Case Study 1: Flat Panel Displays: Assessing the Potential for Civil-Military Integration

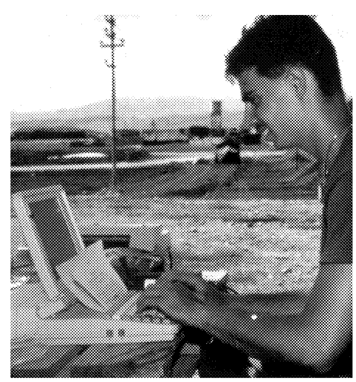
Flat Panel Displays (FPDs) are finding their way into increasing varieties of products, from laptop computers to individual airline movie displays. In some products, they are replacing bulky cathode ray tubes (CRTs); in others, they are making a new product possible. They are used in a wide variety of U.S. weapons systems. A recent Department of Defense (DOD) report noted that:

> 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.[1]

More optimistic estimates are forecasting growth of three to six times the 1993 market by the year 2000, reaching $20 billion to $40 billion.

The DOD report noted that demand is overwhelmingly driven by commercial products, but that FPDs are becoming increasingly important for meeting military requirements. The United States' FPD industry is small and largely research oriented. The U.S. currently relies on foreign suppliers (principally the Japanese) for most of its commercial and defense needs. DOD has stated that it:

> . . . cannot currently rely on the 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.[2]



[1] Flat Panel Display Task Force, *Building U.S. Capabilities in Flat Panel Displays* (Washington, DC: U.S. Department of Defense, October 1994), pp. I-2 to I-3.

[2] Ibid, p. I-6.

In April 1994, DOD announced a National Flat Panel Display Initiative (NFPDI) aimed at providing early, assured access to FPDs for DOD. The initiative envisions an integrated domestic FPD production base capable of servicing both commercial and military markets, almost interchangeably.

This case study briefly describes FPD technology, the structure of the FPD industry, current trends in the industrial base, and the factors favoring and constraining civil-military integration in the FPD industry.

TECHNOLOGY AND USE OF FPDs

Varieties of FPDs

There are many different, competing FPD technologies. The Department of Commerce has grouped current FPD technologies into four broad categories: liquid-crystal displays (LCDs), electroluminescent displays (ELDs), plasma-display panels (PDPs), and field-emission displays (FEDs). Table 2 outlines the technologies, their strengths and weaknesses, and the state of the supporting industrial base. Since then, the extent of the growing Korean capability has become more evident. These technologies, and the Korean capabilities, are discussed in more detail in a forthcoming OTA report on the FPD industry.[3]

Another technology, the digital micromirror device (DMD), is of interest and discussed in this paper because it has the potential to provide large displays and is also receiving heavy investment in the United States from Texas Instruments.

Liquid-Crystal Displays

LCDs are by far the most common class of FPD. Liquid crystals are organic molecules that have crystal-like properties but are liquid at normal temperatures. The molecules can be realigned by weak electromagnetic fields.

An LCD consists of a layer of liquid-crystal material, measuring a mere 1.5 to 6 microns thick, sandwiched between two substrates made of a high-purity glass or a transparent polymer. The inside surface of the glass—that is, the surface in contact with the liquid crystal material—is a thin layer of an alignment material, typically a polymer. The liquid crystal material is said to have a *preferred orientation* when it touches this layer. Etched onto the substrate's outer face is a grid of electrodes. Through various *addressing* schemes, voltages are applied to this grid, turning local areas of liquid-crystal material ON or OFF. The entire sandwich—liquid crystal material, glass substrates, etched electrical grid, and color filters—is in turn flanked by a pair of polarizing filters that selectively absorb visible light. When an electrical field is applied in quick succession to different areas of material, the display produces the illuminated dots known as pixels.

The least expensive LCDs reflect ambient light that strikes the front surface, hits the display's coated rear surface, and is reflected back. More expensive LCDs are artificially illuminated from behind, typically by a diffuse fluorescent bulb. In such backlit LCDs, the screen remains readable when available light is low or glare is high.

LCDs can also be differentiated by the way the liquid-crystal area is electrically addressed (passive vs. active). Passive-matrix liquid crystal displays (PMLCD) are currently the most common. In the liquid-crystal molecules used in passive-matrix LCDs, the switching of the polarization of the light is accomplished by passing the light through crystals that may be aligned in twisted (90°) or supertwisted (270°) configurations when no voltage is applied. When voltage is applied, the liquid crystals align to the electric field creating the display. In a passive-matrix LCD, multiple display points (pixels) are turned on, and like a CRT, it essentially "paints" the display in swift horizontal strokes. In early versions of passive-matrix LCDs, as the number of lines increased, contrast—the difference in brightness between lit and unlit pixels—became increasingly weak. This

[3] U.S. Congress, Office of Technology Assessment, *Flat Panel Displays*, forthcoming, September 1995.

TABLE 2: Flat Panel Display Technologies[a]

Technology	Companies	Type/status	Maximum size (brand)	Manufacturing status	Strengths	Weaknesses
Liquid-Crystal Display (LCD)						
a-Si TFT LCD	~ 15 Japan, 3 U.S. (OIS, Xerox, IBM)	Active/manufacturing	71" (Sharp)	Infrastructure in place; difficult to manufacture; yields of 30-60 '%0	Excellent color, resolution; market penetration	Expensive, power-hungry backlight; not scalable over 17"
p-Si TFT LCD	1 Japan (Seiko-Epson) 2 U.S. (Xerox, DSRC)	Active/developing	13" (Xerox)	Planned for 1995, 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	1 0.5"	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 January 1994	High resolution, video rate; wide viewing angle	Not scalable, new tech; complex drivers
STN LCD, including 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
Metal-insulator-metal (MIM)	2 Japan (Seiko-Epson, Stanley)	Passive/ manufacturing	10" (S-E)	For computers, videophones	$/performance ratio	Slow; cross-talk; flicker
Electro-luminescent Display (ELD)	1 Japan (Sharp) 1 U.S. (Planar	ELD/manufacturing	19" (Planar)	Three volume facilities	Bright, low power, easy	Not fully saturated colors

(continued)

TABLE 2: Flat Panel Display Technologies (Cont'd.)

