calculator company, established ties to Hitachi for displays, and generally regarded displays as a commodity component that it would acquire through supplier arrangements.

Home entertainment is still a market driver for some firms pursuing various types of flat panel technologies. High definition television is one specific segment of this market. Some of the firms that see HDTV as a potential market include Tektronix, which is targeting this market for its plasma-addressed liquid crystal (PALC) technology; Texas Instruments, for digital mirror projection; and Zenith, for flat-tension-mask CRTs. Other technologies, such as Magnascreen's tiled LCD, Photonics' PDP, and Planar's ELD offer prospects for large screen application, but are now mainly targeted at workstation monitors. Should any of these technologies succeed in the computer monitor market, it could potentially be scaled up to larger screens for home entertainment and commercial use.

Military Displays—GE had focused primarily on LCDs for military avionics. GE had invested about $25 million into R&D and about the same amount into pilot production. GE's LCD operation was sold to Thomson of France. It is still operating at small volumes. Litton currently produces a military AMLCD using the cadmium selenide (CdSe) technology obtained from its purchase of Panelvision. Planar Systems (electroluminescent), Photonics (plasma), and OIS (liquid crystal) offer displays for military applications in small volumes. Some firms currently pursuing flat panel technologies for military displays include Raytheon and Texas Instruments using field emission display (FED) technology.

Computer Displays—By far the largest market today for FPDs is for laptop computers. FPDs for computers are a recent development, beginning in the early 1980s. Initial U.S. makers of portable computers with FPDs, such as Compaq, used monochrome plasma displays. Compaq's displays were purchased from Matsushita of Japan. In the mid-1980s, LCDs were too fuzzy. When U.S. computer firms turned to LCDs, there was very limited U.S. production capability. In Japan there were several firms that had technical capabilities and production experience in LCDs derived from their consumer electronics businesses.[1] Apple, Compaq, and IBM say they searched for U.S. firms to make their LCDs, but found insufficient capability compared to that available in Japan.

The Changing FPD Market and Company Strategies

Underlying the heightened interest of many U.S. electronics firms in FPDs is the perception that the electronics product market is undergoing a fundamental transformation. This transformation has several dimensions, all of which raise a great deal of uncertainty regarding which technologies will capture various aspects of the emerging market. However, this uncertainty is also accompanied by another risk—that the technologies and products that are the current market for existing businesses will be overtaken or transformed by such developments as:

- Personal Digital Assistants—Portable, multi-function telecommunications and digital processing systems with high information video displays are a major focus of future

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1 Another major Japanese advantage in LCDs was their ability to use existing integrated circuit knowledge, facilities, and personnel to move into this technology. This ability proved especially attractive when the Japanese firms were confronted with a glut in the memory chip market. Industry sources indicate that the major move by Japanese firms into the liquid crystal display arena was triggered in part by their need to find alternative employment for redundant semiconductor workers.

electronic products. This is an uncertain, high-risk market with many firms offering new products.

- Merging of PCs and workstations with emphasis on the networked office environment.
- Merging of and blurring of distinctions between telecommunications, computers, and video entertainment with development of multimedia applications and hardware,
- Potential explosion of video telecommunications.
- "Green PCs"—a potential future market driver for FPDs.
- New display sizes—large, high definition TVs and small, "virtual reality" goggles.

A common element of these developments is that they all will use FPDs. These prospects and uncertainties have stirred many mainstream U.S. electronics firms, such as Xerox, AT&T, IBM, Motorola, and Texas Instruments, to investigate alternative technologies and development paths related to display technologies. At the same time, incumbent firms in the laptop market, currently the main market for FPDs, are highly concerned about the availability of advanced FPDs to meet their projected demands over the next five years. These concerns have led to their interest in both domestic production of AMLCDs and in alternative display technologies, such as FEDs, that offer prospects of reduced dependence on the small number of existing AMLCD suppliers.

New Directions for U.S. Industry Strategy

Several U.S. electronics firms now are in the midst of major strategic decisions regarding FPDs. There appears to be a window of opportunity for U.S. firms to get into the FPD business. This period of opportunity is driven by five factors: (1) the shortfall in supply of AMLCDs for meeting current and projected demand for laptop and other computer applications; (2) the difficulties of achieving profitability in the manufacture of AMLCDs for use in laptops and smaller applications; (3) the limitations of AMLCDs for use in very large systems; (4) the prospects of a major discontinuity in the technology; and (5) the concerns of some large U.S. firms regarding dependency on a few foreign competitors for a technology that is viewed as strategic to their core businesses.

B. STRATEGIES OF U.S. COMPUTER AND VERTICALLY INTEGRATED ELECTRONICS COMPANIES

A number of vertically integrated electronics companies in the U.S. were queried to determine their interests and concerns regarding FPDs both as consumers and as possible producers. Largely computer and telecommunications electronics firms, these companies represent a different set of consumers from the original U.S. firms that initiated FPD development. Most of them have developed little if any capability in displays, having relied on external (usually Japanese) suppliers for CRTs. Now as retail consumers begin to base their purchase decisions on the quality of the display, domestic electronics companies are becoming increasingly concerned about relying solely on outside vendors for their FPDs. Many of these companies are now considering joint ventures with each other and with smaller U.S. display firms, and some have submitted proposals to the U.S. Government for assistance or have expressed interest in seeing the government take a more active role in establishing a domestic base for FPD supply.

Apple

Apple had an initial foray into the portable computer market in the late 1980s. Their product was uncompetitive with other early portables, such as those made by Compaq and

GRID, and was withdrawn from the market. In the early 1990s, when Apple sought to re-enter the portable market with its new PowerBook laptop computer, it sought to establish a supplier relationship for development and production of a liquid crystal display.

Apple first went to Ovonics (now OIS) in the U.S., but determined that Ovonics could not provide the production quantities Apple needed. Ovonics lacked both technology and production capacity. Moreover, Ovonics wanted Apple to provide it an R&D contract, followed by a pilot plant. Apple found that several Japanese firms were willing to take the risks of product development and to put up their own money to build a factory.[2] Hosiden of Japan was selected, even though it was not yet in the computer display business. Hosiden had been doing research in LCDs funded by Nippon Telephone and Telegraph (NTT). When Apple wanted to provide a color display for the PowerBook, it turned to Sharp as its main supplier. Sharp had worked closely with Compaq to develop a color AMLCD capability. Sharp is also Apple's major supplier for its recently announced personal digital assistant, the Newton.

Demand—Apple will buy approximately 700,000 displays this year. It is shifting toward AMLCDs. Apple has generally sourced components from vendors but is becoming concerned about both technology access and capacity assurance. Capacity is currently a major constraint in both monochrome and color AMLCDs.

Strategic Factors—Given the importance of displays as a product differentiator, and the lack of a wide range of alternative suppliers to meet needs in periods of high demand, Apple sees a competitive U.S. production base as highly desirable. A U.S. supplier base might provide a competitive advantage to Apple, allowing Apple to develop products more quickly and easily, as well as providing access to production capacity. Apple emphasizes, however, that production capability and quality of product at competitive prices are keys to the success of any such venture.

AT&T

About two years ago AT&T became concerned that the display was emerging as a critical component for its future telecommunications and information processing businesses, and that it did not have adequate technology or product access. Based on a world-wide survey of the technology AT&T decided to explore entry into AMLCD production, and as part of this strategy it entered into the Advanced Display Manufacturing Partnership (ADMP) with Xerox and Standish to establish a domestic AMLCD manufacturing test bed. It has also carried on discussions with a potential Japanese partner in Japan.

Demand—AT&T's internal demand projections for high resolution displays are projected to be on the order of one million displays a year by 1995. Based on these demand projections, about a year ago AT&T decided it needed to consider FPD production.

Strategic Factors—Xerox, Standish, and AT&T submitted a proposal to ARPA to support the establishment of the ADMP. Underlying AT&T's commitment to this strategy is that it sees FPDs as the key to future end-use products, particularly with the functional migration from networks to the terminal. Chip-on-glass is already a reality with Toyota using amorphous AMLCD chip-on-glass technology for navigation systems. AT&T believes that chips in future systems will be integrated on the display, and that the display will contain the

2 As in IBM's joint venture with Toshiba, the terms of capital investment available to the Japanese partners were much more favorable than the capital costs facing U.S. contenders.

intellectual property. The crucial software will be in the chip on the glass. AT&T wants to develop the FPD business as an "application specific" type business, not a commodity business.

The display is currently the single biggest cost item for AT&T's videophone. However, it is the part over which it has the least control. AT&T also considers the display to be a product differentiator. The anticipated ability to design a unique display to appeal to its customers is seen by a ATT as giving it an advantage over its competitors who are without FPD manufacturing facilities. These competitors would have to buy generic displays from foreign suppliers. Because the display is one of the features by which consumers will make purchasing decisions in videophones and other products, AT&T considers the display to be a strategic component.

AT&T believes that process changes must be made to overcome the current major technical difficulties in AMLCD manufacturing, and these changes may be available with the next generation of equipment. The key years for changing the process are 1995-96, and this period is when AT&T is considering entry into manufacturing. AT&T also has some in-house capabilities that it believes can be leveraged in the manufacturing process.

Compaq

In 1983, Compaq was one of the earliest firms to market a portable personal computer. These used CRTs; in 1985, Compaq offered one of the first portables using an FPD plasma display. At that time, flat panels were not being used in computers, and Compaq was stressing the state-of-the-art display technology. It had difficulty obtaining the displays it needed, but finally had successful results with Matsushita.

As an early flat panel user, Compaq was approached by Japanese companies as a potential user of advanced LCDs. The first LCDs were poor in comparison to the plasma displays being offered in 1987. The vendors were struggling with their contrast ratios. The shift in liquid crystals from twisted nematic to supertwisted nematic made visible defects that were not visible with the earlier technology. Compaq was still interested in the possibility of using LCDs due to the limitations of plasma displays. The issues were performance capabilities and production capacity. Those displays that were best from the standpoint of visual performance were the most complex products with the most difficult production problems. The ones that looked the best were very hard to build.

Compaq went to several possible vendors, almost all Japanese firms, urging them to reveal the latest developments in their labs. Compaq was seen by LCD vendors as a prime customer because of its interest in putting out products at the high end of the quality spectrum. Epson showed Compaq its latest development—the first double STN screen. The Epson screen was vastly superior compared to the others Compaq had seen and Compaq gave Epson specifications for the display it needed and began to work closely with Epson. After six to eight months, Epson had a product ready for Compaq. However, when Epson started to ramp up production it ran into yield difficulties that resulted in it not having adequate capacity to supply both its other customers (mainly IBM) and Compaq.

About this time (1988), Sharp showed Compaq its version of a double STN panel. Sharp was very aggressive in trying to meet Compaq's specifications and made considerable investments to resolve production problems. Sharp had made a corporate commitment to be the leader in LCDs.[3] Sharp made it clear it wanted to gain an understanding of the computer business and be a key supplier. Sharp exclusively focused its efforts on Compaq at this time, establishing a quasi-partnership relationship. Compaq says it has tried to support U.S. vendors of FPDs. It had early discussions with Planar on ELDs. While the technology was equivalent to plasma, Compaq stated that "ELDs had no significant advantages that warranted switching."

Demand—Compaq introduced the SLT286 portable with a Sharp double STN display in 1988. Sharp had built much of its own equipment for producing this display. Volume reached about 10-12 thousand units per month. From that point on Sharp has remained a primary supplier of displays for Compaq. Compaq also uses Hosiden as a supplier for monochrome displays. Compaq is the leading producer of portable personal computers (PCs) worldwide. Total revenues for Compaq in 1993 were $7.2 billion. It recently announced a $20 million expansion of its manufacturing lines in Houston, Texas, for producing both desktop and portable PCs. Compaq's portable PCs use both PMLCD and AMLCD screens, all of which are sourced from abroad.

Strategic Factors—Not being able to obtain displays in a timely manner in quantities to satisfy its portable PC demand is a key strategic issue for Compaq. The company is working to encourage development of a domestic manufacturing capability in advanced displays and has expressed interest in a "partnership with innovative federal technology policy initiatives."[4]

International Business Machines

In 1984, an IBM internal task force on displays projected that color AMLCD should be the focus of IBM's future efforts in displays. A decision from this task force was that IBM should pursue this technology in partnership with another large-scale consumer. IBM initially looked to form a partnership with GE, but GE's military focus proved incompatible with IBM's commercial interest. IBM then sought to find another U.S. partner, but could not find one.

An IBM spokesman emphasized that in this period (1985-86), "we did not have this [AMLCD] technology ready to go, and neither did anyone else."[5] Thus, IBM was looking for a partner who could make a significant contribution. In 1987, IBM and Toshiba joined in a research and development contract. A fundamental issue was the production process. Both firms had substantial experience in semiconductors and electronics packaging. They determined that problems of AMLCD production included packaging, liquid crystal cell fabrication, and integrated circuit production. IBM officials stated, "Initially moving AMLCD into production was not seen by either party—IBM and Toshiba—as a major problem, but it turned out to be more difficult than we thought it would be in comparison to semiconductors."[6] Both IBM and Toshiba did R&D on various processes over a two to three year period. IBM did separate work on its Yamato pilot line, which cost about $10 million per year to run, and Toshiba had its own pilot line at Taishi.

After the R&D phase concluded, the decision was made to set up Display Technologies Inc. (DTI) as a joint production venture. According to IBM, "When the decision was made in 1989, the entire infrastructure for LCDs was in Japan. Producing anywhere else would have

3 At this time, commercial application of AMLCDs was thought to be ten years away. However, it turned out that just four years later Sharp and Toshiba had an active matrix display available.

