Display's the Thing: The Real Stakes in the Conflict Over High Resolution Displays

Jeffrey Hart and Michael Borrus
BRIE Working Paper 52

I. Display's the Thing: The Real Stakes In the Conflict Over High-Resolution Displays

In Akira Kurasawa's film *Rashomon*, several witnesses to a murder tell the story of what they saw. Despite viewing the same event, the witnesses' stories are radically different, so much so that the event itself is ultimately called into question. So has it been with the debate over the next generation of high-resolution video technology. Some look and see a bigger and better television set (high-definition television or HDTV), but usually dismiss what they see as economically (though perhaps not politically) insignificant.[1] Others look and see a significant component technology (high-resolution displays or HRD) beginning to pervade a wide variety of electronic systems. They recognize in displays a technological kinship to silicon chips -- an industry with potential strategic significance for commercial and military applications.

But the conflict of perspectives should not, as it did in *Rashomon*, cast doubt on the event. The high-resolution display industry is a symbol of a major transformation underway in electronics: that is, the emergence of new component, machinery, and materials technologies driven by commercial, high-volume, integrated micro-systems applications and controlled increasingly by a few integrated producers located outside the United States. This paper argues that the industrial and geographic concentration of the sourcing, development, production, and integration of electronics technologies and systems in Asia portends new patterns of industrial constraint and opportunity, with significant economic and military implications.

I.1. The Architecture of Supply

Should we be concerned about the increasing concentration abroad of electronics technology and know-how? Don't technologies and the capabilities they embody diffuse rapidly across national boarders in a relatively open world economy? If diffusion were perfect and instantaneous, there would be little cause for worry. But, of course, diffusion is not perfect, because not all relevant know-how is internationally accessible through market and non-market mechanisms. Nor is diffusion instantaneous, since the ability to absorb new capabilities depends in part on the available mix of old capabilities. Technology diffusion, like technology development, is a path-dependent process of learning in which today's ability to exploit technology grows out of yesterday's experience and practices. For example, because the demise

[1] For them, a TV set, a desk set, a set of luggage are economically indistinguishable: each affords approximately the same possibility for economic growth; if the economy does not produce one it will produce another.

of the American consumer electronics industry brought with it a sharp decline in corresponding skills, there is today little U.S. capability to competitively produce liquid crystal displays (LCDs) in high volume -- *even though the basic technology is internationally available*.

Or consider the task of fully integrating a new Nikon stepper (a specific kind of semiconductor manufacturing equipment) into an existing fabrication line. The machine can be bought in Japan, but not all of the relevant know-how is embodied in the machine. On-site vendor-supplied technical support is essential to timely and cost-effective integration. Nikon's capacity and willingness to supply that support is much greater in Japan, where most of its engineering resources are located, than in the United States. A U.S.-based firm has far less ability than a Japanese-based counterpart to absorb the new technology in a timely fashion and at low cost -- even though it is available on the market -- because existing domestic capabilities are different (i.e., the domestic economy lacks Nikon's accumulated know-how).

The speed and degree to which technical know-how flows across national boundaries thus depends crucially upon the character of local capabilities. In the U.S., for example, markets are open, employee mobility is very high, firms can be purchased outright, and short-term capital market constraints often push firms to license proprietary technologies. In general, U.S. technology accrues locally but diffuses rapidly even across national boundaries. By contrast, in a country like Japan markets are less open, skilled labor mobility is low, acquisitions are virtually impossible, patient capital is available, and relevant networks (i.e., the supplier network in the Nikon example above) and national institutions are extremely difficult to access. As a result, considerable accrued technological know-how is retained locally in Japan and never diffuses as readily or rapidly across national boundaries.

In other words, successful diffusion of technologies from one economy to another is not automatic even in an open world economy. It depends upon whether or not the relevant capabilities are effectively accessible in the locations in which they reside. In this context, "effective access" exists when technological capabilities are available in the required amount and quality, in a timely fashion, and at a competitive cost. Conversely, the capabilities are not effectively accessible when unavailable at the appropriate quantity, quality, timing, and price.

As electronics pervades the modern economy, industrial innovation depends centrally on the component, materials, machinery, and control technologies (i.e., software in digital electronics) that are combined to create new products and processes. Effective access for a domestic economy to those technological capabilities is a function of the available "supply base" or, to use a spatial metaphor, the "architecture of supply". By "architecture of supply", we mean the structure of the markets and of other organized interactions through which component, materials, and equipment technologies reach producers.[2]

The supply base affects producers in two ways. First, different architectures of supply can either *enable* or *deter* access to appropriate technologies in a timely fashion at a reasonable price. Second, different architectures of supply imply different opportunities to engage in the interaction and support (between suppliers and producers) that are necessary to effectively exploit the technologies that are accessible. These points are worth a closer look.