Technology	Companies	Type/status	Maximum size (brand)	Manufacturing status	Strengths	Weaknesses
Plasma-Display Panels (PDPs)						
PDPs for computers	~5 Japan, 3 Us.	PDP/manufacturing	19" (Plasma-co)	Several large facilities	Bright; multi-colored; scalable	High voltage; limited gray scale
PDPs for televisions	‘6 Japan, 2 U.S.	PDP/manufacturing	45" (NHK)	No proven process	Scalable	Power hungry; high voltage
Field-Emission Display (FED)	~4 U.S., ~6 non-U.S.	FED/prototype	9“ (CNET)	Planned for late 1994	Believed to be scalable	New technology

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, a-Si = amorphous silicon; TFT = thin-film transistor; p-Si = polysilicon; x-Si = single crystal silicon; FLC-ferro-electric crystal; TN = twisted nematic crystals; STN = supertwisted nematic crystal; FSTN = film-compensated STN.

SOURCE: U.S. Department of Defense, *Building Capabilities in Flat Panel Displays,* table 2-1, problem was largely eliminated in the early 1980s with the invention of the supertwisted nematic (STN) LCD, which provide greater contrast.

The passive-matrix LCDs (PMLCDs) main rival is the active-matrix LCD (AMLCD). PMLCDs consume less power and are less costly and therefore continue to dominate the flat panel display business in low-information-content displays—particularly those in watches, instrument readouts, and other devices that must be on continuously. But in many applications, PMLCDs are increasingly losing ground to AMLCDs as the latter's costs decline.[4]

Active-matrix displays do not need to be multiplexed, but are individually activated in one of a number of ways.[5] The result is a colorful, high-contrast image. AMLCDs are used where the desire for high intrinsic brightness, ghost-free moving images, or a rich color palette[6] justifies the price.

The predominant AMLCD technology is the amorphous-silicon thin-film transistor (TFT).[7] It offers good gray shades and color, fast response, and a wide viewing angle. Furthermore, AMLCDs can be made to remain readable when bathed in sunlight and can display information in full color. Compared with current cockpit displays (typically CRTs), AMLCDs are shallower, weigh less, consume less power, are more reliable, and are believed to be easier to maintain.

In several key respects, TFT substrates are processed like integrated circuits (ICs). Both products are made by photolithography, a process that requires a large capital-equipment investment. Both products use thin-film processing and face manufacturing economies that are closely tied to yields. But there are also differences. AMLCDs are larger than typical silicon wafers for integrated circuits. Furthermore, the entire display screen must be free of defects, while the die in defective areas of a silicon wafer used in integrated circuits can be discarded. Finally, the AMLCD manufacturing process generates particulate contamination that necessitates frequent cleaning. AMLCD have thus been more difficult and costly to produce, so their use has been reserved for display types where a passive LCD would be too dim or too low in contrast. Nevertheless, Japanese and Korean firms have made major commitments to improvements and production. Yields are improving steadily and prices are expected to fall as processes improve and supply increases.

The major companies currently producing AMLCDs are Japanese. The market leader in 1993 was Sharp Corp., with 55 percent of the market. The next two largest producers, Nippon Electronic Corp. (NEC) and Display Technologies Inc. (DTI), a joint production venture between IBM and Toshiba, shared about 35 percent of the market.[8]

Electroluminescent Displays (ELDs)

Electroluminescent displays (ELDs) are touted for their ability to be driven at high refresh rates so that high-resolution images can appear flicker-free. Visually, they are highly readable and bright,

[4] New developments in scanning techniques have, however, reportedly brought some renewed interest in PMLCDs.

[5] The terms *multiplexed* and *active* refer to the alternative ways in which individual display points, or pixels, are turned on. In multiplexing, multiple pixels are stimulated by a voltage supplied by a row and a column driver. In an active-matrix color display, there are individual switches and storage devices—thin-film transistors (TFTs), or diodes—attached to each pixel. In a full color AMLCD, each pixel has three subpixels (representing red, green, and blue), each of which can be driven independently.

[6] In theory, AMLCDs have long been able to display thousands of colors. In practice, however, consumers could not buy an active-matrix notebook computer that showed more than 256 colors until late 1993. In October of that year, Apple introduced a color notebook that could display 32,768 colors. The display was made in Japan. Displays with 16.7 million shades of color are available in 1995.

[7] AMLCD made of polysilicon TFT LCDs are being developed. The polysilicon promises to allow circuitry to be integrated directly onto the substrate, potentially greatly reducing manufacturing costs. D. Lieberman, "Hughes Lands Poly LCD," *Electronic Engineering Times*, May 25, 1992 (Issue 694, p. 14).

[8] Flat Panel Display Task Force, op. cit., footnote 1, p. IV-1.

with wide viewing angles and fast response; physically, they are reliable, long-lived, and extremely thin. In producing ELDs, layers of thin phosphor films are deposited onto a sheet of glass, then covered with another sheet. One of the films is luminescent, emitting light when struck by high-voltage electrons.

The use of ELDs has been constrained, however, by difficulties in identifying phosphors with high brightness and the need for costly high-voltage drivers. ELDs are currently used by the military in tanks and command centers and commercially in financial and ATM machines, but there is little current use of ELDs in computers and consumer electronics.

Plasma Displays

Plasma-display panels (PDPs) are composed of front and back substrates with phosphors deposited on the inside of the front plates. An inert gas placed between the glass plates of each cell generates light, with the color depending on the phosphors used. PDPs are rugged, high in contrast, and have a wide viewing angle. Currently, plasma displays are used in submarines and command centers, in engineering workstations, and in portable medical equipment. Their use is limited by their production, relatively high power consumption, and low color brightness.

Field-Emission Displays

The traditional CRT with its deep neck and boxy appearance can make delivery and placement difficult. U.S. researchers are pursuing a radically new breed of CRT. Known as a field-emission display (FED), it may make even large-screen CRT displays thinner than a cigar box. A conventional CRT illuminates all pixels with one or three electron guns. An FED uses a separate tiny electron gun for each pixel. Each electron source contains a large number of very fine microtips; electrons released from the tips are accelerated onto the phosphor, generating light. A conventional CRT must scan each row, illuminating each pixel only for a moment; an FED illuminates each pixel continuously. Proponents argue that FED will bring high resolution to portable, low-power devices.