4 Letter from Joseph Tasker, Compaq.

5 Interview with IBM representatives.

6 Ibid.

been non-competitive." Along with infrastructure and technical know-how, cost was also an issue. DTI was built on Toshiba's property as part of an existing facility. A key benefit to the partners was that Japan at this time had very low capital costs, and, as a Japanese company, DTI had access to Japanese capital markets.[7]

Demand—Currently IBM is supply-constrained on AMLCDs for the ThinkPad notebook computer. Bringing in other suppliers as sources of these displays has been limited by the proprietary nature of the displays, resulting in additional logistical and compatibility issues. Moreover, it is not in DTI's interest for there to be an abundance of suppliers. Capacity of DTI is 500,000 per year, but its production facility is only partially tooled, and the firm will likely double its capacity within the next year.

Strategic Factors—Recently IBM has begun to consider possibilities of a joint production venture in the United States. However, this is only in the discussion stage now and would depend upon the interests of other U.S. firms, as well as appropriate arrangements with DTI and Toshiba, particularly if technology from the DTI facility were to be incorporated into this factory. IBM continues to investigate alternative technologies. The company does not see any other technology replacing AMLCDs in the market in the next three to five years. The designs of the products made at DTI for IBM come from IBM, and Toshiba also provides its own designs. In this way IBM has assured its supply of displays for its portable computers and is not dependent upon the exigencies of the AMLCD market. IBM considers the display a key differentiating component that gives the company a strategic advantage in the portable computer market.

Raytheon

For over 40 years, Raytheon has been a major supplier of high performance Cathode Ray Tubes (CRTs) for avionics, ground vehicles, air traffic control, ship systems, and high end commercial products. For decades, CRTs have been used for high performance display applications because competing technologies could not match their brightness, picture quality, or cost. To realize this performance designers had to accept inherent CRT limitations in reliability, power consumption, and packaging efficiency.

Raytheon has pursued alternative display solutions to provide customers full color with high brightness and true sunlight readability, qualities which were simply unattainable with existing CRT or emerging AMLCD technologies. Raytheon selected Field Emission Display (FED) technology as the most promising avenue for meeting next generation requirements. Raytheon initiated an FED research and development effort in the mid 1980s and produced a matrix-addressed working display design, scores of half-centimeter lab-sample FEDs, and a 2-inch square monochromatic display. In 1993, Raytheon entered into a strategic relationship with Pixel International, the worldwide licensor of Field Emission Technology for France's Laboratoire D'Electronique de Technologie et D'Instrumentation (LETI). This partnership will provide Raytheon with critical proprietary manufacturing technology essential to bringing a competitive product to market.

Demand—Raytheon's product focus will be high performance, high brightness, sunlight readable displays for both the military and commercial markets. Raytheon considers FED to be the highest performance display technology for military color cockpit displays, and believes it has significant advantages over all competing systems. Raytheon sees FEDs being more

7 IBM notes that Japanese firms were able to obtain very cheap capital through the use of convertible bonds that were "repaid" as stock.

power-efficient than LCDs and producing a significantly brighter image. Unlike the LCDs, FEDs have no viewing angle limitations, are insensitive to temperature, and do not smear at high Gs. FEDs require fewer masking levels and has only one high resolution lithography step. FEDs should therefore be lower in cost than AMLCDs.

Strategic Factors—Field Emission Display manufacturing takes advantage of expertise in semiconductor processing as well as CRT design and manufacturing. Many critical manufacturing techniques required to build FEDs are similar to the knowledge base required to build CRTs. Raytheon has experience in these techniques which will be integral parts of the FED manufacturing process, including phosphor formulation and deposition, vacuum sealing, bake-out, burn-in, glass cutting and sealing, gettering, assembly, and display test and characterization.

High brightness is a key issue for many high-end performance display applications. The majority of cockpit displays require greater than 200 fL of brightness, with head-up displays requiring 10,000 fL. Raytheon completed a High Brightness R&D program utilizing cathodes supplied by Pixel to determine if such higher brightness was achievable, and if so, what it would take to develop and manufacture such a product. During this internally funded program, Raytheon achieved record results and drove display brightness significantly beyond all known intensity requirements.

Texas Instruments

TI has explored various display technologies since the early 1970s. It looked at flat tube displays, but saw that manufacturing costs would not be competitive with CRTs for the color TV market. Other technologies (plasma, electroluminescent, liquid crystal) were evaluated in the late 1970s and early 1980s. LCDs were looked at mainly for watches and calculators. However, there was not enough predicted volume in LCDs for TI itself, and TI did not want to sell to outside customers as a vendor.

About two years ago, TI began to look into field emission devices (FEDs) for use in military products. It determined that the internal market demand for military applications was too small to pursue production. FEDs were seen as intrinsically dual use technology. TI concluded that FEDs were a good match to TI's commercial business. First, TI's semiconductor group already produces many of the electronic components such as drivers, controllers, memory, and logic devices used in flat panel displays. Second, most of the FED manufacturing processes are simply scaled-up semiconductor manufacturing processes. Third, TI has strong business relationships already established with all major U.S. flat panel display users through semiconductor sales. Fourth, TI has an internal channel to the single largest commercial market segment for flat panel displays—notebook computers. Based on these factors, TI elected to position its FED project within its Semiconductor Group.

Also, about two and one-half years ago TI formed a corporate venture to address the commercial/dual use display market from 20-inch up to huge cinema size screens utilizing its digital mirror display (DMD) technology, a projection display technology it has developed over the years with support from ARPA. DMDs are semiconductor devices, made in standard semiconductor production facilities using standard processing tools, and as a result offer the potential for high performance displays at affordable prices, as volume drives down the price of these spatial light modulator chips. Today, TI is making one of the largest investments in the history of the company in this technology. This technology complements the smaller screen FED thrust and shows promise for government/defense applications ranging from head mounted displays, electronic workstation displays, cockpit and shipboard rear-projection displays, to very large screen, multimedia command center displays. As the size of displays increases these qualities become increasingly more difficult to obtain. TI plans to supply DMD display "engines" to various end user manufacturers beginning in late 1995 for use in military, commercial, and consumer applications.

Demand—TI consumes over $100 million per year in displays for military and commercial applications. These applications range from small-sized PMLCDs to larger AMLCDs for computers.

Strategic Factors—As a smaller customer, TI faces problems maintaining sources of displays, particularly for AMLCDs. As demand now exceeds supply, vertically integrated suppliers will first fill their internal demands and then the demands of their leading external customers. Smaller customers, such as TI, are caught in the pinch. Key parameters that influenced TI in selecting FEDs over competitive technologies, particularly AMLCDs, were process simplicity, lower factory capitalization cost, semiconductor process similarity, power, size, and weight reduction, and the complement it offered to other existing TI businesses. TI concluded that FEDs could be scaled up more easily past 10" displays than could AMLCDs. TI saw the possibility of a technology discontinuity with FEDs superceding AMLCDs. AMLCDs appeared to be caught in a bind regarding price/yield, power consumption, and speed of performance. As the size of displays increases, these qualities become increasingly more difficult to obtain. TI has licensed key FED technology from Pixel International which was developed over the last 10 years by France's Laboratory de Technologie et d'Instrumentation (LETI). With this approach TI believes it has a 3-5 year head-start over the competition as well as a strong, defendable intellectual property position with which to successfully compete with AMLCD suppliers.

Xerox

The Xerox Palo Alto Research Center (PARC) is now building a new generation of very high-resolution FPDs. These AMLCDs offer image quality and resolution comparable to a laser-printed document, while providing the performance necessary to show full-motion video. These achievements are enabled through the development of high-performance, high-yield manufacturing processes, and the implementation of advanced simulation, modeling, and design capabilities. In addition to state-of-the-art TFT fabrication processes, PARC has in-house high resolution color-filter fabrication capabilities, and advanced high density tape-automated-bonding (TAB) packaging techniques for the attachment of row and column drivers to the displays. Display-controller systems capable of effectively managing the high information content of displays with more than six million pixels are also being built.

From a strong research base in amorphous silicon (a-Si) materials and device physics starting in 1970, PARC has over the last fourteen years established a world class large-area electronics capability in a-Si and polysilicon (p-Si) technology. In the early 1980s, PARC established a group to develop a-Si TFT and sensor technologies for large-area scanning and printing applications. Today, PARC is considered a world leader in amorphous-silicon and polysilicon high resolution AMLCD display technologies.

Demand—Xerox procures hundreds of thousands of CRTs and FPDs annually. An internal supply for some of these displays could provide a significant competitive advantage for the company.

Strategic Factors—Xerox expects that p-Si TFT technology will eventually replace a-Si technology for future generations of AMLCD products. P-Si TFTs, like their a-Si counterparts, can be built on large area glass substrates, but offer much higher drive current, along with the capacity to form both n- and p-channel devices for CMOS circuits. This allows peripheral drive and interface circuits to be built on the same glass substrate as the active matrix, and use a common process flow. Thus, the need for separate single-crystal IC drivers now used with a-Si AMLCDs is eliminated. Xerox predicts that p-Si TFT AMLCDs will offer greater reliability, smaller bezels, higher pixel density, lower cost, simplified packaging and interfacing requirements, and will allow for more accurate gray-scale control, particularly as display resolution increases.

The advanced displays developed at Xerox PARC have given rise to a need for higher-performance display-support systems. To meet its own requirements, PARC has developed a new approach to display-interface and controller design, building the first of a new generation of controllers which can be programmed to perform all the functions necessary to drive a wide variety of displays. PARC's new universal-display controller chip eliminates the need for host systems to provide all the image-control and data-preparation functions, and will both simplify system design and allow much greater interoperability of displays between different systems.

Xerox is particularly interested in the development and delivery of electronic documents, with high resolution "paper-like" FPDs being a critical technology in this business scenario. Xerox believes it can leverage its AMLCD technology to ensure competitive domestic availability of the displays needed for its own product requirements. Xerox is therefore pursuing partnerships for the development of a domestic, high-volume production facility.

Other Partnerships Involving Integrated Electronics Firms

Based on these concerns and interests there are several developments in FPDs involving many other U.S. firms that are currently consumers of FPDs.

- Motorola and In Focus have a joint venture, MOTIF, for actively-addressed PMLCDs. This approach provides a way of extending relatively low-cost PMLCDs by using more complex driver circuitry to emulate an active matrix.
- IBM is open to considering a joint venture for AMLCD production in the United States, but specific details depend on the receptivity of other U.S. firms and IBM's relationship with DTI and Toshiba.
- Compaq is conducting a review of its display position, and is considering a relationship with one or more domestic FPD manufacturers.
- Hewlett-Packard has a venture position in Silicon Video to develop FEDs.

C. U.S. DISPLAY PRODUCERS

In the course of this study, representatives of a number of U.S. companies developing or now producing FPDs were surveyed to determine their strategies and approaches for establishing production of FPDs. In contrast to the large integrated electronics companies, these firms are generally focused on displays as their sole or primary business. Many of these companies have aimed at profitable, low-volume, niche markets such as avionics, industrial equipment, and outdoor signage. Several of these companies have expressed strong ambitions to use such niche businesses as the means to enter much broader based markets for information processing, telecommunications, or consumer applications. Several of these companies have been supported by ARPA R&D contracts, Small Business Innovative Research (SBIR) contracts, or DOE laboratory programs. Even more than the integrated companies, these companies need ready access to retained earnings, debt or equity capital, or government assistance to bring their concepts into commercial production.

This section summarizes non-proprietary information regarding the general business strategies of several FPD firms obtained from interviews with executives of these firms or from publicly available documents.[8]

Alpine PolyVision

Product—Electrochromic displays. Alpine PolyVision's proprietary technology, PolyVision, is a materials technology with electrochemical and physical characteristics which allow it to address applications in a number of product markets, including FPDs. When creating a FPD, PolyVision materials are layered in superimposed film and sandwiched between a transparent electrode supported by a glass or plastic substrate and a second electrode. When a low voltage is applied between the electrodes, rapid chemical reactions occur and a high contrast image is displayed. The formed image will last 8-10 minutes without being refreshed, or can be switched at rates of 10-20 frames per second. PolyVision displays can be produced on larger surface area substrates, as well as flexible and curved plastic and paper substrates, in addition to conventional glass structures.

Market Focus—Alpine PolyVision expects to compete in niche markets for low-information-content displays, markets where LCDs are either too expensive or not satisfactory. Most of these applications are expected to use non-glass, flexible substrates. Likely applications include interest rate and currency exchange boards, menu boards for fast-food and convenience stores, digital readouts for gasoline pumps, large price displays for gasoline stations, point-of-purchase displays for supermarket shelves, and non-glare instruments for aircraft and automobiles.

Strategic Factors—Alpine PolyVision has established partnerships with several firms which have licensed the technology for specific applications. These partners include Corning France for light-sensitive mirrors and architectural glass, COGIDEV for French military displays, McDonnell Douglas Technologies for non-French military displays, The LEGO Group for large signage in Europe, Electronic Retailing Systems International for point-of-purchase displays, and Kyocera for electronic components.

FED Corporation

Product—Field Emission Displays.

Market Focus—FED Corporation has targeted the development of 3"-8" custom direct view displays and 1" or smaller head-mounted displays.

Strategic Factors—FED Corporation was founded in 1992 as an effort to commercialize the development of field emission arrays displays at the Microelectronics Center of North Carolina (MCNC). FED Corporation has a technology development arrangement with Harris Corporation in the area of military displays. Also FED Corporation is supported by government research contracts from ARPA, the Army and Air Force in DoD; NIST and NASA; and has CRADA arrangements with the Lawrence Livermore and Sandia National Laboratories, and Lincoln Laboratory. In January 1994, FED Corporation purchased equipment and moved its base of operations to East Fishkill, NY, where IBM had leased to it a

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8 This summary reviews strategies of a majority of the firms in the U.S. which are in the FPD business. Some companies that are concentrating only on low-information-content displays are not included in this summary. The study team attempted to interview or visit every firm that it knew made high-information-content FPDs in the United States or was doing R&D with production as an objective. A survey of ARPA display contractors was also used as a source, as was an earlier survey by the Department of Commerce.

manufacturing facility that originally produced multi-chip modules. FED Corporation believes that acquiring this facility should accelerate its production by at least one year.