The architecture of the supply base helps to structure technology access, timeliness to market, cost, and opportunities for interaction between suppliers and producers. To see how, consider a supply architecture in which suppliers of all relevant components, machinery, and materials are domestically based and all production capabilities local. Let us say that the suppliers are numerous and highly competitive. They interact with their customers through arms-length transactions in markets that are cleared by prices, and have the local capability to provide high levels of service and support on demand. They do not compete with their customers, and have no other strategic imperative than to make their products (i.e., machinery, components, materials) available to as wide a customer base as possible.

This kind of supply architecture would ensure domestic producers easy access through the market to all relevant technologies in a timely fashion and at a reasonable cost. Moreover, it offers extensive opportunities for suppliers and producers to interact effectively. Since all relevant production and interaction is local with this supply architecture, the domestic economy is supported by a fully capable supply infrastructure. Technological learning cumulates indigenously. Technological spillovers and other external economies accrue locally to the benefit of the domestic economy. In fact, this architecture is a quite accurate description of both

[2] The supply architecture idea originated in the work of Michael Borrus. For an extended discussion, see Borrus, "Japan's New Developmental Trajectory", in *The Changing Face of the Pacific Rim,* Denis Simon, ed., (forthcoming, 1992). Related notions, though developed very differently, can be found in, among others, the work of Theodore Moran, "The Globalization of America's Defense Industries: Managing the Threat of Foreign Dependence" *International Security*, vol. 15, no. 1 (Summer 1990), Bo Carlsson and Staffan Jacobsson, "What Makes the Automation Industry Strategic?" *Economics of Innovation and New Technologies*, vol. 1, no. 4, (1991), and Esben Sloth Anderson, "Approaching National Systems of Innovation from the Production and Linkage Structure," chapter 3 in *National Systems of Innovation - Towards a Theory of Innovation and Interactive Learning*, B.A. Lundvall ed., (forthcoming, London: Pinter Publishers, August 1992)·

the electronics supply base of the U.S. economy through the mid-1970s, and the economic benefits that accrued to the U.S. economy as a result.

Now consider a different kind of supply architecture, one in which domestic producers are dependent on international markets for supply of technology--markets that, in this scenario, are relatively closed to trade and investment. These markets are also simultaneously oligopolistic and geographically concentrated. Moreover, the few major suppliers compete directly with their customers -- that is, they supply components but also produce the electronic systems that incorporate the components. In this case, most of the relevant supplier know-how is geographically concentrated. Opportunities for support and learning by interaction are available only to customers with a significant local presence in the supplier's heartland, and on terms largely dictated by the supplier.

This kind of architecture permits suppliers great strategic leverage. They have the ability to exercise market power or to act in concert to control technology flows. They can begin to dictate access to relevant technologies, the timing with which their customers can incorporate the technologies into new products, and the price the customers pay for the privilege. The suppliers can set the level of support and interaction with customers to emphasize their own learning rather than that of their customers. Such strategic leverage can have irreversible, long-term consequences. For example, it can result in subtle pressures that delay a customer's new product introduction. Studies estimate that a new electronics product that is only 6 months late to market may sacrifice up to one-third of its potential revenue stream.[3] Reduced revenues retard R&D, further delaying new products, and initiate a competitive downward spiral. Indeed, the nature of this supply base -- characterized by oligopoly, economies of scale and learning, first mover advantages, and the potential to dictate downward spirals to competitors -- tempts established suppliers to engage in predatory policies and practices to preserve their leverage.[4]

This kind of supply architecture would significantly constrain producers abroad who were dependent on it and would have great potential to eliminate opportunities for the dependent foreign economy to capture spillovers and other externalities. From the perspective of the

---

[3] Based on data developed in Don G. Reinertsen, "Whodunnit? The Search for New Product Killers", *Electronic Business*, (July 1983), pp.62-66. In general, see George Stalk and Thomas M. Hout, *Competing Against Time*, (New York: Free Press, 1990).

[4] In particular, subsidized, sunk investment by the oligopolists creates over-capacity and raises huge barriers to new entry, thereby preserving the supply base for those who control it.

distant economy, most of the relevant production activities lie abroad, as do all of the leading edge activities that generate most of the spillovers. The pace of domestic technical progress -- the ability to exploit the machinery, materials, and component technologies that underlie all electronics -- is effectively controlled from outside the domestic economy.