Digital Micromirror Device (DMD) Displays

Digital Micromirror Device Displays are being developed by Texas Instruments (TI) Inc. The DMD covers each memory cell of a CMOS static RAM with a movable micromirror. Electrostatic forces based on the data in the cell tilt the mirror either +10 degrees (on) or -10 degrees (off), modulating the light incident on its surface. Light reflected from on-mirrors passes through a projection lens and creates images on a screen. Light from the off-mirrors is reflected away from the projection lens and trapped. Shades of gray are determined by the on-state of the mirror. Color can be added.

The Advanced Research Projects Agency (ARPA) has been involved in the development of DMD, but TI is making significant investments in the technology on its own. Large systems (diagonals of 16 ft.) have been demonstrated. Although there are concerns about the durability of the mirror hinges, the company claims that the DMD should meet the temperature and environmental requirements for both commercial and military application. TI also touts the commonality of production with conventional memory chips.

But there are also several challenges to be addressed. One of the biggest is actually developing the lithography to fabricate the chip.

Other Kinds of Flat Panel Displays

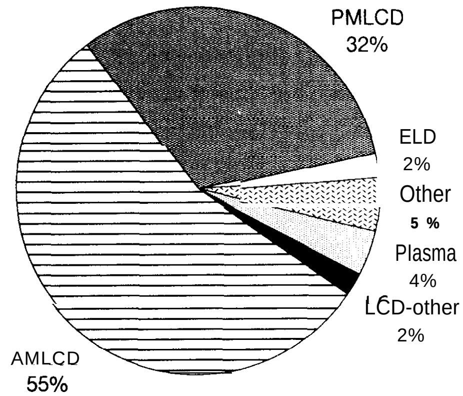
The aforementioned varieties of FPD are geared toward products requiring high information content, multiple colors, or both, in their displays. That class of display is the focus of this study, but other FPD technologies will probably have a place in the future. Light-emitting diodes (LEDs), for example, appeared in the 1960s as an extension of the semiconductor revolution. The first digital watches used LEDs to display the time. By selectively doping crystal materials, engineers can obtain a wide range of visible colors. Two factors have hindered the progress toward using LEDs, however. First, blue LEDs were dimmer than the other two colors of the color triad. This is reportedly no longer true, with CaN LEDs produced by Nichia Chemical of Japan now very bright. Second, all LEDs would have to be processed on a single gallium-arsenide wafer; so far, attempts to do this have failed. As a result, many companies have shelved the idea.

In the United States, the main producer of LEDs is Hewlett-Packard (HP). Together with Los Alamos National Laboratory, HP is exploring new materials—such as polymers instead of inorganic materials—to make more efficient, longer lived LEDs.[9]

From the standpoint of civil-military integration in FPD, DOD faces two broad problems. One is the perceived need for a domestic industry. The other is selecting technologies for military application that both meet military performance needs and will be commercial winners. In the world of competing FPD technologies, this will certainly be difficult.

The projected global use of various FPD technologies is shown in figure 3.

FIGURE 3: Flat Panel Display Demand: Year 2000 Projected Global Market Share for All Technologies.



SOURCE: U.S. Department of Defense, *Building U.S. Capabilities in Flat Panel Displays,* based on data from Stanford Resources, Inc.,1994

▮ The Flat Panel Display Market

Defense Applications

The military relies on a broad range of devices that use high-resolution FPDs. The Department of Defense has estimated that DOD will need a total of approximately 75,000 units by the end of the decade,[10] with annual DOD demand expected to average 25,000 between 2000-2009 and 90,000 between 2010-2019. These figures pale beside the civilian market, but FPDs are increasingly important to the U.S. defense effort. Military flat panel displays are found in surface warships, submarines, fixed-wing aircraft, helicopters, and ground fighting vehicles, as well as in airborne warning and control systems (AWACS) aircraft and in many garrison situations, and are expected to find their way into soldiers' helmets. According to DOD's 1992 Key *Technologies Plan:*

> Particularly needed are high-information-content displays that range from miniature, helmet-mounted devices, through portable and vehicular systems, and up to large screen displays for command post, shipboard, and command centers. Sought are flat-panel displays that offer megapixel resolution, consume low power, and provide virtual reality to the "man in the loop."[11]

Generally speaking, military FPDs are aimed at the five applications shown in table 3.

FPDs are expected to replace CRTs and mechanical displays in virtually all new DOD aircraft, and will be retrofitted into existing cockpits to help give new life to aging aircraft. The prototypes of Lockheed's YF-22 Advanced Tactical

[9] M. Ryan, "Government Labs Go Commercial," *Electronic Engineering Times, Nov. 8, 1993* (Issue 769, p. 49).

[10] Flat Panel Display Task Force, op. cit., footnote 1, p. III-14.

[11] Director of Defense Research and Engineering, *DOD Key Technologies Plan,* July 1992, p. 5-7.

TABLE 3: Flat Panel Display Defense Applications
. Primary military cockpit and flight instruments
. Militarized computers
. Military ground vehicles
. Military helmet-mounted systems
. Military command-and-control-center systems

SOURCE. Office of Technology Assessment, 1995

Fighter (ATF) and those of Northrop's YF-23, for example, each used six active-matrix LCDs. All the displays were built by General Electric (GE).[12]

The production-version F-22 cockpit will require seven AMLCDs At the end of 1994, some 422 F-22s were slated to be built, requiring some 3,000 AMLCDs including spares. However, like all major weapon systems, the F-22 faces an uncertain procurement cycle and final numbers are uncertain. These displays are currently to be built by Optical Imaging Systems, Inc. (01 S), in Troy, Michigan.

In the first decade of the 21st century, some 1,034 AH-64 Apache helicopters are eligible to be re-instrumented or at least to have their cockpits retrofitted with AMLCD displays as part of an Army program to lengthen the service life of deployed Apaches. DOD will also need other large flight instruments and displays, such as those needed on the AWACS aircraft. These must deliver high resolution over screens measuring 20 inches or more in diagonal.