Kopin Corporation

Product—Active Matrix Displays. Kopin has developed a process whereby they manufacture an active matrix display on special silicon wafers which can be processed like integrated circuits. Kopin removes the upper layer of single crystal Si from the underlying wafer, and transfers the single crystal layer onto a transparent medium (glass or plastic). This active matrix works as does any LCD for projection displays and helmet-mounted displays, but with greater electron mobility.

Market Focus—Kopin plans to manufacture these displays for workstation and larger applications. The company also has developed a small, pocket-sized projector for home and office uses. They are also exploring the head-mounted display for the virtual reality and video games markets.

Strategic Factors—Kopin is developing high-resolution, active-matrix displays under an ARPA contract. Kopin will manufacture its display in-house, carefully protecting its technology and thin-film transfer process. It will contract for the initial end-use products, although it also plans to sell the display as a module to other companies, which will make the end-product. It will not attempt to create processes that other companies already do better, for example, they will purchase optics. Kopin's process uses conventional semiconductor foundries for most of its wafer processing, which Kopin believes gives them a substantial cost advantage.

Motif

Product—Active Addressing Liquid Crystal Displays (AALCDs).

Market Focus—Motif will market AALCDs that integrate the Motorola manufactured ASICs embodying the Active Addressing system with Motif manufactured PMLCDs. Motif's current LCD facility will have the ability to manufacture up to 300,000 yielded LCDs (up to 8" diagonal) per year and will supply these LCDs to both its parent companies (InFocus Systems and Motorola) for use in their respective projection and communications products as well as the merchant markets (including computer, transportation, and industrial).

Strategic Factors—Motif Inc. was formed in October 1992 as a jointly owned venture between InFocus Systems and Motorola for the purpose of producing low-cost, video speed LCDs. InFocus' work on a new PMLCD driving method called Active-Addressing caught the attention of Motorola, who was looking for a strategic source of LCDs. In Focus was looking for a partner, and subsequently found one in Motorola, who had both high volume manufacturing expertise in addition to IC design and foundry capabilities. Motif's Active Addressing places proprietary pixel-addressing algorithms and circuitry in custom ASICs, reducing manufacturing costs significantly from more complex AMLCDs. The process combines the low-cost and reliable manufacturing capability already in place for PMLCDs with the response rates and contrast ratios of the much more expensive AMLCDs.

OIS (Optical Imaging Systems)

Product—Active Matrix LCDs.

Market Focus—Display revenues were $11.7 million in 1993. The majority of the revenue resulted from engineering development programs for military and space applications, including the F-22, F-18, F-16, Space Shuttle, and C-141 aircraft. Production and delivery of these systems will begin in FY 1995 with the Space Shuttle. Commercial avionic deliveries, including B-777 and B-727, were also made during the year. A contract was signed with Apple Computer for the development and delivery of personal computer displays to that industry. The value of contracts OIS is currently administering exceeds $44 million.

Strategic Factors—OIS's stated near term market goal is to be "the premier supplier to the military and commercial avionics markets." Applications in ground-based, seaborn, and ruggedized systems also fall within this scope. In March 1993, OIS was awarded $48 million in matching ARPA funds for the construction of an AMLCD pilot line. Basic construction of the plant is substantially complete with deliveries anticipated to begin in mid-1996. This dual use facility will have the capacity to service both the military and commercial markets and provide a basis for penetrating the consumer electronics market with prototype and second-source capacity.

Photonics Imaging

Product—Plasma Display Panels (PDPs). Photonics Imaging is involved in the research and manufacturing of large area, monochrome (orange) PDPs suitable for such applications as high-information displays, command-and-control displays, video conferencing monitors, and other large size, bright display applications. It is also developing full-color plasma displays. Plasma displays are one of the technologies that may be close to providing direct-view, large displays suitable for both HDTV and workstation applications.

Market Focus—Photonics' plasma displays are used mainly in military, business and industrial equipment and other where color is not critical. Photonics expects to lead the way in manufacturing large-area FPDs in the United States. The company's leadership wants to develop the manufacturing process to get these displays into the market. However, the company lacks capital and has not yet found a partner willing to take the risks involved with being first to market large-area, full-color plasma displays.

Strategic Factors—Photonics Imaging has developed a large area (30"), high resolution (1024x768), full color, full gray-scale, video rate plasma display with ARPA support and is working on a higher resolution version. This work is recognized as the most advanced in the world in terms of full-color, high resolution FPDs. The company feels that it can take this technology to 50"-60" without the massive investment needed for AMLCDs.

Planar Systems

Product—Electroluminescent Displays (ELDs)

Market Focus—Planar Systems, Inc. (Beaverton, OR) is a manufacturer of both FPDs and CRT-based display products. Founded in 1983, Planar employs over 400 people worldwide and now is the world-market-share leader in ELDs, producing and selling over 100,000 units per year from EL production facilities in Espoo, Finland, and Beaverton, OR. Planar has focused on commercial and military market sectors which emphasize the performance characteristics of its ELD and CRT technologies. These benefits include an exceptionally wide viewing angle, clarity and resolution, brightness and contrast, rapid response time, environmental ruggedness, and color capability. The primary market sectors that Planar serves today are medical, industrial, test, telecommunication, transportation, business, and military.

Strategic Factors—Planar's precision, proprietary manufacturing processes allow production of state-of-the-art color and monochrome ELDs in high volume with high quality and yield. During the first half of 1994, Planar introduced its first full color ELD and is the only ELD supplier in the world with both monochrome and color production. Planar is developing and introducing a line of liquid crystal, color shutter displays for certain military and commercial applications. This technology is used to create a high definition color image from monochrome light sources. Planar is also developing a proprietary EL active matrix technology for head-mounted commercial and military applications.

Plasmaco, Inc.

Product—AC Plasma Display Panels.

Market Focus—Plasmaco is marketing a 21.3 inch monochrome PDP, 1.5 inches deep, with a resolution of 1280 x 1024. Plasmaco's displays are used on stock exchange trading floors and on U.S. Navy surface ships and submarines. With R&D funding from NIST, Plasmaco has developed a color display which it expects to bring to market in early 1995.

Strategic Factors—Privately owned Plasmaco obtained its production facility from IBM in 1987. It is still a small company and has recently refocused its efforts on the two displays mentioned above.

Standish Industries

Product—Passive Matrix LCDs. Standish Industries specializes in customized displays. Standish's strengths include its basic knowledge and continuing research on liquid crystals. Because of this expertise, many companies work with Standish on active matrix and single crystal silicon FPDs, including Xerox, David Sarnoff Research Center, and Kopin.

Market Focus—Standish is the largest U.S. manufacturer of FPDs. One percent of production is for defense use.

Strategic Factors—Standish is a partner in Xerox's development of a 13", 6.3-million pixel, monochrome AMLCD with 3072x2048 resolution that is 20 times as sharp as a monochromatic 640x480 VGA display. Standish has received about $4 million from ARPA, most of it going to establish a passive matrix and color filter manufacturing line to show process improvements. Standish is participating with AT&T and Xerox in a joint venture by bringing in its manufacturing process and liquid crystal knowledge. Standish feels very strongly about the need for a domestic manufacturing infrastructure. They also see ferroelectric displays and actively-addressed displays as having a very viable future in a host of different applications.

Tektronix

Product—Plasma-addressed liquid-crystal (PALC) displays. PALC uses the electrical properties of an ionized gas to replace the transistors needed to operate a typical TFT display.

Market Focus—Tektronix has developed a licensing program to exploit PALC technology, based on establishing multiple sources of customer devices. Presently, Sony Corporation has obtained a license, and other firms are evaluating the technology.

Strategic Factors—Tektronix has contracted Technical Visions, Inc. to continue the development of PALC.

Strategic Factors Affecting Interest in U.S. Display Production

Underlying the current industry strategies regarding FPDs are some fundamental issues of perspective or strategic view of the individual firms. Some key factors that differentiate the views of firms are the following:

- Displays are seen either as primarily a commodity component, or they are seen as a "key discriminating technology of strategic significance."
- Belief that U.S. firms can catch up with or leapfrog over Japanese industry in FPDs, or that the U.S. industry is hopelessly behind.
- Belief that Japanese firms can or will deny access to technology or capacity disadvantageously relative to Japanese competitors, or that foreign suppliers will continue to provide to major U.S. customers the displays they need when they are needed.
- Belief that U.S. government can or will sustain efforts to support U.S. infrastructure and support ability of U.S. firms to enter into high-risk investments before technology is proven to be viable or belief that the Federal government either will not or should not do this.

D. JAPANESE FLAT PANEL INDUSTRY

Japanese companies now dominate the global FPD industry. In achieving this dominance these firms have pursued different approaches and not all have been equally successful. It is clear that several large Japanese electronics firms identified FPDs as a singularly important technology and invested large amounts of resources over many years to develop and produce FPDs as a key component for electronic products. At the outset Japanese firms pursued a variety of display technologies, and some focused on technologies, including ELD, plasma, and MIM LCD, that have been dwarfed in the market by TFT AMLCD. The competition in the LCD arena has been intense. Firms initially focused on developing and perfecting simple LCDs for use in watches and calculators. They then built on this base to develop increasingly more complex and larger displays as components for U.S. laptop computer producers and for their own brands of downstream products, such as the Sharp ViewCam camcorder and the NEC Versa computer. Perhaps of greatest significance is that these Japanese firms targeted potential applications in high volume, high-information-content consumer products—especially high resolution television, which Japanese public agencies supported financially. With this vision and support, these firms, particularly Sharp, through major investments of their own and close cooperation with both U.S. and Japanese user companies, grew to dominate FPD supply.

The Role of Japanese Companies

Japanese FPD makers have increasingly focused on manufacturing AMLCDs in Japan and PMLCDs elsewhere in Asia: Hong Kong, Singapore, South Korea, and Taiwan. This trend follows past Japanese practices in which technologies perfected by Japanese engineers are first put into high-volume manufacturing in Japan, but once mature the production is shifted to surrounding, lower-cost nations, while production in Japan shifts to the next generation technology. PMLCDs have become a commodity product with mature demand and little in the way of proprietary manufacturing secrets to guard. Several Japanese manufacturers have either abandoned the passive LCD business or transferred production out of Japan to concentrate their development on the potentially most profitable AMLCD.

Practically all of Japan's major consumer electronics companies are huge, diversified organizations with ready access to retained profits, public and government financing opportunities, sizable internal demand for FPDs, vertical integration, relationships with key suppliers of components and materials, large distribution systems, and vast experience in mass production. Table 6-1 shows that the four leading AMLCD producers had 1993 revenues ranging from approximately $900 million at Sharp to approximately $200 million at Hosiden.

TABLE 6-1
1993 AMLCD SALES BY JAPANESE COMPANIES

Company	Sales ($ millions)	Sales (¥ billions)
Sharp	$ 871.6	¥ 95.0
NEC	367.0	40.0
DTI/Toshiba	321.1	35.0
Hosiden	188.1	20.5
Hitachi	73.4	8.0
Sanyo	73.4	8.0
Seiko-Epson (FY1992)	59.6	6.5

Source: Nomura Research Institute estimates for sales in yen. Dollar values converted at ¥/$ = 109.

The fact that the bulk of Japanese consumption of FPDs is for end-products such as camcorders and laptops benefits these firms' display production operations, since close contact is maintained with their customers to keep up with market trends. Japanese companies have worked to identify high volume segments and the potential for use of technologies in different product areas through horizontal lines of communication between engineering and sales departments.

All but one of the top 10 LCD makers in 1993 had substantial internal demand for FPDs, contributing to better information flows and reducing the risk of selling into the open market. The vertical integration of major Japanese companies gives them substantial high-volume component manufacturing experience, an existing distribution network for their products and first access to the latest in-house innovations. U.S. startups, by contrast, often seek funding for R&D or production from potential customers, who have frequently turned instead to well-capitalized Japanese suppliers with better process technology and without the need for pre-production financial assistance.[9]

One analysis describes five key strategic issues facing the major Japanese flat panel display producers:[10]

(1) The degree of integration of their FPD operations—
Some firms, such as Sharp and NEC, have opted for highly integrated operations covering display components and products, value added post processing, in-house production, and panel integration; others rely much more on external vendors.

(2) Role of large size displays—

9 Component maker Hosiden Corp., the sole exception among the top 10, relied upon a supplier relationship with Apple Computer to guarantee an outlet for its product and for close technological cooperation with the customer. With revenues of less than $1 billion per year, no base or vertical integration in consumer products, and little experience in related manufacturing such as semiconductors, Hosiden bet its future on AMLCDs.

10 Nomura, pp. 28-29.

Sharp and others are aiming to penetrate the CRT market with 15-inch class FPDs, while others, particularly those in the CRT business, are less aggressive in this area.

(3) Dominance of 10-inch or smaller displays—
The current leaders in computer notebook displays are banking on their continued dominance; others, such as Casio and Sanyo, are focusing on smaller displays for such applications as palm-tops and PDAs as an alternative business thrust.

(4) General purpose or customized displays—
There is division between companies that see FPDs as a commodity product, much like Dynamic Random Access Memory (DRAM) integrated circuits, and those that see the main market being for specialized products adapted for specific user needs (much like application-specific ICs—ASICs). Which of these approaches dominates clearly favors different investment strategies and different technological capabilities.