I.2. High-Volume Electronics

The latter kind of restrictive supply architecture is emerging today in electronics. It poses real constraints for firms outside Asia and may significantly limit their ability to effectively pursue new opportunities in both commercial and military electronics.[5] The emergence of this restrictive supply architecture is being driven by a new competitive dynamic in the market for final electronic systems.

Competitive developments in electronic systems are normally analyzed according to the markets for their application -- consumer, computers and data processing, office automation, telecommunications, industrial, professional, and military. Today, however, the aggregate market data actually disguise an underlying dynamic: products whose markets are growing the fastest, though they appear diverse by conventional categories, actually share many of the same specific characteristics and technologies. Consider the following product set for instance: lap-top, note-book, and hand-held computers, optical-disk mass storage systems, smartcards, portable faxes, copiers, printers and electronic datebooks, portable and cellular telephones and pagers, camcorders, electronic still cameras, compact disc players, hand-held televisions, controllers for machine tools, robots and other industrial machinery, engine, transmission, and suspension controls, navigation, and other automotive systems like those for anti-skid braking.

These products are miniaturized systems built around embedded, often dedicated, microprocessors (or microcontrollers) with embedded software for control and applications. They are multi-functional, combining computing functionality with communications, consumer functionality with office functionality, etc. By virtue of their size, such products are increasingly portable. They are also networkable; that is, their capabilities are significantly enhanced by being networked together into larger information systems.

[5] As suggested below, through creative strategies the very largest multinational firms are often able to overcome many -- though usually not all -- of the constraints inherent in a particular supply architecture. By contrast, small and medium-sized firms are much more constrained by the existing architecture, more dependent on national channels of technology flow.

The most distinct characteristic of these products, however, is that they comprise sophisticated, industrially significant technologies that are manufactured in volumes and at costs traditionally associated with consumer demand. Taken together, these products define a new electronics-industry segment being generated largely in Japan with only limited participation by firms outside Japanese industry -- high-volume electronics. The emergence of high-volume electronics has two significant implications.

First, because development costs for the underlying component, materials, and machinery technologies are spread across mass market volumes, the new product segment can support the development of new technologies that used to be supported only through military spending, other public subsidy, or monopoly profits. Second, to meet consumer-like price points the underlying technologies must be pushed to the lowest possible production cost levels without sacrificing high-performance functionality, quality, or reliability (an electronic component for engine control, for example, is a highly complex device that can not fail in operation). The overall result is that high-volume electronics is beginning to drive the development, costs, quality, and manufacture of leading-edge technological inputs critical to all electronics, including military. At stake is a breathtaking range of essential technologies from semiconductors and storage devices to packaging, optics, interfaces, machinery and materials. As the next section suggests, nowhere are these implications clearer than in the case of high-resolution displays.

II. High-Resolution Displays and Systems

Advanced displays (the core technology) and *integrated display systems* (i.e., electronics systems integrated with the core technology) may well provide strategic leverage to shape competitive outcomes in future electronics markets. Advanced displays will contribute a sizeable and perhaps increasing portion of the total value-added of electronic systems. As the first full color LCD notebooks suggest, displays will be used competitively to differentiate products.

There will be extensive integration of advanced displays with other component technologies to create cheaper, more portable, and more user-friendly information-processing products. Integrated display systems will require the development or refinement of technologies used in almost every branch of microelectronics -- lithography, etching, deposition, bonding, packaging, testing, etc. Those who manufacture both displays and high-volume systems may increasingly shape the most important underlying technologies. In short, control over display technologies could become almost as important in future electronics markets as control over integrated circuit technology has been for the last three decades.

II.1. Advanced Displays and Integrated-Display Systems

An advanced display is one which allows the display of large amounts of information over a wide range of image sizes. For this reason, advanced displays are sometimes called "high-information-content displays." When the information to be displayed involves full-color images, then the greater the brightness, contrast, and accuracy of the colors in the image, the better the display. When the information includes animation or real-time video, the speed with which frames can be displayed and the degree of dynamic resolution (absence of blurs caused by motion of the images) are measures of the sophistication of the display.

One way of thinking about advanced displays is in terms of pixels and bits per pixel.[6] A pixel is the smallest addressable part of a display. In monochrome displays, each pixel is a dot that can be on or off or some shade of gray.[7] In color displays, it is generally necessary to combine red, green, and blue (and sometimes white) dots in clusters to get the desired color for an individual pixel.[8] The more pixels a display has, the more information it can convey. The more variation in brightness that is possible at each dot, the more information the display can convey.