The ground soldiers fighting the Persian Gulf War owed part of their victory to the ease with which they were able to receive character-based and graphical data in the field. Lap-top computers became the information lifeline to the command-and-control structure. As DOD analyzes the strengths and weaknesses of these machines, a new generation, sporting higher color resolutions and high-speed wireless data links, will almost certainly be developed.

Flat panel displays are being planned for future tanks as well as for several tank, armored personnel carrier (APC), and mobile command-and-control station upgrade programs. CRTs take up too much space in a tank's cramped interior. For such punishing applications, it is thought that the more rugged plasma and electroluminescent displays may be used.

The Army has been developing the Soldier's Integrated Protective Ensemble (SIPE) and a follow-on production program. The goal is to equip each soldier's helmet with a flat panel display of tremendous information density. Such a development would greatly increase the number of displays required.

Command-and-control FPDs are needed in all environments (i.e., air, land, and sea). Large-area FPD screens are needed for AWACS and airborne command posts such as Looking Glass and J-STARS as well as for ground and sea control stations and command centers. These operations centers must monitor huge amounts of information over hundreds of cubic miles of space, air, sea, and vast stretches of land. Such applications have driven ARPA to fund a wide range of ideas for large, high-resolution displays.

Command and control, however, is not the only reason that DOD needs large, flat screens. A concomitant need is to accurately simulate operations or the performance of a new weapon system in the heat of battle. Simulation might dramatically speed the development process by creating a prototype of a weapon system on-screen. Simulated battlefield scenarios might allow a mission to be rehearsed just hours before it begins. The trend is to replace electromechanical simulators with panoramic displays that tie together warfare environ-

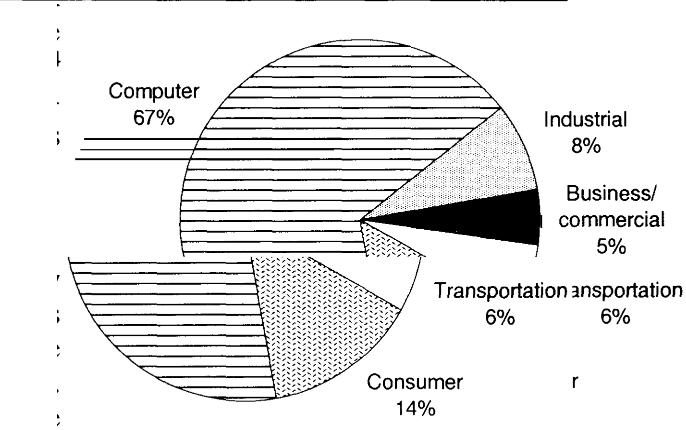
[12] Subsequently, GE sold its AMLCD production facility to the French company Sextant through Thomson CSF, and the plant is now in France.

ments seamlessly in a virtual reality.[13] Under current planning, by the end of the decade a new concept, Distributed Interactive Simulation (DIS), would be used in performing extensive joint-service training and readiness exercises.[14] Such simulations could radically compress development and training cycles while saving dollars and lives.

Commercial Applications

As noted earlier, commercial flat panel display sales are expected to more than double in 10 years from their 1993 level of $6.5 billion, with more optimistic estimates reaching $20 to $40 billion. The current demand for AMLCDs is intense. The broad demand categories estimated for the year 2000 are shown in figure *4.*

FIGURE 4: Flat Panel Display Demand: Year 2000 Projected Global Market Share by Application



SOURCE: U.S. Department of Defense, *Building U.S. Capabilities in Flat Panel Displays,* based on data from Stanford Resources, Inc. ,1995

Computers are expected to continue to comprise the greatest market share. Indeed, displays (whose production is dominated by the Japanese) represent the largest single portion of manufacturing value added in portable computers. In 1993, portable computers became the fastest-growing niche in personal computers. Industry analysts say the market for portables is growing nearly four times as fast as that for desktop computers.[15]

Lap-top, notebook, and subnotebook computers all use flat panel displays. The changing nature of the market is illustrated by what has been happening in subnotebooks. These computers weigh less than 5 pounds. Because of their small battery supplies, the displays of subnotebooks were initially dull and monochromatic. But these too now have active-matrix color screens. AMLCDs are widespread on all portable computers, and the number of color portables sold is expected to increase from about 4 million units in 1993 to 15 million by the year 2000.

FPDs may also eventually displace color CRTs in desktop computers, but cost is currently an inhibitor. Most CRT monitors sell for between $350 and $1,000. Initial FPDs would be much more expensive, but the prices would surely fall with increased production volume.[16]

Consumer applications of FPDs include televisions, games, personal assistants, videocassette recorders, and camcorders. Video communications might be an area of explosive growth. Projection TVs based on CRTs currently dominate applications for large screens, but DMD and some of the other FPD technologies are aiming at this market. Indeed, when consumers think of flat-panel displays, many imagine the wall-hung tele-

[13] See U.S. Congress, Office of Technology Assessment, *Virtual Reality and Technologies for Combat Simulation--Background paper,* OTA-BP-ISS-136 (Washington, DC: U.S. Government Printing Office, September 1994), for a discussion of developments.

[14] M. Tapscott, “Paradigm Change from Simulators to Si... *Defense Electronics,* September 1993, p. 36.

[15] K. Pope, "Changing Work Habits Fuel Popularity of Notebooks," *Wall Street Journal, Nov.* 11, 1993, p. B-1. New reports estimate these shipments even higher and note that the rapid improvement in color flat panel display quality is helping to fuel user demand.