(5) Size of future demand—
A major concern is whether a third round of large-scale production investment needs to be made after 1995, or whether demand will level off. Sharp and NEC have the most aggressive plans for future investment, while others are more concerned about whether potential over-capacity would reduce returns on such investments.

Profiles of Top Five Japanese AMLCD Producers

Sharp Corporation[11]

Sharp is an integrated electronics company with business ranging from consumer appliances and electronics, to information systems, to electronic components. Total corporate sales in 1993 were $13 billion. About three-quarters of Sharp's business is consumer and information end products. The largest product revenue has been consumer electronics (TV, video systems, audio systems) reflecting Sharp's early entry into consumer radio and TV. However, the combination of information products and electronic components reached forty percent of Sharp's business in 1990.

Sharp is the clear leader worldwide in flat panel displays. This leadership stems from a corporate decision in the mid 1950s to pursue semiconductor technology as response to corporate concerns that Sharp, as primarily an assembly firm, would become progressively noncompetitive—especially with the advent of digital electronics. Thus, in 1966 Sharp introduced the world's first electronic calculators incorporating integrated circuits. Sharp's electronics components expertise proved a major advantage that permitted it in the early 1970s to beat back aggressive competition from Casio in electronic calculators by incorporating successively: liquid crystal displays, improved CMOS integrated circuits, and photovoltaic cells into calculators. By the end of the 1970s Sharp held nearly half of Japan's domestic market share in calculators. From this base Sharp diversified its information equipment business into micro computers, electronic cash registers, copiers, personal computers, word processors and facsimile machines.

With the experience gained from its first use of LCDs in calculators, Sharp sustained its leadership in this technology by developing larger, higher quality LCDs. Among its successes were a new thin-film-transistor (TFT) active matrix technology which led to a 3-inch color

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11 Based on interviews, Sharp Corporation documents, and Tomo Noda, "Sharp Corporation: Corporate Strategy," Case Study N9-793-064, Boston, MA: Harvard Business School, June 11, 1993.

LCD in 1986, a 14-inch color TFT LCD in 1988, and a 16.5 inch multimedia color TFT LCD in 1992. These components developments have been directly instrumental in Sharp introducing "first-in-the-world products," especially the "ViewCam" camcorder.

Sharp's success in developing LCDs and integrating these into a range of products has resulted in the company increasingly associating itself with this technology. With its early development of LCDs, their incorporation into calculators, and the sustained R&D and production investments for larger and more capable LCDs, Sharp is today the clear leader in LCDs. It has made the largest investment in LCDs and is now the largest producer of FPDs, both active and passive, with an estimated world market share of about 44 percent in 1993. Investment in 1990-1992 is estimated to have totaled ¥100 billion, while the company has announced plans for approximately ¥33 billion in 1994-95.[12] Sharp is also one of the few companies known to be making money in FPDs, with 1993 profits estimated at ¥15 billion for AMLCDs and ¥5 billion for PMLCDs on sales of ¥95 billion and ¥75 billion, respectively.[13] With profits thinning in PMLCDs, however, it is restructuring its operations, and putting more efforts on moving its passive display (STN) production off shore. The company has devoted heavy resources to LCDs, which have become its largest profit center. Sharp was the first company to mass produce LCDs. In November 1991, Sharp also became the first company to assemble LCDs on a large scale in the U.S., first with monochrome STN displays, then color STN display assembly in July 1993, at its plant in Camas, Washington.

Sharp Corporation TFT LCD Sales and Profits (¥100 million)[14]

	1991	1992	1993	1994	1995	1996	1997
Sales	1150	1400	1700	2300	3000	4000	5000
Profits	50	100	155	210	225	250	300

Sharp had sales of ¥140 billion in 1992 with profits of ¥10 billion.[15] The LCD division is the most profitable division in Sharp and is the greatest contributor to Sharp's overall profits.[16]

NEC

NEC is focusing all its LCD resources in 10" color TFT displays, which have strong internal demand from its notebook computer and workstation divisions. With strong financing, excellent process technology and the number one share of the personal computer market in Japan, NEC is already a major player in FPDs. Existing production is 50,000 panels per month of 10" color TFT displays, and with additional investment of ¥60 billion planned, NEC seeks to boost production to 160,000 panels per month.[17]

NEC, the second largest TFT producer, is projected to achieve LCD sales in 1997 equivalent to those to Sharp in 1993.[18] NEC has used its semiconductor-based clean process technology to rapidly improve production yields. NEC is projected to invest an additional ¥30

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12 From published Japanese industry sources through Seam International Associates.

13 Nomura Research Institute estimates.

14 Ibid.

15 Nomura, 1993, pg. 53.

16 Ibid.

17 Seam International and NRI.

18 Nomura, pg. 52.

billion for production facilities to be brought on line in 1995. When the Phase II facilities are fully operational and supplying full color TFT displays for personal computers, the existing production facilities will be converted to produce small and medium displays for TV phones and navigation applications. NEC is shifting from being mainly an internal, captive producer to also being a merchant vendor. Outside sales, which in 1993 were 30 percent of NEC's LCD business, are projected to reach 50 percent in 1995. As shown in the projections below, with yields improving and volume increasing, NEC's FPD business is projected to be increasingly profitable.[19]

NEC TFT LCD Sales and Profits (¥100 million)

	1991	1992	1993	1994	1995	1996	1997
Sales	120	160	400	700	1000	1200	1700
Profits	Red	Red	10	30	75	100	120

Toshiba

Toshiba produces FPDs both independently and through its 50-50 joint venture with IBM, Display Technology Inc. (DTI). DTI's production is split evenly between its joint owners and has quickly raised yields and become profitable ahead of schedule. With demand strong for each company's notebook computer products, a second line is being added which will double DTI's current capacity of 30,000 10" color TFT panels per month. Toshiba and IBM chose to work together to reduce the financial burden and lower risks, as well as share production technology. Through 1993, Toshiba made capital investments in LCDs of ¥80 billion. Toshiba's independent LCD operations have not been as successful, with forays into several technologies and applications. Toshiba is phasing out of monochrome STN displays, transferring technology to Korean manufacturer Orion Electric.[20]

Toshiba's strategy has been characterized as being based on three elements: (1) LCDs are identified as key devices in the man-machine interface and a company-wide approach has been taken with regard to investments on the order of ¥80 billion; (2) Alliances, particularly one with IBM, but also with other major users and with suppliers; (3) Three-tiered R&D structure featuring its Electronics Technology Research Institute, the Fukaya pilot line, and the joint venture with IBM.[21]

Toshiba TFT LCD Sales and Profits (¥100 million)[22]

	1991	1992	1993	1994	1995	1996	1997
Sales	300	400	550	700	880	1020	1050
Profits	Red	Red	25	30	40	55	60

19 Ibid., pg. 54.
20 Ibid., pg. 55.
21 Ibid.
22 Ibid.

Hosiden

Hosiden is the exception among leading AMLCD makers due to its small size and experience, which is limited to low-tech electronics components. With sales of less than ¥100 billion per year, and profits of less than ¥5 billion, Hosiden is taking a huge risk in betting its future on AMLCDs. The company benefited considerably from extensive access to technology from NTT. The company's aggressive president is also said to have made such quick progress into this new field by developing close relationships with leading AMLCD researchers in Japan, such as Tohoku University.[23] Because of the company's relatively weak financial position compared with other LCD makers, Hosiden secured a relationship with Apple Computer, becoming sole supplier of monochrome TFT displays for the PowerBook computer. Hosiden is aggressively boosting capacity for color TFT displays to take it from 80,000 panels per month to 150,000, on the way to 300,000 or more, and is raising the ratio of color products. Hosiden has also won a contract to supply large color panels for use in the cockpits of Boeing airplanes.

Hosiden's success is attributed to four factors: (1) high yields based on proprietary processes; (2) strategy of joint development with large users and the use of government aid and technological resources; (3) timely capital investment and excellent ROI; (4) joint development with advanced users in high value added niche markets.[24]

Hosiden TFT LCD Sales and Profits (¥100 million)[25]

	1991	1992	1993	1994	1995	1996	1997
Sales	155	195	260	350	600	750	1000
Profits	10	15	25	35	50	60	75

Hitachi

Hitachi is one of Japan's largest diversified electronics companies and was an early player in LCDs for use in a wide variety of consumer products. The company was slow to recognize the importance of TFT displays, however, and heavy emphasis on STN displays led to large losses as a flood of supply pushed prices sharply downward. Hitachi has taken steps to recover, though, transferring production of some PMLCDs to its Taiwanese subsidiary and refocusing its TFT production on 10" color displays. Sales of its active matrix displays are not expected to surpass passive matrix until 1995.

Hitachi TFT LCD Sales and Profits (¥100 million)[26]

	1991	1992	1993	1994	1995	1996	1997
Sales	300	255	340	380	500	550	600
Profits	Red	Red	Red	5	15	20	30

23 Interview with chief Washington representative, Japan Development Bank, January 1994.
24 Nomura, op. cit., pg. 56.
25 Ibid.
26 Ibid., pg. 57.

E. KEY CONCERNS OF U.S. INDUSTRY

U.S. firms face the following obstacles to entering high volume display production.

Uncertainties and high entry costs—As discussed in Chapter IV, U.S. firms face major technical and manufacturing uncertainties: factory cost models show that small differences in technical, input requirement, and market pricing parameters generate huge swings in what otherwise might seem to be an acceptable rate of return on investments. High entry costs for a volume production facility (ranging up to $400 million, sunk into highly specialized plant and equipment), pose another major barrier to entry. Furthermore, plant costs are only the tip of the financial iceberg for serious entry into the business: equally formidable investments in marketing, distribution, and service infrastructure, and continuing follow-on technology expenditures will be required to remain competitive in an extremely dynamic business environment.

Fear of foreign actions—FPD consumers worry about possible reprisals from their established suppliers when considering link-ups to potential U.S. suppliers. Foreign government support or other forms of intervention on behalf of their producers raise strategic concerns for U.S. producers considering market entry (i.e., American firms contesting this market must worry about individually facing alone foreign competitors backed implicitly or explicitly by the full resources mobilized by their national governments). Finally, the inability to obtain needed components, materials, and equipment (with the best possible pricing and delivery times) from foreign producers linked to their overseas competitors is another common concern for potential American entrants.

"Second-Mover" Disadvantages—When the major Japanese players in this industry made large investments in the LCD business in the 1980s, they enjoyed a significant cost-of-capital advantage relative to American firms in a highly capital intensive business. That advantage may have disappeared, but, as "second movers," U.S. firms face some significant disadvantages in entering the industry today. A lack of experience in volume production means their manufacturing costs will be well above those of their Japanese competitors, since costs fall sharply in this industry along a learning curve (i.e., average costs fall with cumulative experience in production). Lack of a domestic infrastructure in materials and equipment is another potentially critical disadvantage: cost models discussed earlier suggest that materials currently constitute about 36 percent of manufacturing cost, and capital equipment another 37 percent, in the active matrix FPD business. Clearly, access to the best and most technically advanced materials and capital equipment, at the best possible price, will be critical to competitive success.

Market Concentration—Sharp and Hosiden together have about 90 percent of the AMLCD world merchant market (with NEC and DTI being largely captive producers). Offsetting the display market's current unattractive appearance of initially low profits and low yields is a consensus by U.S. computer manufacturers that they do not want vertically integrated competitors to control the supply of such components as FPDs. Hosiden, as a component supplier is an exception in this situation, but Hosiden's production capacity is falling behind that of the market leaders.

Weak Foreign Partners—For a domestic firm to consider putting an AMLCD line in the U.S., there needs to be an infrastructure of tool suppliers and materials in the U.S. Some of these firms believe that the only way to get an AMLCD line in the U.S. is to buy it from

Japan. However, none of the most efficient FPD manufacturers will agree to any technology transfer arrangements with potential domestic entrants. If a domestic firm were to acquire technology from a foreign producer, the likely "repatriated" technology would not be from one of the world's high volume, low-cost facilities.

F. SUMMARY

Many U.S. firms are pursuing a variety of FPD technologies, most of which are targeted for niche products, military applications, or their own internal demand. Faced with a shortage of capital and a weak domestic infrastructure, many U.S. firms have been reticent to enter into large volume manufacturing. However, with FPDs seen as product differentiators, a number of U.S. companies have expressed interest in becoming high-volume FPD manufacturers, but only if risk factors associated with such large investments can be substantially reduced.

CHAPTER VII: GOVERNMENT POLICIES AND PROGRAMS

Following some initial encouragement by Japan's Ministry of International Trade and Industry (MITI), Japanese companies now produce 98 percent of the world's active matrix liquid crystal displays (AMLCDs). Countries in East Asia and Europe are pursuing their own national programs for economic development of domestic FPD industries. The United States FPD program to date has focused on research and development and military applications.

A. JAPAN

While Japan's success in FPDs is indisputable, MITI's actual contribution to this success is subject to debate. "Many US observers have a wrong impression of the Japanese LCD industry," writes Norihiko Naono in the *Electronic News*. "The US cannot create an FPD industry via government funding. Japanese success is not due to MITI funding, but due to other factors." Sharp is the world's premier FPD manufacturer, and perhaps the only really profitable manufacturer. Throughout its corporate history, Sharp has been a maverick as far as its reliance on either MITI's recommendations or mandates. Sharp's market-dominating position has been attributed to good, solid business practices of corporate research, timely capital investments, consumer-oriented advertising, state-of-the-art products, and, relative to its fellow FPD manufacturers, low prices. Others have qualified this explanation by asserting that the favorable business environment provided by the Japanese government, including the low cost of capital, has been an essential ingredient of Sharp's success.