At the moment, the architecture of supply for displays is relatively open because cathode ray tube (CRT) technology, the still dominant display technology, is supplied by numerous, highly-competitive firms all over the world. New technology, controlled by many fewer companies, principally in Japan, is gradually displacing the CRT. Through the 1980s, however, the overwhelming majority of television displays were still based on variants of the cathode ray tube.

The CRT was invented by Ferdinand Braun in 1897 and was initially used in oscilloscopes. CRTs were first used to display video images in a device called a "kinescope", demonstrated in

---

6 Pixel is short for picture element.

7 In monochrome displays with "grey-scaling," the dot may be clear, opaque, or some intermediate degree of opacity. Henceforth, when we refer to a dot being switched "on or off," we do not exclude the possibility of the dot being some shade of grey.

1929 by its inventor, Vladimir Zworykin.[9] Further development of the device continued in the RCA laboratories of Zworykin, and in the workshop of Alan Dumont in the 1930s. It was not until after World War II that the CRT became a component in a consumer electronics product, the television. Since that time, televisions have been the main source of demand for CRTs, although in the last decade CRTs have been increasingly used in computer monitors.

CRT technology has developed incrementally since the 1930s, moving from monochrome to color, from lower to higher resolution, from rounded to rectangular and flat display surfaces. Current research on CRTs is oriented toward making the display surface larger while also reducing the overall bulk of the display. Almost all current projection televisions use three CRTs (one each for red, green, and blue colors) together with optical devices to project images onto flat screens. The invention of CRT-projection systems has led to the adoption of a terminological distinction between "direct-view" and projection displays.

The primary alternatives to CRTs for television displays are liquid crystal displays (LCDs). LCDs were developed initially in the Pittsburgh laboratories of Westinghouse and at the David Sarnoff Research Center (then owned by RCA) in Princeton, New Jersey. George Heilmeier and Richard Williams of the Sarnoff lab first put forward the idea that liquid crystals could be used for displays in 1963. Jim Fergason at Westinghouse began to pursue his own approach to LCDs in 1964. Fergason left Westinghouse in 1970 to found a new company called Liquid Xtal, which later failed due to delays in obtaining patents. Peter Brody, also at Westinghouse, pioneered "active matrix" addressing of LCDs. Brody left Westinghouse in 1979 and two years later founded his own firm, Panelvision, which was sold to Litton Industries in 1985.

LCD technology was first applied to watches and calculators for relatively small monochrome displays of numerical data by companies like Citizen, Seiko-Epson, Texas Instruments, and Hewlett-Packard. Sharp introduced the first calculator with an LCD in 1973.[10] LCD technology depends on the ability of liquid crystals to change the polarization of transmitted light in the presence of a small electric field. In a monochrome LCD with no levels

---

8 See David E. Mentley, Joseph A. Castellano, and Yves Blanchard, *High Definition Television: Information Display Industry Survey Report* (San Jose, Calif.: Stanford Resources, Inc., 1990), p. 30.

9 Robert Sobel, *RCA* (New York: Stein and Day, 1986), pp. 122-5. An independent inventor in Utah named Philo T. Farnsworth produced the first electronic television in 1927. He rejected early buy-out offers but eventually licensed his key patents to RCA. After doing so, Farnsworth was exposed to a series of expensive but unsuccessful legal challenges to his patent rights by RCA's attorneys. See "TV Celebrates its First 50 Years," *Video*, May 1989, p. 66.

of gray, each pixel is a dot of liquid crystal that can be switched on or off by applying voltages at the proper row and column positions on the edge of the display (a process called "multiplexing").[11]

Monochrome LCDs were scaled upward in the mid 1980s to be used in portable computers and miniature black and white televisions. Because of low brightness and low contrast, these displays were not initially very successful commercially, so "super-twist" displays and a variety of new forms of backlighting were developed to make them more commercially viable. Multiplexed color LCDs have been developed subsequently for many applications, including hand-held televisions. Again, low brightness and contrast initially limited sales of these displays. The latest generation of devices are brighter, and they have been used successfully in a variety of applications.[12]

More recently, color LCD technology has moved beyond multiplexing toward "active matrix" addressing of pixels. An active-matrix LCD (AM-LCD) has a transistor on the glass panel next to each liquid crystal dot that switches it on or off. Whenever a dot is switched, it stays on or off until it is switched again. An active-matrix display can respond faster to update image information than a multiplexed display, because it does not have to address pixels that remain the same from one frame to the next. This makes active-matrix displays much more attractive than multiplexed displays for high information-content applications.