[16] Some manufacturers are already introducing FPDs as desktop monitors. In 1993, IBM introduced a premium-priced desktop PC that included a flat-panel color display. That fall, CTX International, Inc., introduced a 9.4-inch VGA desktop color monitor, featuring a color AMLCD, with a list price of $3,395. Key advantages are said to be portability and lower power consumption.

vision that has been the subject of *Popular Science* cover stories for many years. Such displays might promote the spread of high-definition television (HDTV). According to James E. Carnes, president and CEO of the David Sarnoff Research Center:

> The success of HDTV is dependent on displays. HDTV will become a very popular medium if we have a flat-panel display that provides bright pictures, with a screen size greater than 70 inches, that fits inside the door, for $2,000. The problem is that we don't know how and when it's coming.[17]

Again, no single technology holds an undisputed lead in this application area. The DMD appears promising. Other firms tout plasma displays. In the United States, Photonics Imaging has been working on the problem and has developed a 30-inch high resolution full color, video rate plasma display with ARPA support. In Japan, some 50 companies have allied to form the Japanese Plasma Display Technical Forum. As its organizer explains, "The display industry has already accepted the idea that the plasma display is the way to go for over 20-inch flat-panel displays."[18] Fujitsu has announced an $800 million investment in a plasma plant. Plasma-display makers believe they can bypass the dismal yields that have long plagued the AMLCD makers, but they have not yet demonstrated a high volume capability to do so.

Automobiles offer additional commercial opportunities for the use of FPD. The Nippon Electric Corp. (NEC), for example, has estimated that by 1996, automotive display panels and videophones will fuel a rise in demand for commercial AMLCDs.[19] Car-based displays share with military displays the need to operate in temperature extremes.[20]

Manufacturers are also developing flat-panel touch-screen displays that will be used in the interactive information kiosks found in airports, museums, and stores, where space can be costly. The displays would be built into walls or counters, freeing up floorspace for merchandise. Such displays are used in automatic teller machines; they are also likely to find a home on the control consoles of machine tools and in crowded financial trading centers, where (as a manager at Sharp Corp. explained) "traders have no time for keyboards and no space for a CRT, but they do want a bright, colorful, high-resolution display."[21]

Industry Structure and Leadership

The DOD Flat Panel Display Task Force reported that while there are over 50 firms worldwide producing flat-panel displays, Japanese firms dominate the market.[22] The U.S. FDP industry remains quite small.

The global FPD industry, by most definitions, exhibits a good deal of civil-military integration because so many of the component parts of military FPDs come from Japanese commercial firms. Although more than a half-dozen domestic manufacturers offer military specification (Mil-Spec) AMLCDs with diagonal sizes as high as 10.4 inches, the display itself is usually made in Japan. LCDs (PMLCDs and AMLCDs) accounted for about 87 percent of global FPD shipments in 1993. One company, Sharp Corp.,

[17] D. Lieberman and J. Yoshida, "Flat Panels Jockey for HDTV Position," *Electronic Engineering Times*, May 24, 1993 (Issue 747), p. 1.

[18] Ibid., p. 62.

[19] D. Lammers, "No Letup in Japan's LCD Investments," *Electronic Engineering Times*, p. 20, Mar. 15, 1993 (Issue 737).

[20] According to the Armor All Products Corp., when a car is parked in direct sunlight on a 105 °F (41 °C) day, the interior temperature can soar to 240 °F (116 °C) on the dashboard. Sharp reports that an LCD screen will be permanently damaged through irreversible chemical changes when it approaches 212 °F (100 °C). For this reason, Sharp and other LCD makers are developing temperature-resistant displays for car dashboards. C. Lu, "Taking Care of Your PowerBook," *MACWORLD*, January 1994, pp. 178, 180.

[21] D. Lieberman, "Color Flat Panels Make Comdex Scene," *Electronic Engineering Times*, Nov. 15, 1993 (Issue 772), p. 52.

[22] Flat Panel Display Task Force, op. cit., footnote 1, p. IV-1-IV-2.

claimed 55 percent of the world AMLCD market. Japanese dominance of the AMLCD market is reportedly the result of very large capital outlays, estimated to be $3 billion for manufacturing facilities.[23] Such outlays demand long-term corporate commitments since FPD production-line investments are large and cannot be recouped over short periods.

While research and development in high-information-content flat panel displays is accelerating in the United States, there is still only a small production capability. A major reason for this is said to be a lack of American investment capital. IBM, for example, reportedly established its AMLCD joint-production venture with Toshiba (DTI) in Japan partly because of the low capital costs then available in Japan and the access to Japanese capital markets.[24]

U.S. production of FPDs is currently concentrated in "niche products" largely designed and manufactured for DOD procurement. U.S. defense contractors point to the Japanese technological lead and lower prices as the reasons for why they have turned to Japan when choosing an AMLCD source.

Between 1987 and 1994, much of the domestic AMLCD production base disappeared or became internationalized. When Thomson purchased GE's consumer electronics operations in 1987, it also acquired the process that GE developed for making amorphous-silicon AMLCDs. Thomson moved the plant to France. And in another move, Litton purchased PanelVision and moved it from Pittsburgh to Canada. In each case, when the U.S. company's management was faced with deciding between selling the pilot plant and spending up to a hundred million dollars to ramp up from pilot to volume production, they opted to sell the pilot plant. IBM, as noted above, decided to work jointly with Toshiba in Japan.

U.S. production of AMLCD (low volume), is largely concentrated at OIS, Image Quest, Xerox, and Litton (Canada).[25] OIS has been making all its displays essentially by hand with a capacity of about 3,000 AMLCDs per year.[26] It has a new $100 million ($50 million from ARPA) automated facility in Wayne County, Michigan, coming on line in mid-1995. Its 40,000 units per year capacity is still only a fraction of the Japanese capability.

A partnership between AT&T, Xerox, and Standish also plans a domestic AMLCD production testbed. Raytheon reportedly plans to produce FEDs at its Quincy, Massachusetts plant. TI is making investments in FED, as well as in DMD.

The flat panel display industry in Europe is highly fragmented. Its capabilities thus far are predominantly in research, not production. Despite an established presence in video consumer electronics, the major European electronics firms are far behind the Japanese in the development of advanced displays.[27] Companies involved in the field include AEG (Germany), which is working on AMLCDs; Philips (The Netherlands), which is working on AMLCDs for a range of products, including televisions, with Sharp (Japan); Olivetti & Co. (Italy), which is working with Seiko (Japan); and Thomson S.A. (France). A consortium of four firms (Philips, CNET-SAGEM,[28] Merck, and Thomson) has invested a reported $70 million

[23] The DOD FPD Task Force and others have estimated that Japanese production investments will increase dramatically in the future.