Japanese Support for Flat Panel Displays

The Government of Japan (GOJ) generally has played a relatively indirect role in the development of Japan's FPD industry. GOJ-backed FPD initiatives launched in 1988 have been closely linked with Japan's high definition television (HDTV) effort focusing almost exclusively on development of very large FPDs. Japanese firms have invested approximately $3 billion in the more mature, small to medium sized FPDs, dominated by LCDs, without any significant government funding. Even in the very large FPD sector, the GOJ's role is now decreasing due to the limited success of its FPD initiatives.

In the 1980s, several Japanese integrated electronics firms and Japan's Key Technology Center—a joint partnership between MITI and the Ministry of Posts and Telecommunications (MPT)—came to the conclusion that FPDs would become a critical technology for consumer and information electronics. Japanese firms built upon initial technical developments licensed from the U.S. and the U.K. to perfect FPD applications in high volume, low-information-content applications. Some ventured to scale these developments toward consumer TV applications, particularly with the HDTV projects of the government ministries. However, most companies focused on scaling from watches, games, and calculators upward in complexity to portable TVs and then to 10" laptop computers.

The Japanese government's most direct FPD initiatives have been the Giant Technology Corporation (GTC) and the High Definition Television Engineering Corporation (HDTEC). GTC set an ambitious goal in 1988 to develop a one meter square AMLCD using conventional printing techniques (instead of photolithography) to form the active matrix of transistors on the large glass substrates. Although GTC still exists, the one meter square AMLCD effort has been abandoned, and GTC's focus has apparently shifted to color plasma displays and incremental improvements in AMLCD process technologies. GTC's budget of approximately

$25 million has been funded 30 percent from 17 participating companies and 70 percent from Japan's Key Technology Center, a publicly funded research corporation.

HDTEC's main goal has been the development of an HDTV LCD projector. With approximately $30 million in public and private support, again with 70 percent of funding from their government, several Japanese members of HDTEC have developed both front and rear projection LCD systems. Sharp, for example, began marketing a front projection AMLCD system for standard television over two years ago and now offers an HDTV resolution AMLCD projector on the Japanese market.

The Japan Broadcasting Corporation (NHK), Japan's public broadcasting corporation, has been conducting research on HDTV for more than 20 years. NHK conducts joint R&D with many private companies on a variety of technologies and transfers results to interested Japanese firms. Over the past three years, NHK researchers have demonstrated a variety of color PDP prototypes measuring 30"-40" in diagonal. Although independently developed AC PDP prototypes at other firms may have longer lifetime and brightness than the NHK group's DC PDP technology, NHK's activities are likely to create the infrastructure and basic demand for HDTV in Japan which would have been unlikely without government support.

Nippon Telegraph & Telephone Corporation, long a Japanese government monopoly but now partially privatized, has also had close cooperation with a number of private firms. By law, NTT is not permitted to manufacture equipment, so it frequently transfers its technology to private manufacturers. For example, Hosiden has been a primary recipient of NTT's FPD technology transfers.

A 1994 report on the display industry noted, "the supply base for flat panel manufacturing is stronger in Japan than in any other country. All the necessary tooling and materials activities are located in Japan, and at least one Japanese firm focuses on each of the developing technologies."[1] Even in certain areas of the supply chain where Japan is not yet established, such as the manufacturing of liquid crystal chemicals, gray-scale drivers, and high performance glass, explicit efforts are being made to develop Japanese sources while encouraging foreign firms to locate in Japan or forming joint ventures with Japanese firms to service the local market.

Market Structure and Export Controls

Aside from open government R&D investments in FPD technology, less transparent actions are alleged to have given Japanese companies advantages in global competition. U.S. companies have complained of restrictions on access to key FPD components, materials, and equipment marketed by Japanese suppliers. Instances in which Japanese producers have been given preference in acquiring the best available inputs, to the disadvantage of foreign competitors left with the residual supply available for export, have been alleged by U.S. industry.

Less controversially, the Japanese government's export control procedures have created obstacles for U.S. defense suppliers in gaining access to exports of flat panel display products. Japan's "three principles on arms exports" prohibit the export of military equipment, but permit the export of dual use products without restriction. The question of whether an item falls into the category of an arms export (which includes parts and accessories, as well as finished

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1 "Display's the Thing: The Real Stakes in the Conflict over High-Resolution Displays," Michael Borrus and Jeffrey A. Hart, *Journal of Policy Analysis and Management*, Vol. 13, No. 1, Winter 1994, p. 21.

products) is settled on the basis of judgments based on shape, features, and other technical aspects of the item.

In practice, these interpretations have been made by officials on a case-by-case basis, and have reportedly discouraged the export of products for military use with some frequency. These export control policies are commonly cited by Japanese companies as a significant barrier to supplying products for use in military applications, even where technology that is clearly fundamentally commercial in nature is at issue. In only one instance—in reaction to the threat of restrictions on U.S. imports of ceramic semiconductor packages associated with a Section 232 trade action[2]—has the Japanese government been willing to give explicit assurances that exports of a class of dual use products to the U.S. for military use would not be subject to potential restrictions under the "three principles." No such assurances have been given in the case of flat panel displays, or other dual use products.

Thus, the availability of leading edge Japanese display products for export and use in future U.S. defense applications remains subject to a significant element of uncertainty. Until these export control policies are revised or clarified, assured access to Japanese dual use technology and products by DoD must be viewed as problematic. Where a high degree of dependence on Japanese suppliers is the case—as in flat panel displays—significant uncertainty over the reliability of supply of needed products and technologies will continue to exist under current procedures.

The ambiguities in Japanese export control policies have indirectly reinforced a Japanese industry "allergy" toward working with Defense customers that is prevalent in Japan. In the course of preparing this study an executive from Sharp Corporation made clear to U.S. DoD officials that as a matter of corporate policy Sharp would not work with the U.S. Department of Defense either by shipping products directly to military users or by working with DoD and its contractors to customize or modify Sharp's off-the-shelf products. In the aftermath of the announcement of the National Flat Panel Display Initiative in April 1994, however, there have been some signals from Sharp that this position may change.

B. KOREA

Republic of Korea (ROK) direct government support for FPD development is also limited. Although the ROK has twice attempted to fund an FPD consortium to develop LCDs and PDPs, neither of these efforts has materialized. The most recent effort was to be sponsored by the Ministry of Trade, Industry and Energy (MTIE) through the Electro-21 Project—a government-supported initiative to develop 51 electronics technologies. According to press reports, the proposed FPD portion of Electro-21 was abandoned due to budget constraints and corporate rivalry among the proposed consortium members who are vying for the lead in Korean FPD development. Based on discussions with Korean industry executives, there appears to be close guidance by the Korean government to Korea's financial institutions to encourage indigenous FPD investment. This guidance includes favorable interest rates and repayment terms for research, development, and plant construction for FPD ventures. In addition, high priority investments can receive other special considerations regarding other key factors in starting these types of businesses, including land and government technical support.

2 Section 232 of the Trade Expansion Act of 1962.

C. TAIWAN

The government of Taiwan (GOT) is fostering the development of Taiwan's LCD industry through R&D performed by the Industrial Technology Research Institute (ITRI) and through government grants and low interest loans to potential manufacturers. These efforts are designed to help Taiwanese LCD firms make the transition from simple twisted nematic LCDs—used in watches and calculators—to large, color, super-twisted nematic (STN) LCDs for notebook computers and eventually to AMLCD production.

ITRI is offering incentives for Taiwanese firms to begin mass production of large color STN panels. According to press reports, this incentive program will provide up to two-thirds of the costs of an STN facility through government grants and low interest loans.

D. EUROPE

Current European Community (EC) R&D efforts are conducted under the "Third Framework Program of Community Research and Technological Development (1990–1994)." Framework R&D programs focus on pre-competitive research and technological development rather than on product development. R&D efforts under the Framework that show promise may become eligible for future product development funding under Eureka or other government or industry programs.

Although R&D on FPD technologies is not included as a discrete budget category under the Third Framework, it is encompassed within two broader budget categories: Information Technologies and Communication Technologies. Within the Information Technologies portion of the Third Framework, the EC has budgeted approximately $296 million for R&D on "advanced business and home systems." One area of emphasis under this activity is the development of peripherals technologies, where FPDs are among the research areas identified.

Under the Communication Technologies element of the Third Framework, the EC has budgeted approximately $88 million for R&D on "image and data communication" technologies. These activities focus on development of the technologies needed for the introduction and exploitation of advanced, low-cost and flexible image and data communication services for business and domestic needs. In particular, this research will address the impact of new transfer modes on high resolution visual services, where it will concentrate on digital HDTV, including coding and presentation techniques for still, moving, and three-dimensional images.

The EC has also recently announced its "Fourth Framework Program of Community Research and Technological Development (1994–1998)." Presently, the Fourth Framework effort has developed 28 research "themes" within four broad activities. The EC has budgeted over $14 billion for Fourth Framework R&D activities of which about $5 billion will be spent under the Information and Communications Technologies theme, where "flat screens" have been specifically identified as an area of interest. However, the EC has not developed more detailed research programs within each of the thematic areas, and it is unknown how much of this funding will support FPD R&D.

The EC's support for the European FPD industry includes direct subsidies, although to date these have been limited. The EC acknowledges providing $20 million in support of "Flat Panel Display," the European AMLCD consortium, which includes Philips, Thomson, and SAGEM.

E. UNITED STATES

National Research Programs

Table 7-1 shows U.S. government actual spending, and planned spending, by agency, for research and development on flat panel displays and related technologies that will total over half a billion dollars through FY1995. This information was compiled by DoD through interviews with the principal government agencies involved in FPD R&D. This table may not capture all FPD-related programs in the U.S. Government (USG), but it represents the bulk of programs directly applicable to displays. Early USG support came primarily from the Advanced Research Projects Agency (ARPA), then known as the Defense Advanced Research Projects Agency (DARPA). ARPA funding in FY1989 and FY1990 was $5 million and $30 million, respectively.

TABLE 7-1
FLAT PANEL DISPLAYS: U.S. GOVERNMENT R&D PROGRAMS
($ MILLIONS)

AGENCY	FY91	FY92	FY93	FY94	FY95*	5-YEAR TOTAL	PRIOR TO FY91
DEFENSE	**$78.3**	**$79.6**	**$156.0**	**$83.2**	**$72.4**	**$469.5**	**$40.2**
ARPA	74.5	75.0	151.2	79.0	68.0	447.7	35.0
Services	2.6	4.5	4.8	4.2	4.4	20.5	1.7
SBIR	1.2	.1	—	—	—	1.3	3.5
COMMERCE	**2.1**	**5.4**	**7.4**	**6.0**	**5.1**	**26.0**	—
NIST Internal	.3	.5	1.8	1.2	1.2	5.0	0
ATP	1.8	4.9	5.6	4.8	3.9	21.0	—
ENERGY	**0**	**1.7**	**3.8**	**3.8**	**2.0**	**11.3**	**0**
NASA	**2.5**	**3.2**	**3.5**	**7.6**	**11.4**	**28.2**	**10.0**
NSF	—	**.3**	**.4**	**.4**	**.4**	**1.5**	—
TOTAL	**$82.9**	**$90.2**	**$171.1**	**$101.0**	**$91.3**	**$536.5**	**$50.2**

Source: Agency Program Offices *President's Budget Request

U.S. Trade Policies

In addition to financial supports, governments affect industries through the legal and regulatory frameworks controlling the competitive environment within which industries operate. While these measures are usually broadly applicable across industries, they also may be tailored to a specific industry's interests. In the case of FPDs, the most notable examples of government efforts to tailor the competitive environment to the interests of domestic manufacturers are in three areas of trade policy: most favored nation (MFN) tariff rates, rules of origin, and anti-dumping duties.

MFN Tariffs—The actual tariff applied to a given FPD import depends on the display's end use. For example, in the U.S. there is no duty on imports of FPDs intended for use as output devices of ADP equipment and having a visual display diagonal not exceeding 30.5 cm (about 11 inches). Larger versions of these displays are covered under a separate subheading that carries an ad valorem duty of 3.7 percent. FPDs intended for use in television receivers are subject to a five percent MFN tariff.

Current FPD tariff ranges in the U.S. and other countries that are major consumers or producers of FPDs are as follows:

Country	MFN Tariff
U.S.	0 - 5%
Japan	Duty Free
EC	4.4 - 4.9%
Korea	9%
Taiwan	5.0 - 7.5%

During the Uruguay Round of trade negotiations, the U.S. proposed multilateral elimination of electronics tariffs, including those on FPDs, as part of its "zero for zero" initiative. However, the European Union (EU) showed strong reluctance to move in this manner in the electronic component sector, and at one time sought specific exceptions for FPDs. Overall, the conclusion of the Uruguay Round brought a phased 50-65 percent reduction of EU electronics tariffs on various types of electronics components. Korea has also not shown a willingness to eliminate its tariffs on FPDs but has announced intentions to lower its FPD tariff to 8 percent ad valorem under a unilateral market liberalization program.

Rules of Origin—Presently, most countries use "substantial transformation" as the basic rule of origin for determining whether FPDs are domestic or imported products. Substantial transformation is a highly discretionary rule of origin for a final product that does not necessarily require any specific manufacturing processes to take place within a country's borders.