One interesting and relatively new alternative to electronic addressing of liquid crystals is "plasma addressing," developed by a research group at Tektronix. The plasma-addressed liquid crystal display (PALCD) uses columns and rows of gas plasma to address each liquid crystal dot. Like the electronic AM-LCD, the PALCD dots remain on or off until switched again.

AM-LCDs can be used for both direct-view and projection displays. A direct-view LCD requires some sort of backlighting, preferably flat to take advantage of the flatness of the LCD panel itself. A projection LCD uses the same sort of white light source used in slide or movie projectors to project the image on a flat screen.

---

[10] See, Frank Hayes, "Displays -- Down the DRAM Drain?" *Byte*, February, 1991, p.232.

[11] If the LCD has one or more levels of gray, gray-scaling is achieved by varying the voltage applied.

[12] The latest version of super twist technology is called "tripple super twist nematic" (TSTN). A firm called In-Focus Systems, based in Beaverton, Oregon, uses TSTN multiplexed LCDs to make direct-view and projection LCDs. The manufacturing of these LCDs is done by Kyocera and Seiko-Epson. Telephone conversation with Dave Mentley, Stanford Resources Inc., May 1991.

While AM-LCDs are the main competition to CRTs in advanced displays, a few additional candidates need to be mentioned: electroluminescence (EL), plasma display panels (PDP), vacuum-fluorescent displays (VFD), field-emission displays (FED, also called cold cathode or microtip displays), light-valve projectors, and laser projectors.[13] Light-valve and laser projection are both alternative methods for image projection, while EL, PDP, and FED technologies are useful mainly for producing direct-view flat-panel displays. U.S.-owned firms may be ahead or at least competitive with Japanese firms in some of these technologies, but Japanese firms are well ahead in both CRT and AM-LCD technologies -- particularly in the cumulative expertise they hold in applications and volume manufacturing.

II.2. Why LCDs Will Win The Market

Of the many emerging technologies, LCDs are most likely to triumph in the market. First, LCD technology is superior to any foreseeable alternative. Second, LCD production is backed by huge sunk investment and accumulated learning (especially in Japan). On the technological superiority score, LCDs are rugged with relatively long lifetimes and a wide operative temperature range. They are also capable of high-resolution and color display with acceptable contrast and speed, and they consume very little power. They can be made very flat, and they are compatible with existing silicon chip technology for support and driver circuitry. They also have no apparent negative health impacts from electromagnetic fields. In terms of growth, LCD technology finds itself on a rapid learning curve, backed by a long accumulation of production experience, and supported by annual volumes in the millions from calculator, toy, portable computer, and hand-held TV applications. In fact, Japanese firms are so certain this technology will succeed that they have invested several billion dollars in new production facilities to make LCDs a *fait accompli* in the market.

No other alternative can boast as many technological advantages or as much sponsorship. LCDs will prove daunting to any challenger technology, including the well-established CRT. In the past, the main advantages of CRTs over LCDs were their greater resolution, brightness, higher contrast, and wider viewing angle under various levels of ambient lighting. But the problems of resolution, brightness, contrast, and viewing angle in LCDs have now been solved.

---

[13] Note that these alternatives, though they show the most promise for commercialization, are a small portion -- probably less than 10% -- of the experimental approaches to new display development.

The only problem that remains is size. With the exception of some experimental systems, direct-view AM-LCDs at the moment remain limited to less than 14 inches diagonally.[14] But the size of AM-LCDs is increasing incrementally at a few centimeters per year. When the size problem is eventually solved, as it will be in less than ten years at current rates of improvement, the main difference between CRTs and LCDs will be price.

CRTs are much cheaper to produce than LCD flat panels of equivalent size. A color CRT for a 19-inch television costs around $60 to manufacture. A 10-inch color AM-LCD for a laptop computer costs at least $3,000. Large CRTs are much more expensive than smaller ones. For example, a CRT for a 38-inch direct-view television costs around $1,000 to manufacture, partly because of the lower volumes but also because of lower yields. The glass content of a large CRT tends to make it very heavy and hard to handle. In addition, special shadow masks and electron guns are necessary in larger CRTs. Small but bright monochrome CRTs for projection televisions are also quite expensive but still considerably less expensive than AM-LCDs for LCD projectors.