[24] Flat Panel Display Task Force, op. cit., footnote 1, pp. VI-7 and -8.

[25] "How to Build AMLCD at Home," *The Clock*, vol. 3, No. 2 (Santa Monica, CA, May 1995), pp. 16-19.

[26] B. Robinson, "U.S. Flat Panels Could Take Off with AF," *Electronic Engineering Times*, Mar. 2, 1993 (Issue 682), p. 20.

[27] M. Borrus and J.A. Hart, "Display's the Thing: The Real Stakes in the Conflict over High-Resolution Displays," Working Paper 52, Berkeley Roundtable on the International Economy, Berkeley, CA, March 1992, p. 29.

[28] Centre National d'Etudes des Telecommunications is the research arm of France Telecom; SAGEM is Societé d'Applications Generales d'Electricité et de Mechanique.

in an AMLCD plant in Eindhoven, The Netherlands.

A number of Korean and Taiwanese firms are also entering the market. Samsung and Goldstar (Korea) are said to be well into production.

Industry Trends

American firms have been very active in flat-panel-display R&D. U.S. AMLCD research and development has been directed toward a broad spectrum of activities. R&D has received a further boost as a result of the National Flat Panel Display Initiative. The NFPDI promises to provide, on a competitive basis, 50 percent of the R&D costs for next generation process and manufacturing procedures for firms that will build high volume current generation manufacturing factories now.[29]

The outlook for increased domestic production is improving with the OIS production, the pilot facilities, and the interest by large firms like TI. But the big production investments appear to be occurring in the Far East—Japan and Korea. No U.S. firm has yet made a large production commitment of the size occurring in those two countries.

There are clearly trends toward cooperation among firms, both domestically and internationally. The IBM/Toshiba joint production at DTI in Japan is one example.[30] Hughes Aircraft has launched a manufacturing and marketing agreement with Japan Victor Co. (JVC) to develop, manufacture, and market liquid-crystal light-valve (LCLV) projectors, also known as hybrid image-light amplifiers (ILAs).[31] The Advanced Display Manufacturing Partnership (ADMP) involving AT&T, Xerox, and Standish is another example. Several consortia, such as the U.S. Display Consortium, are aimed at establishing the industrial infrastructure of fundamental knowledge, process technology, and mass-production techniques that are needed for U.S. firms to become globally competitive.

U.S. companies are also licensing technology from several foreign firms. TI, for example, gained access to a 25-inch color plasma display developed by Oki Electric Industry Co. and NHK in 1992 under an agreement with NHK, Japan's national broadcasting company.[32] TI and Raytheon have also licensed FED technology developed by France's Laboratory de Technologie et d' Instrumetation from Pixel International.[33]

CIVIL-MILITARY INTEGRATION

As noted earlier, the civil and military components of the *global FPD base* are considerably integrated. There is, however, little integration in the United States base at the production level, since almost no U.S. FPD production base exists. The DOD is interested in developing an *integrated U.S. base* because, the Department argues:

> 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.[34]

Even in the United States, however, there is some level of integration. OIS's AMLCDs, for example, are not exclusively for the military. Commer

[29] "Into the Wild Blue Yonder," *The Clock* 2(3):1 (Santa Monica, CA: September 1994).

[30] IBM reported that when the decision was made in 1989, Japan was the only place to locate that made business sense. Flat Panel Display Task Force, op. cit., footnote 1, pp. VI-7 and -8.

[31] In the LCLV system, a CRT photoelectrically transfers an image onto the liquid-crystal layer of a light valve. The image then travels through a polarized-beam splitter. After being amplified with the light from a xenon arc lamp, the image is fed through a projection lens and onto a screen.

[32] J. Yoshida and D. Lieberman, "At SID: Color Plasma Takes on LCD Panels," *Electronic Engineering Times*, May 18, 1992 (Issue 693), p. 1.

[33] Flat Panel Display Task Force, op. cit., footnote 1, p. VI-10.

[34] Ibid., p. I-6.

cial airlines have shown interest in the company's cockpit displays. Indeed, only about half of the 14 displays that OIS was developing in early 1993 were designed for the military market.[35] OIS displays are also used in Boeing's 777 aircraft.

Factors Favoring Integration

Certain technical, market, and policy factors favor integration.

Technical Factors

The current Japanese ability to produce many of the components used in both American military and civilian FPD applications in the same facility makes it clear that technical barriers to such integration are not a major problem. Because many technologies have both defense and commercial uses, there are few technical reasons for separating the R&D functions. Indeed, U.S. firms often currently combine the research on their defense and commercial displays at one facility, but because of acquisition rules, often separate defense and civilian production.

Trends in design and manufacturing, such as the use of computer-aided design (CAD) and computer-aided engineering (CAE) systems, allow firms to design and develop flat-panel displays in alternative (e.g., military and civilian) versions quickly.

Acceptance of common standards by suppliers and flat-panel manufacturers alike would also aid integration. For example, if equipment manufacturers standardize substrate sizes, products such as chemical-vapor-deposition machinery, inspection stations, and material-handling lines will be able to work with a greater range of ancillary equipment. Standardized pinouts will reduce the variety of connections, bringing economies of scale. The Air Force Cockpit Office is working on an AMLCD standard. In a 1992 survey exploring where FPD standards would be most useful, Japanese LCD manufacturers cited channel number, pin arrangement (number and pitch), methods for evaluating reliability, and methods for packaging.[36]

The Semiconductor Equipment and Materials International (SEMI) North American Flat-Panel Display Division was created to serve as the equipment and materials liaison body to the U.S. Display Consortium (USDC). In close cooperation with the USDC, SEMI is leading a domestic initiative to create physical and process standards for FPD equipment, materials, and components. Standardization can catalyze product development and—by allowing the economies that come from large-volume component production—and expand market opportunities. By helping to make equipment and processes interoperable, SEMI and USDC hope to help the U.S. FPD industrial base capture economies of scale.

Market Factors Favoring Integration

Military displays are typically tailored for specific applications. They are often square, a shape suited for all-aspect radar tracking. As commercial applications for flat displays expand beyond lap-top computers, square displays will become more common. Automated teller machines, for example, use square displays. Because such machines are often difficult to shield from the sun, they may also need bright displays such as those used in cockpits.