During the North American Free Trade Agreement (NAFTA) negotiations, the U.S. sought to develop stricter, more precise rules of origin for FPDs. Through these changes, U.S. negotiators sought to create increased certainty that significant levels of manufacturing must take place within a NAFTA country before FPDs would receive preferential tariff treatment. Specifically, the three NAFTA countries (U.S., Canada, and Mexico) finally agreed to the following rules of origin affecting FPDs:

- Stand-alone FPDs must be manufactured in a NAFTA country to receive preferential tariff treatment. The location of manufacture is determined by tariff shift principles, which require that manufacturing activity in the NAFTA country must be sufficient to cause the product's tariff classification to "shift" to a sufficiently broad level of classification. (In the case of FPDs, this is effectively at the four digit level of the Harmonized Tariff System).
- Television sets with FPDs, including projector sets, are required to contain displays manufactured in a NAFTA country to receive preferential tariff treatment.
- Radar apparatus must have a NAFTA display element (either FPD or cathode ray tube) to receive preferential tariff treatment.
- FPDs contained in HDTVs, and one-half of their customized semiconductors, must be manufactured in a NAFTA country for the HDTVs to receive preferential tariff treatment.

The treatment of FPDs used in computers represents a significant exception to these stricter rules of origin. Under NAFTA, computers may use imported FPDs and still receive preferential tariff treatment. This less restrictive rule of origin was an important issue for computer manufacturers during the NAFTA negotiations. The U.S. sought to develop stricter, more precise rules of origin for FPDs, and in particular for end-products using FPDs.

Anti-Dumping Duties—On July 18, 1990, U.S. manufacturers of high-information-content (HIC) FPDs filed an anti-dumping petition with the Department of Commerce against imports of HIC FPDs from Japan. In its July 8, 1991, final determination under that investigation, Commerce defined two classes of products subject to its dumping finding:

• AMLCDs	62.67 percent dumping margins
• ELDs	7.02 percent dumping margins.

Commerce also found *de minimis* dumping margins for plasma displays (and therefore imposed no duty) and rescinded its investigation with respect to PMLCDs on the grounds that none of the petitioners had legal standing in this area.

In August 1991, the International Trade Commission (ITC) found that U.S. producers of HIC FPDs had been injured by reason of dumped imports from Japan. In making its determination, the ITC did not distinguish between ELDs and AMLCDs but instead found that all HIC FPDs constitute one "like product." This finding was consistent with the perspective of the petitioners and with ITC and Commerce preliminary findings, but it differed with the perspective of the respondents (Japanese suppliers and U.S. purchasers of FPDs), as well as with Commerce's final determination. On the basis of the ITC determination, imports of AMLCDs and ELDs became subject to anti-dumping duties equal to the above margins, and retroactive to the Commerce preliminary determination of February 21, 1991.

Following the ITC's determination, Hosiden Corporation, a Japanese manufacturer of AMLCDs, filed an appeal with the Court of International Trade (CIT). Hosiden argued that the ITC was bound by Commerce's definition of "like product" and must therefore determine injury on a product-by-product basis. On December 29, 1992, the CIT ruled in favor of Hosiden and remanded the issue to the ITC for further investigation. The ITC immediately appealed the remand order to the U.S. Court of Appeals for the Federal Circuit (USCAFC). However, the USCAFC ruled that the ITC and the CIT must first complete the remand process before ITC may appeal the CIT's ruling.

In March 1993, the ITC issued its determination under the remand investigation. The ITC continued to find injury in the case of AMLCDs, but found that U.S. producers of ELDs have not suffered injury as a result of imports of ELDs at less than fair value. Because of delays associated with the aborted appeal to the USCAFC, the CIT did not issue an approval of the ITC's determination until April 1993. Having completed the remand process, the ITC had 60 days to renew its appeal of the remand order. Instead, the antidumping duties on ELDs were eliminated and the withdrawal of support for AMLCD duties by OIS—the sole U.S. producer of AMLCDs and therefore the sole U.S. producer with priority in this case—resulted in the elimination of AMLCD duties as well.

A specific concern of this study is to develop the FPD infrastructure. The present tariff structure charges no duties on finished displays and on complete kits of components required to assemble flat panels used in computers. Parts, components, and incomplete kits, by contrast, are charged duties at varying rates. Companies using foreign parts and components in producing FPDs are, therefore, discouraged in moving production operations to the U.S., since a tariff is charged on input materials but not on kits and assembled displays. Moreover, since this tariff differential impedes the development of U.S.-based production operations equipment by foreign companies, it also hurts the development of the U.S. parts and components supply infrastructure. Therefore, rationalizing the tariff structure to charge tariffs on components and parts at a rate not greater than that rate charged on complete kits and finished displays would promote domestic materials and equipment infrastructure development.

Without such tariff rationalization, FPD companies who believe that their profitability or competitive position suffers from the current tariff irrationalities seek relief by applying for a foreign trade zone (FTZ). Companies willing to make the investment of time and money in seeking an FTZ achieve many of the benefits that they would derive from tariff rationalization, but the FTZ benefits are limited to companies in that particular zone. The benefits of tariff rationalization would apply broadly and promote domestic infrastructure development.

F. SUMMARY

The amount of direct funding for FPD-related programs varies considerably by country. Although it is clear that many Asian governments focused specific policies and programs on supporting their respective FPD industries, it is difficult to measure the extent to which their actions have directly benefited their FPD producers. As in many other technologies, government support helps to gain attention and provide reassurance to private firms considering investments in R&D and manufacturing. Moreover, government loan programs supporting high technology projects by development agencies and other sources may also provide benefits.

CHAPTER VIII: RECOMMENDATION: NATIONAL FLAT PANEL DISPLAY INITIATIVE

A. TECHNOLOGY AND NATIONAL SECURITY

U.S. national security demands that United States military forces have guaranteed, cost-effective access to the world's best technology. The traditional approach for the U.S. government to meet defense technology requirements would be to use the Department of Defense (DoD) budget to conduct R&D, then procure from specialized defense suppliers, and through this build necessary production capabilities. In the past, when DoD requirements constituted a significant portion of high technology markets, this approach was often successful. DoD demand was then sufficient to sustain both the technology and production base at the leading edge, though with the penalty of higher costs than might have been obtained by purchasing commercial products. But today, with the declining DoD budget, demand levels, and resources, this approach is both unaffordable and ineffective.

Such a specialized approach is unaffordable because it does not take advantage of the economies of scale that come from high volume commercial production. Moreover, it is ineffective because it is unlikely that a defense-unique industry could keep pace in important areas with the rapid technological innovation driven by a highly dynamic commercial sector.

DoD is entering a new era in which it will increasingly rely on commercial components and technologies to meet defense requirements. Maintaining the technological superiority of defense forces will therefore necessarily require that commercial industry be able to supply products using leading edge technologies at competitive, affordable prices. Thus, a new goal for DoD R&D must be to ensure that the key elements of the domestic commercial technology base that are critical for national security remain at the leading edge.

The Clinton Administration has developed a new technology strategy that promises to deal effectively with these major changes affecting our national and economic security in the 1990s. That strategy includes the dual use technology vision outlined by Secretary of Defense William Perry and Deputy Secretary of Defense John Deutch. At the heart of this vision are two key principles:

- To reduce costs, and accelerate the introduction of new technologies into defense systems, DoD must make use of components, technologies and subsystems developed by commercial industry, wherever possible, and develop defense unique products only where necessary.

- To capitalize on this acquisition strategy, DoD's R&D efforts must focus on critical dual use technologies and capabilities that will continue to be advanced through industry's efforts to remain competitive in commercial markets. Thus, even where the military applications are specialized or unique, the underlying technologies will be sustainable through commercial forces.

B. IMPLEMENTING A DUAL USE INITIATIVE

Any initiative under the dual use strategy, rather than maintaining defense-unique producers, seeks to foster the creation of a viable domestic industry that is competitive in global markets and able to meet defense requirements drawing on the commercial technology base. This dual use strategy may call for initial government investments, but these investments will mean substantially lower future outlays as DoD acquires its products at much lower cost from commercial suppliers, and relies on a healthy, dynamic, domestic commercial industry to carry the weight of future R&D investments at the leading edge.

To be successful, new initiatives must be guided by six overriding principles:

- The initiative must be of sufficient scope and duration to attract significant industry participation.
- Industry must be willing to share in the costs of the initiative. The extent of industry willingness to bear such costs is one of the most important measures of the initiative's value.
- The initiative should be based on principles of competition among firms and technologies. Central to this principle is the notion that the initiative will go forward only if industry responds with acceptable proposals and plays a lead role in determining the technologies to pursue.
- Given the international nature of modern, high-technology industries and the emphasis on achieving leading-edge capabilities, DoD programs should have the flexibility to consider participation by foreign-owned entities that satisfies program objectives.
- The initiative should be consistent with other government policy objectives. In particular, given the leading role of the United States in supporting an open international trading system and the benefits that such a system has for our economic security, the initiative should be consistent with U.S. obligations under the General Agreement on Tariffs and Trade and the World Trade Organization.
- The initiative must be subject to sunset provisions and include clear measures of success to force and guide decisions about the continuing necessity of the initiative over the medium- to long-term.

C. RATIONALE FOR ACTION

U.S national security requirements will not be met by current domestic or foreign suppliers. The world's dominant supplier and technology leader (with approximately 55% market share for mainstream active matrix LCD displays) has stated that it will not directly supply technology or products to the U.S. military, or make customized display products for military use available to U.S. defense contractors. Negative foreign private sector attitudes toward working with DoD are compounded by ambiguities in foreign government controls on the export of technologies tailored for military end use.

U.S. military requirements for FPDs cannot be met by either the existing U.S. industrial base or by current foreign producers. The military need for FPDs has been clearly defined.

First, our military must have early access to the latest generation of leading edge display technologies while still in prototype form in order to work out the tactics and strategies for their use. Second, we must have assured access to responsive suppliers who will customize commercially-derived technology to produce displays that operate in both desert and Arctic temperature ranges, are readable in sunlight, have special color filters or sensors that work in a night vision environment, offer extremely high resolutions, and are available in nonstandard sizes. FPDs with such features are important for a wide range of military applications, including the cockpits of such aircraft as the AWACS and JSTARS, main battle tank fire control and situational displays, command and control centers, and mobile troop operations. Third, we must have affordable access that allows these systems to be fielded in significant numbers.

The U.S. military now lacks early, assured, and affordable access to such FPD products and technologies for military applications from either domestic or foreign sources. DoD cannot currently rely on the existing overseas supply base to furnish customized or specialized products or capabilities that will be required to support future DoD needs, or to provide leading edge technology to DoD before it is in widespread commercial use. Thus, for this critical defense technology, the high degree of geographic concentration of this industry, coupled with the unwillingness of foreign suppliers to serve DoD needs, and the extremely limited volume production in the United States, raise concerns about early and assured access to both the supply of display products and to leading edge FPD technology.

The concentration of FPD production in a few firms which also compete with U.S. computer, telecommunications, and consumer electronics firms, raises economic concerns about product and technology access, and the possible exercise of monopoly power. Currently U.S. electronic systems firms are highly dependent on allocations of supply from these foreign producers. Though it has not yet materialized as a concrete problem, potential denial of access to leading edge technology clearly is considered a strategic, long term concern by many U.S. display users. These users, too, provide an important component of the broader economic infrastructure serving defense needs.

The same concern is more immediately apparent within the tiny domestic display industry, where there are worries that foreign producers have competitive advantages in access to components, materials, and equipment. There have been complaints of restrictions, and other uncompetitive practices in the supply and pricing of FPD components, materials and equipment.

Economic security may also be affected by ripple effects on industries for which FPDs are a key component. Technological spillovers may be significant: a robust domestic FPD industry is viewed by many industry experts to be linked to the future competitiveness of the information processing, telecommunications, and other electronic systems industries. Furthermore, many of the processes and equipment used in flat panel manufacture are based on technology used in semiconductor production, and significant synergies between the two sectors might be exploited by equipment and material manufacturers. If, as is expected, the entire design of important new products is embedded in electronics actually integrated into the display itself, sensitive design information for new products might have to be transferred to potential foreign competitors if no domestic supply base exists. With greater integration of electronics onto displays this dependency may increasingly impair the competitive position of U.S. electronics firms, and the overall health of a sector increasingly vital to DoD. In the future such externalities may become increasingly significant.

Moreover, a wide range of currently unimagined and unforeseen new applications may be enabled by this technology. Both national and economic security rationales, therefore, suggest that the social return from federal investments in this area are likely to vastly exceed the private return to any individual investor.

It is the conclusion of this study that defense technology needs cannot be met effectively through niche military suppliers. Even success in meeting defense-specific applications would not be assured by such suppliers, particularly over time, as it is unlikely that military-unique vendors could sustain themselves without very large and continuing DoD R&D funding. Moreover, the military-unique approach, would not provide DoD the benefits of a dual use strategy—continued technology leadership sustained by ongoing innovation driven by the commercial mainstream, and affordability, through integration into a high volume commercial production base. With the predominantly commercial demand for FPDs, military needs for FPDs would best be met through a dual use technology strategy. That is, the DoD (and other mission agencies) should look to a healthy domestic commercial sector for the capabilities to meet its critical requirements rather than utilizing the traditional defense model of financing both technology and production using a dedicated supplier base.

D. A NATIONAL FLAT PANEL DISPLAY INITIATIVE

To meet the identified defense technology and production needs for FPDs through a dual use strategy, a set of recommended actions has been formulated as the National Flat Panel Display Initiative to

- Support U.S. FPD research and development
- Build national expertise in high volume process technology
- Encourage U. S. development of industrial capabilities in flat panel display production available to defense through focused R&D incentives
- Foster market development.

As outlined above, U.S. requirements for a domestic FPD production base stem from both the uncertainties of meeting FPD demand for military and commercial applications, as well as the need to ensure that other segments of the electronics industry are able to capture the positive externalities that derive from experience in volume production of FPDs. Thus, both consumers and producers in the U.S. have an interest in seeing the development of a competitive domestic production capability.