The advantage of direct-view AM-LCDs and other flat-panel displays is mainly in compactness and lower power usage -- and therefore in the portability of systems. These qualities are particularly desirable in portable televisions and high-end portable computers and workstations. The market for portable electronic devices has grown very rapidly in the last ten years. Flat-panel displays cannot compete yet with CRTs in markets for inexpensive televisions or computer displays. When large-area flat panels come to match CRTs in brightness, contrast and viewing angle, and can be manufactured at reasonably low prices, then the advantages of compactness and low power usage will permit them to displace CRTs in a wider variety of applications.

One estimate of large-area flat panel costs comes from Eiji Taneko of the Giant Electronics Corporation of Japan. Taneko predicts that his company will be able to market a full-color 40-

[14] Toshiba and IBM have publicized their 14-inch AM-LCD, but have not shown it in public. Sharp has marketed an LCD projector for NTSC signals that projects a 50-inch image. Sharp and Sanyo have demonstrated prototype high-resolution LCD projectors, but neither appears to be ready for commercialization. A 19-inch EL flat panel is being manufactured currently by Planar Systems for Digital Equipment Corporation. Large color PDPs were demonstrated in May 1991 at the Society for Information Display by three different firms: Mitsubishi (33-inch), Thomson (23-inch), and Photonics Imaging (17-inch). Electroplasma demonstrated a 19-inch monochrome PDP at the same show, while Plasmaco showed a very large monochrome PDP.

inch AM-LCD at around $1,000 per unit in the year 2000. Barring a breakthrough in CRT manufacturing technology, this will make AM-LCDs quite competitive with CRTs at that size.[15]

For large-area projection displays, non-CRT systems have a chance to displace CRT projectors more rapidly because they are likely to be price-competitive earlier than direct-view flat panels. For example, the Sharp XV-100 LCD projector for NTSC signals sells for around $3,000 (discounted), only $1,000 above the cost for a comparable CRT projector. In addition, CRT projectors are likely to continue to be bulkier than LCD projectors; wherever space is at a premium, consumers may be willing to pay extra for the less bulky LCD product.

III. LCD Dominance and the Architecture of Supply

As LCD's win in the market, a few major Japanese firms -- especially Sharp, Matsushita, Hitachi, Toshiba, and Seiko-Epson -- are coming to dominate the development of advanced displays. These firms are, of course, vertically-integrated producers of electronics components and systems and are likely to be predominant suppliers of integrated display systems. As these firms come to dominate in the market, they will shift the character of the supply base in electronics, making it less accessible for other firms in the industry.

These firms -- a few vertically-integrated, oligopolistic suppliers whose production activities and ownership are concentrated in Japan -- will increasingly be in position to dictate access to underlying electronics technologies, their quality and price, and the speed with which users can incorporate them into new products. U.S. systems firms that depend on these suppliers for displays will be vulnerable to unfavorable prices, delayed or erratic deliveries of the latest devices, and other predatory behavior. Such practices may not necessarily be illegal, though they would provide strong competitive leverage in the market. Many firms, including U.S.-owned companies, have engaged in such practices when they were in the same position. In both DRAMs and in laptop LCD panels, there have already been incidents which bear this out.[16]

---

15 Panel on "Large-Area Displays", International Symposium of the Society for Information Display, May 5-10, 1991.

16 On problems with DRAMs, see Charles Ferguson, "Dependence: The Present Danger," *Harvard Business Review*, (July-August 1990), p. 66. On the LCD incidents, see Advanced Display Manufacturers of America (ADMA), Antidumping Petition Before the International Trade Administration of the U.S. Department of Commerce and the U.S. International Trade Commission: *High Information Content Flat Panel Displays and Subassemblies Thereof from Japan*, July 17, 1990. The petition was prepared by the law firm of Collier, Shannon, and Scott with the assistance of Georgetown Economic Services for the Advanced Display Manufacturers of America. The preliminary ruling of the Department of Commerce, on February 14, 1991, assigned low dumping

Indeed, given the nature of this technology and the markets that support it -- involving scale and learning economies, oligopoly, and strong first mover advantages -- it would be surprising if Japanese firms resisted the temptation to engage in predatory behavior. Their aims would be to reduce the amount of competition abroad, prevent new entry, and entrench their hegemony. For example, predatory pricing could limit their foreign display competitors to low-volume, niche markets. This was, in fact, precisely the problem that led to the positive findings by the Department of Commerce and the International Trade Commission on the anti-dumping petition filed against Japanese display manufacturers by the Advanced Display Manufacturers of America (ADMA).[17] Such predatory behavior will significantly shape the underlying architecture of supply in component technologies.