Civil-military integration market opportunities also appear possible for large displays in the emerging sector of simulation. Civilian demand for large, flat displays may be driven by HDTV. Military demand is likely to be driven by the growing need to simulate the complex environments of the battlefield. Large flat displays have been sought by the Director of Defense Research

[35] Robinson, op. cit., footnote 34.

[36] R. Kawano and K. Fujita, "TFT Driver Standardization Urgently Needed," *NIKKEI MICRODEVICES*, Dec. 10, 1992, pp. 183-185; reprinted in English in *Science & Technology, Japan, Flat Panel Display 1993*, JPRS Report, Foreign Broadcast Information Service, Nov. 16, 1993, JPRS-JST-93-093-L, pp. 50-52.

and Engineering (DDR&E) for several years. The defense rationale was explained in DDR&E's 1992 *Defense, Science, and Technology Strategy*:

> A new generation of distributed, seamless simulations can create realistic, "synthetic" battlefields to better understand the complexities of future power projection roles and missions. They then can communicate these needs in an operational context more clearly to the development community, which is also on the "net." As candidate solutions are proposed across the community, they can be tried out synthetically and shown to all concerned.[37]

Similarly, large displays are needed by industry to simulate factory floor operations before building new products and facilities. Other areas of the common civil and military interest have been suggested by Brian Kushner, Vice President of MCC:

> Many other partnership priorities could help smooth the integration of commercial and defense industrial sectors and create an effective network of public-private coordination. For example, the DOD's recently published *Defense, Science, and Technology Strategy* emphasizes the creation of "synthetic environments" through simulation technology as a means of "involving the war fighters" in the development and implementation of technology. There is a substantial overlap with commercial requirements for improved graphical interfaces and artificial environments that can support a wide range of business and consumer transactions. Cooperative efforts here could result in substantial leverage for both sectors.[38]

Market demand for high-resolution color images in small head-mounted or helmet-mounted flat-panel displays is also developing in both the defense and commercial sectors. The emerging civilian market for "virtual reality" is fueling a quest for head-mounted displays. Such displays would be used in recreational activities, such as computer games. Real-estate agents, architects, and builders also seek to use small helmet-mounted FPDs to help clients more accurately determine their wants and needs by "walking through" a building even before the first cornerstone is laid.

The military market, meanwhile, is driven by the need for soldiers to be able to view maps, targets, and alphanumeric characters in great detail on displays no larger than 2 inches diagonally. Technologies allowing circuitry to be integrated directly on the glass may possess great promise here.

Policy Initiatives

One of the objectives of the National Flat Panel Display Initiative is an integrated "domestic" FPD base. But the DOD is also interested in global acquisition—if it provides early, assured access to techgnology. Even before this latest initiative, the U.S. government pursued an international integration strategy that sought access to Japan's essentially commercial FPD technology.

In October 1993,[39] for example, a DOD team, led by the Department's Undersecretary for Acquisition and Technology, visited Japan to examine the potential for exchanging U.S. military technologies, including sensors and smart weapons, for Japanese expertise in mass-production technologies, including flat-panel displays. Such ideas have met with some Japanese resistance because they match commercially useful technology developed by Japanese firms—with their own money—with technology developed with U.S. government money. Still, officials express some optimism about increased cooperation. Developments in Korea may offer other opportunities for cooperation and assured access to technology.

Government funding of R&D efforts that might affect civil-military integration in the FPD industry includes the Defense Advanced Research Projects Agency (DARPA, now ARPA) support for

[37] Director of Defense Research and Engineering, *Defense Science and Technology Strategy*, July 1992, p. I-12.

[38] B.G. Kushner, "Dual-Use Concept Gains Respect," *Electronic Engineering Times*, Nov. 9, 1992 (Issue 720), p. 54.

[39] G. Leopold and M. Ryan, "Exports Enter Eastern Endgame," *Electronic Engineering Times*, Nov. 8, 1993 (Issue 769), p. 50.

research and development related to high-definition displays involving work in display technology, multimedia computer systems, video-signal compression, high-resolution graphics, and corollary fields going back more than two decades. Many believe that without government support, the U.S. flat-panel display industry would have ceased to exist or would have been bought out by Japanese or Korean companies.

In recent years, the government has spent about $100 million annually on FPD R&D. The National Flat Panel Display Initiative builds on this experience. It uses focused government R&D investments to encourage private investment in FPD production, because government decision-makers believe:

> U.S. companies are at the leading edge in understanding the functioning and design of FPDs of all types and technologies, (but) 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.[40]

In 1992, DARPA began Phase 2 of its three-phase High-Definition Systems (HDS) program, designed to help U.S. FPD manufacturers to develop the capability to produce such displays on assembly lines. In February 1993, ARPA awarded $10 million to each of four universities to establish Phosphor Technology Centers of Excellence, with additional funding coming from the participating universities. In December 1993, under its Technology Reinvestment Project, ARPA awarded funding to the University of Central Florida (Orlando) to launch a National Alliance for Photonics Education.

At the same time, ARPA committed $20 million to the U.S. Display Consortium. The consortium's interim chief executive officer called the investment "a great example of ARPA leading the way in the development of dual-use technology. The importance of display technology in both commercial and military applications makes absolutely critical the funding of a U.S.-based infrastructure to serve domestic manufacturers."[41] ARPA is scheduled to fund a decreasing share of USDC's operating expenses, and the consortium is expected to be self-supporting by 2003.

Under the Bush Administration, officials in DARPA's HDS program were careful not to tout commercial applications as a goal of their funding.[42] All that changed under the Clinton Administration, which has made it clear that it views FPDs as a strategic technology.

The National Flat Panel Display Initiative includes efforts that will establish an infrastructure of basic technology, equipment, low-cost manufacturing processes, standards, and quality-assurance techniques that will allow U.S. manufacturers, should they choose, to produce flat-panel displays domestically in high volume.