This study judges that penetration of 15 percent of the world market (up from the current 3 percent) is both an achievable near-term goal and an appropriate point at which to consider whether a government flat panel display program should be redefined, reduced, or terminated. This level of market share is probably sufficient to nurture and sustain the critical mass of U.S. infrastructure suppliers needed for the long term success of the U.S. FPD industry, to permit industry to exploit continued government R&D investments in advanced display technology, and to satisfy DoD needs at acceptable costs. This level of market share is also judged to be a point at which momentum should be strong enough for continued success. The year 2000 is a realistic target date for achieving this goal through an initiative encompassing the elements described below.

1. SUPPORT FPD RESEARCH AND DEVELOPMENT

In recent years the U.S. government has typically spent about $100 million annually on FPD R&D, with ARPA, the Department of Commerce (DOC), and the Department of Energy (DOE) taking leading roles. These efforts have focused largely on product technology, with lesser emphasis on process technology. They have addressed issues of basic science and technology as well as applications in specific product development. As a result of these efforts, U.S. companies are at the leading edge in understanding the functioning and design of FPDs of all types and technologies. However, U.S. industry lags considerably behind the leading edge in its understanding of the manufacturing processes and controls necessary to produce FPDs in high volumes at sustainable yield rates.

Under the National Flat Panel Display Initiative, the U.S. government will not only continue to fund R&D that pushes the leading edge in product technology, but will also seek opportunities to direct resources toward promising work in the area of process and manufacturing technology. Specifically, research objectives should continue in the areas of lower cost displays, increased display performance and functionality, manufacturing processes, and "intelligent displays" which integrate additional capabilities into the display unit.

While U.S. industry continues in its current nascent state, it is important to support the ARPA and DOE R&D programs with adequate levels of funding. For ARPA, the core R&D and infrastructure program should be about $70 million per year. ARPA should continue to develop a diverse portfolio of technologies and encourage innovative new approaches. The ARPA research program should also support longer range, particularly risky research areas, consistent with the overall ARPA mission. A balance of product and process technology should be nurtured to assure that new product developments can be moved quickly and cost effectively to the market. This program would also continue to support consortia efforts within the industry which create domestic infrastructure of equipment, component, and materials suppliers, and encourage synergy and the pooling of technological and financial resources.

For DOE, the level of support recommended is $10-20 million per year, covering both research and technology transfer efforts. DOE should increase funding for the DOE national laboratories in cost-shared programs which support accelerated display development, consistent with its mission. As part of the National Flat Panel Display Initiative, DOE should establish an explicit outreach program to actively pursue the transfer of laboratory technology useful to flat panel display production to industry. To enable a coordinated government program, it is suggested that interagency coordination be established to clearly link each agency's R&D efforts to the overall goal of this program.

2. BUILD NATIONAL EXPERTISE IN HIGH VOLUME PROCESS TECHNOLOGY

Since there are currently no high volume producers of flat panel displays in the U.S., the knowledge base does not exist to manufacture most flat panel products in high volume at competitive prices. Accomplishing the goals of this FPD initiative requires high volume production. Therefore, it is imperative for industry to gain this knowledge, and that such knowledge be widely available to reduce the considerable risks and uncertainties faced by start-ups, thereby encouraging new entrants.

Under a congressionally-mandated program, DoD has already supported the establishment of a low volume AMLCD manufacturing plant to satisfy near term military needs. Further DoD support for manufacturing test beds, that develop and demonstrate production processes and produce displays in pilot quantities, can contribute to development of a sound foundation of knowledge necessary for future establishment of competitive high volume manufacturing capabilities. Additional support for such a test bed, with government cost-sharing of up to $50 million, is a sound and productive investment.

To be truly successful, the participants in a government-funded manufacturing test bed program must be willing to agree to disseminate the knowledge gained about production processes for flat panel displays to U.S. suppliers and industry. In addition, the FPD manufacturing test bed program should engage in an active outreach program to assure that continuing technology transfer takes place to encourage potential U.S. entrants.

The timing of this manufacturing test bed is critical. The National FPD Initiative seeks to encourage decisions by the private sector to establish high volume FPD manufacturing plants in the U.S. These high volume plants, in turn, are absolutely dependent upon adequate process technology and infrastructure development which this test bed program will support. The test bed is an important element in reducing the uncertainty, and the costs facing potential entrants in this arena.

3. ENCOURAGE U.S. INDUSTRY INVESTMENT IN FLAT PANEL DISPLAY PRODUCTION THROUGH FOCUSED R&D INCENTIVES

Under current conditions, risks are simply too great for industry to make the large scale investments required to build U.S. high volume FPD factories. Although some companies have considered plans for high volume production, no concrete investment for such a facility has been made to date.

To encourage such investment, the government should be prepared to make competitive awards for next generation research and development to companies demonstrating firm commitments to volume manufacturing. Through a series of sequential competitions, selected companies committed to new investments in volume production facilities for current generation products would be eligible to receive R&D support for follow-on technology development for next generation products and manufacturing processes, commensurate with the level of commitment demonstrated to volume production. Each of these competitions would be neutral with respect to technology, open to any flat panel display technology to which a firm is willing to commit resources. Important considerations in assessing proposals would include a commitment to invest in volume production, the quality of the technical proposal for follow-on R&D, and the degree of firms' commitment to match government R&D support. This R&D support would be distributed over a five year period and be subject to pre-negotiated goals and standards as well as appropriate oversight. The total program size would be scaled around follow-on technology support for as many as four world class, volume production facilities, to be established over the next five years.

The linkage of R&D funding to a commitment to produce is not an uncommon DoD practice. For example, in funding military aircraft R&D DoD is concerned with not just the technical quality of the proposed research, but also with the credibility and commitment of the proposer to move the results into production. For FPDs the situation requires analogous credibility and commitment to produce; otherwise, there would be no point in sustaining R&D efforts in this area.

These R&D funds would be used to conduct precompetitive research and development on future generations of FPD products and manufacturing processes. Firms would be expected, at a minimum, to match any government R&D support for this effort. This R&D incentive program would be aimed at supporting the long term ongoing investment in technology required to develop new products and processes that meet both government and commercial needs, by firms that commit to producing FPDs with current generation product and process technology. The follow-on R&D incentives associated with manufacturing facility commitments should have management controls built in to ensure that R&D investments are appropriately focused. Decisions to continue with subsequent competitions would be contingent on a determination of need, and the success of prior efforts. Numerous "exit ramps" should be designed into this initiative to facilitate termination of individual projects of the entire program, if warranted.

4. FOSTER MARKET DEVELOPMENT

a. Internal Market Development—Consolidation of the Government Market

Although small relative to world-wide demand, the U.S. government will be a very large buyer, in absolute terms, of products utilizing flat panel displays, for general purpose applications—laptop computers, personal computers, and workstations. To contribute to the establishment of a U.S. flat panel industry, the Federal government should consolidate its buying program for general purpose displays.

Through the authority of a National Economic Council (NEC) directive, an Executive Agent should be appointed to manage a program to consolidate the acquisition of general purpose displays involving all agencies of the Executive Branch. The Executive Agent, in consultation with the General Services Administration, as appropriate, will support the agencies in: (1) assessing their needs for systems using flat panel displays over the next five years; (2) providing technical assistance in designing acquisition programs to take advantage of the best technology which satisfies those needs; (3) providing industry with the resulting market demand data; (4) developing and suggesting an overall government purchasing strategy that will maximize lot sizes for buys; (5) coordinating agency purchases. In addition, the Federal Government should provide funding and develop purchasing incentives which promote the use of domestically produced flat panel displays for national security applications, in a manner consistent with international agreements.

b. Internal Market Development—Stimulation of Demand

A second task directed by the NEC to the Executive Agent should be the convening of an interagency working group to explore the potential of flat panel display technology to meet future government needs. The working group would be tasked to identify applications and specify products, not currently in mass production, that could serve two purposes: (1) improve agency performance through insertion of leading edge technology, and (2) drive market demand for new products that could provide a large and specific target for a developing U.S. flat panel industry.

The possibilities that have been discussed include portable electronic blackboards, low energy computers, portable video conferencing, high resolution imagery and data display, and other applications involving the utilization of the emerging National Information Infrastructure. The Agent would report its conclusions and recommendations to the NEC for further action.

c. External Market Development—International Trade

Export Promotion—As part of its existing export promotion effort, DOC should include an aggressive program for products of the U.S. FPD industry and its supporting industries.

Market Access—Under the leadership of the U.S. Trade Representative, an effort should be made to assure access to foreign FPD markets.

Rationalizing Tariffs—The DOC should conduct an analysis of the current U.S. tariffs on products related to flat panel display production and develop recommendations on altering those policies that impede the development of domestic manufacturing of flat panel displays. Current tariffs on FPD components may have the effect of driving manufacturing activity overseas that might otherwise be based onshore. The DOC should fully cooperate with the effort of the FPD industry to use Foreign Trade Zone procedures in order to facilitate full onshore production.

Access to Foreign Dual Use Technology—The DoD is currently working to facilitate access by U.S. suppliers to foreign dual use technologies of potential value in DoD applications in exchange for foreign access to U.S. military systems technology. Such an effort is already underway with our Japanese allies in a new DoD policy known as "Technology for Technology." The U.S. government may wish to consider flat panel displays as a potential candidate technology area for this program.

Assessing Global Competition—Under the leadership of the U.S. Trade Representative and DOC, with the participation of DoD, DOE, Department of the Treasury (Customs), Department of Justice, and other government agencies, an interagency program to assess competitive behavior in world flat panel display markets should be established. The objective of the analysis would be to quickly identify technology, pricing and availability trends that could potentially affect the success of U.S. FPD programs. Practices this program should seek to detect include price discrimination, predatory pricing, denial of products, inability to gain expected access to export markets, restricted access to technology, and other changes in market behavior that may reflect significant departures from competitive norms in world markets.

5. MANAGEMENT AND EVALUATION

a. Program Management

To maintain a broad-based, national perspective, the overall strategic oversight of the program should be performed by the NEC. It is crucial that the program does not degenerate into a collection of effectively independent actions. Day-to-day management of the program should be conducted by individual agencies with periodic review and coordination through the NEC.

b. Program Evaluation

In support of its role to provide strategic oversight, the NEC should establish continuing oversight and review of the FPD program. The process should seek a balance of inputs from government, business, and academic perspectives, and a rigorous independent review. The review process should evaluate progress toward the stated goals and recommend to the NEC that the program be modified, terminated, or continued.

E. FLAT PANEL DISPLAYS WITHIN DOD'S DUAL USE TECHNOLOGY STRATEGY

The National Flat Panel Display Initiative recommended here represents a major new dual use initiative organized through DoD, and reflects the Clinton Administration's new technology strategy. Flat panel displays are by no means the only technology area in which the new dual use strategy is appropriate, but they are a good choice for a first effort designed to implement this strategy. Many recent technology assessments include flat panel display technology among the handful of critical technologies that offer a promise of substantial payoffs in terms of both national security and economic benefits. Furthermore, after five years of substantial investments by the DoD in technology and infrastructure, the domestic industry is at the threshold of achieving critical mass. A set of decisions is needed to encourage the promising first results from these technical investments to take root as a stable, reliable industrial asset, serving both DoD and commercial markets.

The proposals laid out in this initiative reflect judgments on a number of key issues that will be faced more broadly, in other contexts, as the DoD dual use technology vision is implemented:

- DoD is, and will remain, only a small part of the overall market for flat panel displays. Nonetheless, DoD has critical requirements for flat panel display technologies that are sufficiently important to motivate investments in the creation of future capabilities.
- DoD will certainly do something to diminish current uncertainties over its access to leading edge display capabilities. The choice is not so much whether something will be done, as what: a traditional policy of support for a defense-unique, captive industrial base, or a strategy aimed instead at investing in the creation of dual use capabilities permitting DoD needs to be served by a competitive commercial supplier base. The latter strategy will be more effective, and at a considerably lower cost over the medium and long run.

The actual measures proposed above contain a number of important features that are certain to have broader, canonical application to future initiatives in other technology areas:

- A great emphasis is put on policies that create and maintain competition among both technologies and firms. The benefits and disciplines of market forces should be harnessed to encourage efficient and effective choices whenever possible.
- Policies are suggested that work not only on the supply side of the market, through creation of new technologies, but also pay attention to demand, in both domestic and foreign markets. Such an integrated program will also focus on government leveraging its role as a user of technology in leading edge applications, and using its resources to pry open maximum access to global markets for U.S. producers.

- The measures outlined above are an interagency initiative. A variety of Federal agencies will be working together, on a single common agenda, to achieve a level of effort and focus that would be impossible for any single agency working in isolation. The problems cross agency boundaries; so, too, will the Clinton Administration's responses.

APPENDIX A: THE AMLCD COST AND REVENUE MODEL

This appendix documents the AMLCD cost and revenue model referenced in chapter IV, section D and summarizes the analyses of commercial investment decisions.

A. OVERVIEW OF THE MODEL

The measure of effectiveness used in this model is the internal rate of return over seven years: one year to construct a facility and six years of operation, with no salvage value. During the six operational years, revenues vary with the selling price, production yield, and capacity utilization. Selling price is assumed to drop annually under competitive pressures while yield and capacity utilization increase due to learning. On the cost side, the model considers the following:

- research, development, and investment costs;
- manufacturing costs that vary as a function of throughput including direct materials, direct labor, indirect labor, fringe benefits, overtime, warranty, supplies, and utilities; and
- fixed operating costs that vary as a function of the facility size including rent, insurance, equipment maintenance, and property taxes.

Table A-1 summarizes the revenue and cost models. Equations are arranged in outline form, with high-level equations on the left and sub-equations for high-level variables indented underneath. Variables followed by a "$_t$" vary by year; others are assumed to remain constant throughout the six-year analysis period. The single letters A, B, C, D, E, and F are cost coefficients determined from analyses of industry data.