In turn, a restrictive supply architecture will create severe problems for U.S. systems firms whose strategy depends on an open, accessible architecture for supplying components. Its threat is already having a significant impact on the corporate strategies of U.S.- and European-owned firms, and on U.S.- and European-based production activities. Several examples will suffice to demonstrate the implications. IBM has moved development of notebook and smaller computers out of the United States to its IBM-Japan subsidiary because that is the only place that guarantees access to the appropriate skills and necessary technologies. For similar reasons, Philips has moved development of hand-held TVs out of Europe to its Marantz subsidiary in Japan.

Very few other systems firms have the resources and domestic Japanese market presence to follow suit. Others, including Apple and Compaq, have had to form precarious alliances with competitors (Sony and Citizen Watch, respectively) in order to get access to the needed technology and skills. And even if individual firms manage to adjust successfully, the domestic U.S. economy will increasingly lose the locus of activities that underpin modern electronics -- and with it, eventually, most of the relevant component know-how.

As the supply architecture for displays shifts, there are likely to be three significant impacts on the U.S. economy. First, there will be a significant loss of know-how in component

---

margins to a number of Japanese firms, but the final ruling, in August 1991, assigned considerably higher dumping margins. The International Trade Commission determined that anti-dumping duties should be 62.7% on AM-LCD's from Japan, although only 7.02% on EL displays. See, U.S. International Trade Commission, "Certain High Information Content Flat Panel Displays and Glass Therefore from Japan" (Washington, D.C.: U.S. Department of Commerce, August 1991), Investigation # 731-TA-469 (Final), Publication # A-588-817.

manufacturing activities. Second, there will be a progressive loss of new market opportunities. Third, the competitive dependencies that result may well undermine the existing competitive strengths of U.S.-based firms. The overall result will be a significant diminution of electronics capabilities in the United States -- perhaps a relegation of the United States to second class status in the industry. Each of these major impacts is worth a closer look.

III.1 High-Resolution Displays Will Drive Electronics Manufacturing

Because buyers are willing to pay a premium for ever flatter, more compact displays, high-resolution displays (HRDs) are pushing the limits of the associated manufacturing technologies. There are significant impacts on the types of manufacturing equipment required to manufacture AM-LCDs, on the new, high-volume, processing capabilities high-resolution flat panels require, and on related manufacturing technologies like packaging, materials, and other kinds of components.

Flat-panel manufacturing requires the use of lithography and deposition equipment, including steppers developed originally for semiconductor manufacturing and adapted for flat-panel production. Methods used to increase yields in semiconductor production -- such as clean rooms and statistical quality control -- are also used in flat-panel production. High-volume production of flat panels, therefore, can be a driver for innovation in semiconductor production equipment. This innovation is not likely to be in the area of making smaller line-width devices but rather in equipment for large-area processing.

The next generation of flat-panel manufacturing equipment will be aimed at integrating displays with LSI, VLSI, and ULSI circuitry on large glass panels.[18] Steppers and advanced lithography equipment for semiconductor manufacturing are designed for relatively low variance in the size of objects on relatively small circular silicon or gallium arsenide substrates.[19] By contrast, steppers and deposition equipment for integrated displays will have to handle larger variation in the size of objects on a much larger rectangular glass substrate. The approach of companies like Nikon and MRS Technology is to adapt stepper alignment machines to the larger areas. The approach of the Giant Electronics Corporation in Japan -- and perhaps the

---

[17] ADMA, *ibid*.

[18] Large Scale Integration (LSI), Very Large Scale Integration (VLSI), and Ultra Large Scale Integration (ULSI)

[19] Leading-edge silicon wafer processing equipment handles 8-inch diameter wafers.

economical winner in the future market -- is to move away from steppers to printing technologies.

Deposition equipment for semiconductors has much in common with deposition equipment for flat panels. Both need to be able to deposit thin films of metal and metallic compounds on substrates. Since many flat panels have multiple layers of thin-film oxides, deposition equipment optimized for oxide deposition may be better for flat-panel processing than the nitride deposition machines used in most wafer fabs. But whatever machines are eventually used, the underlying thin-film deposition technologies remain much the same.

The substrates for semiconductors are usually either silicon or gallium arsenide, while the substrates for flat panels are usually glass. Glass-handling robots, which use the same technologies as wafer-handling robots (for semiconductor or flat-panel production lines) but have been modified to deal with the larger size and different physical properties of glass panels, are being marketed.