Factors Inhibiting Integration

The greatest single inhibitor to the civil-military integration of a U.S. FPD industry is the lack of a commercially viable domestic industry. Domestic CMI in this industry, as in shipbuilding, requires the development of a commercially viable component. However, in contrast to the shipbuilding industry in the United States, where few large commercial ships have been produced even with

[40] Flat Panel Display Task Force, op. cit., footnote 1, p. I-8.

[41] B. Robinson and D. Lieberman, "Consortium Wins DARPA Flat-Panel Award," *Electronic Engineering Times*, Feb. 8, 1993 (Issue 732), p. 10.

[42] Explaining the reasoning behind the Phosphor Centers of Excellence, Lance Glasser, director of the Agency's Electronic Systems Technology Office, explained, "It's more to provide the capability than anything else. We want to be in the position a few years from now for U.S. manufacturers to be able to decide whether they want to manufacture in the U.S. themselves or not." B. Robinson, "DARPA in Flat-Out Panel Push, *Electronic Engineering Times*, Aug. 3, 1992 (Issue 704), p. 60.

foreign components, there is a developing indigenous FPD industry here.

Technical Factors

Although technical factors do not appear to be a major inhibition to integration, there are some technical factors that constrain the degree of integration. For example, although a military flat-panel display may not look much different from its commercial counterpart, the users of military displays seldom enjoy ordinary viewing conditions or benign environments. Thus, although by many performance yardsticks commercial electronics have overtaken their military counterparts, that is not true of flat-panel displays. Military FPDs must satisfy performance demands that commercial products do not need to meet. Nevertheless, some of the gap can be bridged by repackaging, possibly as a separate activity so it does not add to commercial costs.

Difficult lighting conditions

Military displays must be able to be read when bathed in midday sunlight. This requirement calls for brightness levels as high as 10,000 foot-lamberts—some 200 times the brightness of commercial displays. Because color is used to represent threats and conditions, the display's colors must remain stable when exposed over long periods to ultraviolet light. If the display is backlit (as most AMLCDs are), there must be a fail-safe backup so that the pilot can always read the display in the blinding sun.

Superior viewing

In battle, seconds count; pilots and soldiers must be able to pick information off their displays instantly and from oblique angles. Backgrounds must be jet black to absorb stray light. The backlight must be adjustable to provide satisfactory viewing over a wide combination of available light and available power. Commercial resolution (typically 80 to 96 pixels per inch) is too coarse to render finely detailed maps. Military displays need as many as 128 color pixels per inch.

Extreme environmental conditions

To ensure that they will operate reliably in temperatures ranging from Arctic winters to Sahara summers, military flat-panel displays are typically equipped with built-in heaters for the panel itself; backlit displays include a second heater to keep the backlight from failing. They must also withstand the shock and vibration of daily life in aircraft and armored vehicles. Displays used on Navy airplanes, aboard ships, and in submarines must withstand humid, salt-spray conditions that would quickly corrode commercial displays.

Low power

Many military displays draw their power from small, soldier-carried battery packs. Commercial displays may draw too much power to serve in the field. Accordingly, soldier-carried military displays must have extremely efficient backlights and glass that transmits unusually high amounts of light.

Voltage differences

Many DOD communication systems are designed to draw current at 12 or 24 volts. These levels differ starkly from the consumer sector, where the standard device voltage long ago migrated from 12 to 5 volts. By 1995, led by the demand for long-lived portable computers, 3.3-volt systems will begin to outsell 5-volt systems. With consumers demanding ever-longer battery life, the industry is heading toward 2.2 volts. In the face of these changes, the military may adopt lower voltage sources. There are several technical hurdles to overcome in this area.

Interconnections

Many weapon systems use the MIL-1553D data bus. Military flat-panel displays must possess the necessary connectors to receive data from this bus, and the bus connectors, as well as the power connectors, must be rugged and highly reliable. These connectors are seldom used in commercial flat panel displays.

Market Factors

Much of the FPD used by consumers are likely to remain extremely price-sensitive. However, there is little chance that the price pressures on military cockpit displays will ever come close to the commodity pricing that these devices call for. On the other hand, there may be a great deal of overlap between defense and commercial aircraft FPD needs. In this case, the need is to examine markets that are driven by similar performance need.

Policy Factors

Acquisition law and regulations still inhibit the purchase of many commercial items. While the Federal Acquisition Streamlining Act of 1994 (FASA) will eliminate many of the barriers to integration relating to commercial products (e.g., it will drop requirements for cost and pricing data), FASA does not address many of the constraints that exist with militarily unique items. Thus, acquisition procedures such as government cost-accounting rules and in-plant oversight will still have an impact on the level of integration within firms and facilities.

DOD's changes in the use of military specifications and standards may greatly reduce the barriers to CMI. This, however, remains to be seen and will depend on how changes are implemented. Few of the current military specifications would be of value to most consumers. Hence, it may be difficult for a display that met these specifications to find a broad commercial acceptance. Nevertheless, much of the ruggedness that certain Mil-Specs require can be, and indeed is, provided by careful packaging (e.g., hermetic seals and durable housing). Thus, there is no reason that ruggedization requirements, by themselves, must preclude commercial FPDs from showing up in cockpits and on the battlefield.

Implications of Enhanced Integration

The relatively small military market, representing, by some estimates as little as 1 percent of the total market for flat-panel displays, makes some integration with the commercial market imperative—if the military is going to have early access to new technology. Because of the military's special performance needs, the commercial base might also benefit from selected developments—even if the overall military effort remains quite small.

Whether the integration needs to occur in a domestically based industry or an internationally based industry is a question that continues to be debated. Many argue that there are strategic reasons for ensuring a healthy, integrated domestic production base. There is concern among U.S. observers that loss of the AMLCD market by U.S. firms may also result in a significant loss of the U.S. IC industry as more functions (such as logic, display driving, and diagnostic testing) are embodied within the AMLCD structure in lieu of being manufactured as separate elements. The observers also fear that a lack of manufacturing experience may lead to a situation where the military will not have access to the best technology. Others argue that a globally robust and dispersed FPD industry can provide the Nation with its military needs. What is needed, according to these observers, is the capability to maintain access to global technology developments and the design talent to incorporate these developments into military systems. Whichever argument is correct, it is clear that some level of integration is preferred.