B. SENSITIVITY ANALYSIS

To examine the sensitivity of the internal rate of return to cost and revenue, a "base case" was constructed using the best available estimates of technical and cost factors gathered from industry. Figure A-1, below, shows the breakdown of the present value[1] of total base case costs accrued over the seven years modeled. Materials and supplies account for 39 percent of the cost. Investment costs represent 33 percent of the total—a relatively high proportion after six years of production. Direct labor is only five percent of the cost structure. Other costs including indirect labor, utilities, rent, insurance, maintenance, warranties, and taxes comprise the remaining 23 percent. The resulting internal rate of return was 11.9 percent.

Investment risk depends two factors. First is the degree of sensitivity of the internal rate of return to changes in the magnitude of a parameter. Second is the potential range of plausible variation in the parameter itself. The remainder of this appendix presents sensitivity analysis for costs and revenues and lists some of the sources of uncertainty in estimating these factors. Sensitivities are examined by varying parameters between -30 percent and +30 percent of their base case values with all other parameters held constant. (Simultaneous changes in several parameters could either intensify or decrease the effects.)

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1 A five percent discount rate was used to calculate present values for the purpose of cost breakdowns.

Table A-1
SUMMARY OF COST AND REVENUE MODEL

Internal Rate of Return = f[Revenue$_t$, Cost$_t$] = Discount rate which gives a net present value of zero on cash flows associated with a firm's sales receipts and outlays for plant, equipment and operations

Revenue$_t$ = Initial Selling Price * (1 - Rate of Price Decline)$^{(t - 1)}$ * Yielded Substrates$_t$ * Panels per Substrate

Yielded Substrates$_t$ = Substrate Starts$_t$ * Yield$_t$

Yield$_t$ = Learning Coefficient* (Cumulative Yielded Substrates$_{t-1}$$^{\text{Learning Elasticity}}$)

Cost$_t$ = R&D + Investment + Manufacturing$_t$ + Fixed Operating

R&D = Fixed Sunk Cost

Investment = Capital per Substrate Start * Facility Capacity

Manufacturing$_t$ = Direct Materials$_t$ + Direct Labor$_t$ + Other Direct + Indirect Costs$_t$

Direct Materials$_t$ = [A * Substrate Starts$_t$ + B * Yielded Substrates$_t$] * (1+ Material Inflation)$^{(t - 1)}$

Substrate Starts$_t$ = Facility Capacity * Capacity Utilization$_t$

Yielded Substrates$_t$ = Substrate Starts$_t$ * Yield$_t$

Direct Labor$_t$ = C * Substrate Starts$_t$ * Average Salary* (1 + Labor Inflation)$^{(t - 1)}$

Indirect Costs$_t$ = D * (Direct Materials$_t$ + Direct Labor$_t$ + Other Direct)

Fixed Operating = E * Investment + F

Sensitivities to Cost Changes

Figure A-2 graphs the change in the internal rate of return as costs are varied from their base case values. Because direct labor and indirect costs[2] represent a relatively small portion of total cost, the internal rate of return does not vary greatly as they are changed: between 10.8 and 13.0 percent as direct labor changes, and between 10.5 and 13.3 percent as indirect cost changes. Hence, the lines representing the sensitivity of internal rate of return to changes in these parameters are nearly flat across the full -30 percent to +30 percent range.

Sensitivities to investment and direct material costs were much greater, as indicated by the steepness of those lines in Figure A-2. The internal rate of return varied between 2.4 and 19.9 percent with direct material costs. Each ten percent increase in direct costs corresponded to approximately a three percentage point change in the internal rate of return. The range of variation was even greater for investment costs (from 1.7 to 27.5 percent). A ten percent drop in investment costs led to a five percent increase in the internal rate of return, while a ten percent rise led to a three-and-a-half percent decrease, over the departures from the base case considered.

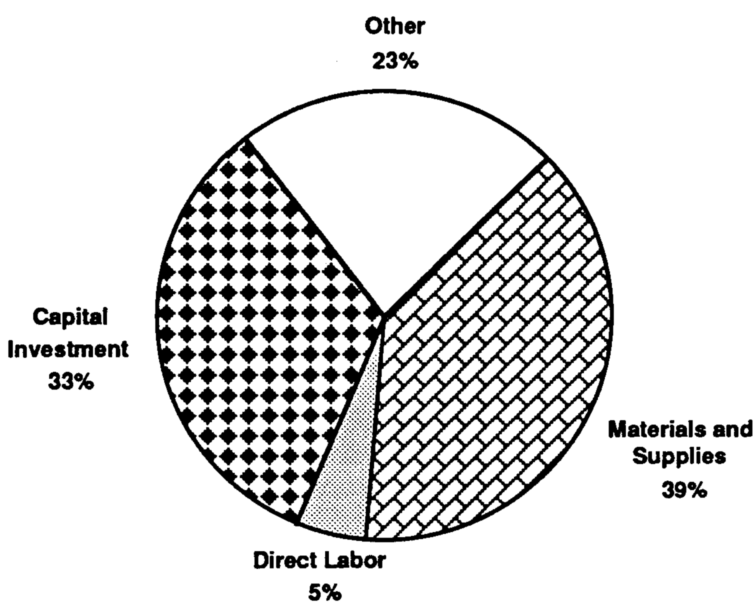
2 Indirect costs are the principal variant in the "other" cost category.

In addition to generating the greatest potential variation among the four cost components, actual investment costs are also the hardest to predict. Data collected from various industry sources were quite disparate. Elements of this uncertainty include the availability and type of equipment needed, lack of pilot facility experience, and the costs of new construction or modifications to existing facilities that might be required. This combination of high sensitivity and high uncertainty can be a significant inhibition to industry investment.

FIGURE A-1

CALCULATED AMLCD MANUFACTURING COST STRUCTURE

Factory Construction and Operation Over 7-Year Life Cycle



Sensitivities to Revenue Changes

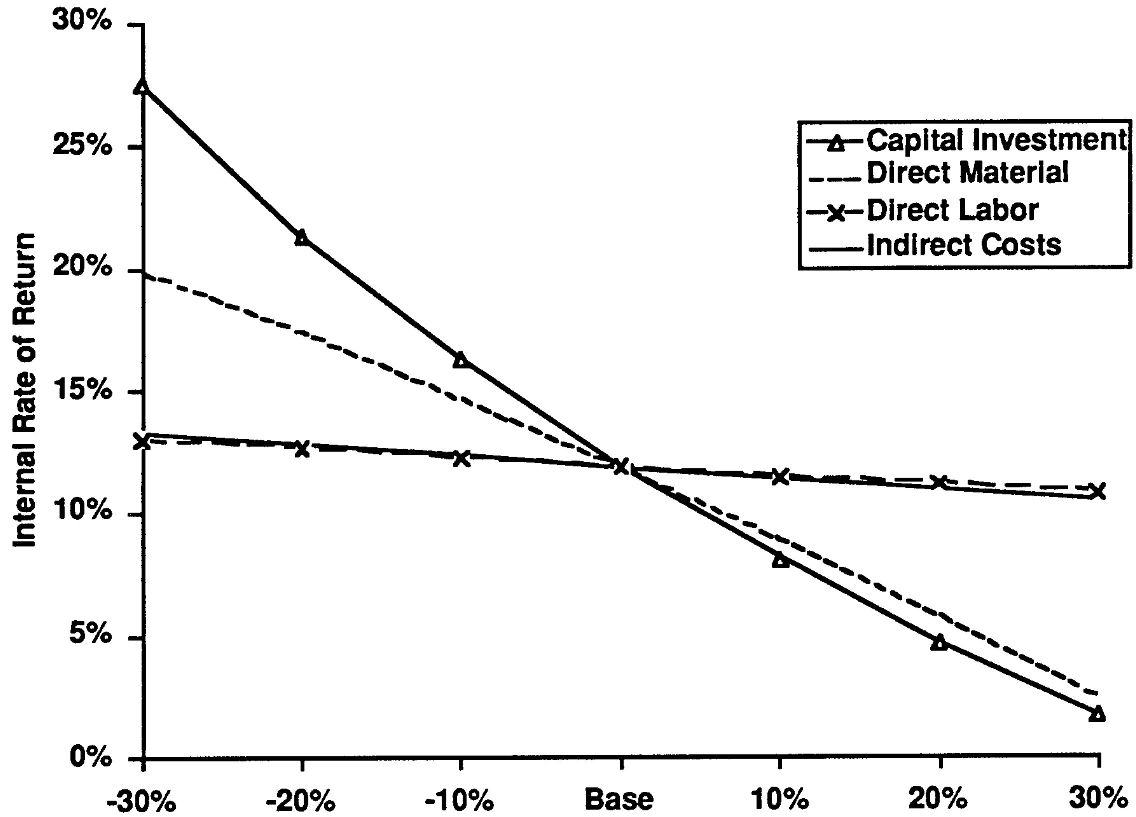
The two principal determinants of revenue are display selling price and yield.[3] Uncertainty about the selling price over time is modeled by varying the constant rate of price decline that has been assumed. Yield variation is modeled as a single proportional change from the yields associated with the base case for each year of production. Figure A-3 shows how the internal rate of return changes as the rate of price decline and yield are varied in this fashion.

3 It should be noted that total operating costs for the plant, especially those for direct material, are also a function of yield. However, the impact of changes in yield is more direct and much more significant in determining profitability.

FIGURE A-2

INTERNAL RATE OF RETURN SENSITIVITY TO COST PARAMETERS

AMLCD Factory Construction and Operation Over 7-Year Life Cycle



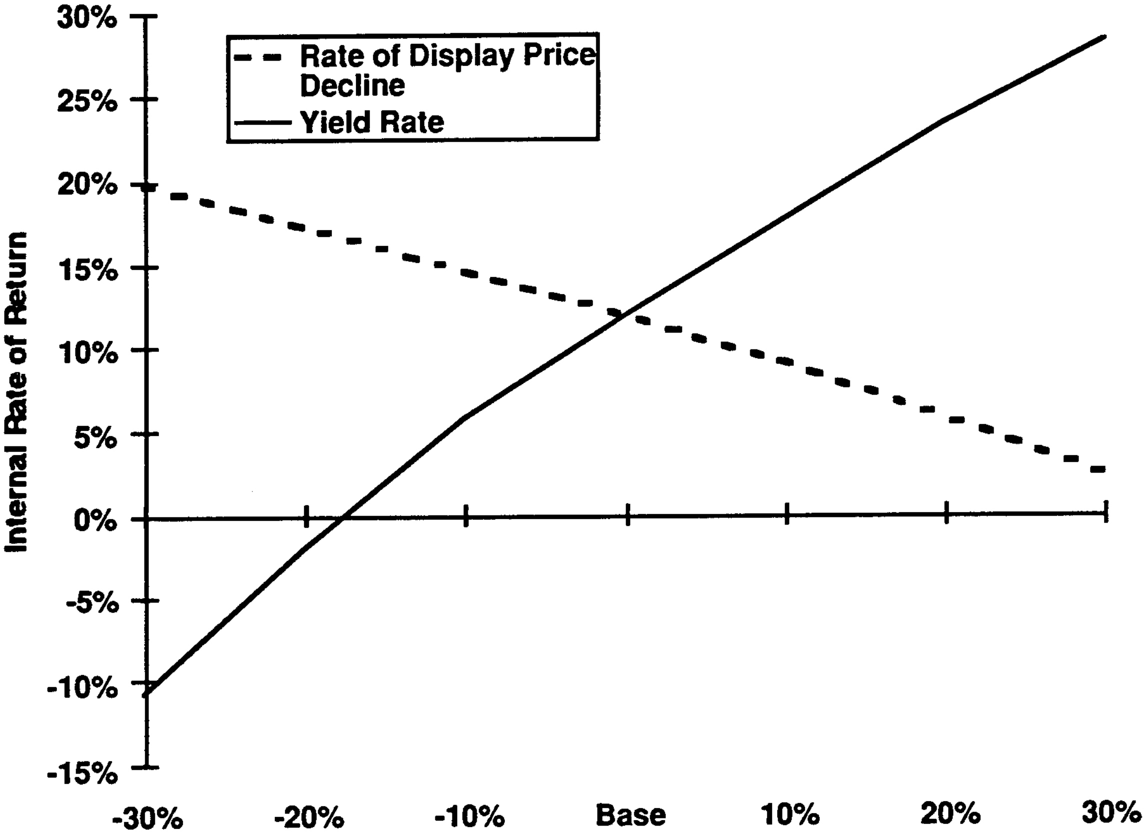
The sensitivities are significant in both cases. The internal rate of return varied between 2.4 and 19.8 percent with changes to the rate of price decline, with a ten percent increase in the rate of price decline corresponding to a nearly three percentage point decline in the internal rate of return. Internal rate of return was even more sensitive to changes in yield—from -10.8 to 28.3 percent—with a ten percent improvement in yield rates causing a six percentage point increase in the internal rate of return.

Uncertainty about selling price is reflected by the difficulty of forecasting both supply and demand for flat panel displays. Uncertainty about yield is accentuated by the absence of large scale commercial manufacturing experience in the U.S.

FIGURE A-3

INTERNAL RATE OF RETURN SENSITIVITY TO PRICE AND YIELD

AMLCD Factory Construction and Operation Over 7-Year Life Cycle



C. CONCLUSION

A company considering a large investment in a flat panel display production facility would be faced with significant uncertainty in four essential cost and revenue elements: investment costs, direct material costs, selling price, and yield. Large degrees of uncertainty affect three of these four elements. Reducing these uncertainties will improve the risk characteristics of investment in flat panel display manufacturing. U.S. firms will invest in such a facility only if the level of risk is acceptable and can be reasonably predicted.

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