In other words, while manufacturing equipment for advanced displays will be different in some respects from that for semiconductors, there will continue to be many common features as well. One can expect that firms that manufacture both integrated displays and advanced integrated circuits (ICs) will have some advantages in overall electronics manufacturing technology over those that specialize in displays or ICs alone. Similarly, equipment firms that have customers for both IC production machines and flat-panel equipment may do better than equipment firms that are limited to one or the other market.

Whatever the outcome with individual firms, the architecture of supply of the underlying machinery will shift to favor those who produce for both IC and display uses. There will also be a shift in the locus of relevant process know-how as AM-LCDs come to dominate. Fabricating AM-LCDs is somewhat more difficult than manufacturing conventional LCDs because semiconductor circuitry and liquid crystals must be deposited accurately and reliably on the same glass substrate. In the 1970s, the Casio Corporation developed a new technology to do this called amorphous-silicon processing. Casio originally applied amorphous-silicon to the manufacturing of calculators. Casio's "credit-card" calculators, made with this process, were very successful in the market because of their small size and low price.

Amorphous-silicon (a-si) processing involves the deposition of thin films of metals and metallic oxides -- using an impure form of silicon crystal that has certain desirable properties --

on a glass substrate that also contains the liquid crystal pixels. A-si technology has evolved considerably since its introduction. Initially, there were significant problems of electrical leakage in a-si circuits. These were solved by adopting a variety of new deposition techniques. A-si technology has proven to be reliable in high-volume manufacturing, even though yields are not as high as manufacturers would like. Most current research on a-si technology is aimed at reducing manufacturing costs by increasing yields: for example, by reducing the number of masks needed to etch circuits and by improving alignment techniques for large panels.

A-si may be replaced eventually by poly-silicon (p-si) processing technology because p-si circuitry can be more complex than a-si circuitry. The ability to place driver and logic circuitry on the glass substrate of the display panel using p-si technology may make it possible to reduce interconnection costs and increase yields of assembled displays. The main problem with p-si processing is that it requires higher temperatures than a-si processing; the negative effects of high temperature on the glass itself can negatively affect manufacturing yields. Glass that holds up well under high-temperature processing is considerably more expensive than low-temperature glass. Research underway targets these problems, and innovations are likely.

Such processing innovations are likely to be complemented by packaging innovations. Display manufacturers are leading innovators in advanced packaging techniques like "chip-on-glass" (COG), tape-automated bonding (TAB), and flexible circuits.[20] COG is used to put driver circuitry on the glass substrate. This is done by bonding an unpackaged integrated circuit chip to the panel and then connecting it to the display with automated wire-bonding equipment. TAB techniques can be used for placing the chip in the proper location on the glass substrate: this is called "TAB-on-glass" or TOG. Flexible circuits are used on the ribbon cables connecting the display to the rest of the system. These and other foreseeable packaging technologies are likely to be applicable to a wide variety of electronics systems.

In similar fashion, a range of complementary materials and component technologies are likely to benefit from their synergy with advanced displays. These include battery technology for portable applications, a range of ICs including CCDs (charge-coupled devices), DSPs (digital

[20] See, for example, Roger R. Reinke, "Interconnection Method of Liquid Crystal Driver LSIs by Tab-On-Glass and Board to Glass Using Anisotropic Conductive Film and Monosotropic Heat Seal Connectors," paper prepared for presentation at the 41st Electronic Components and Technology Conference, sponsored by the Electronic Industries Association and the IEEE Components Hybrids and Manufacturing Technology Society, no date; Ray P. Prasad, *Surface Mount Technology: Principles and Practice*, (New York: Van Nostrand, 1989), chap. 1.

signal processors), RAMs (random access memory), light sources (for back-lighting), and precision mechanical components.[21] As the next sub-section suggests, emerging component technologies associated with speech, hand-writing, and touch recognition are also likely to be affected by progress in displays. Finally, innovative applications of chemical technologies are also likely as the need for better latching, contrast, and temperature range performance increases.

On top of these technological impacts, advances in microsystems integration are likely to be driven by display systems. Integrated displays will be more compact, more functional, and eventually cheaper than displays with no integration. Systems manufacturers who are successful in integrating system circuitry onto display panels may therefore displace manufacturers who are not. There will be major manufacturing advantages for firms integrating at least some of the electronic circuitry of the system onto the display panel. Even though microprocessors and memory devices are likely to remain on separate circuit boards, driver, logic, and testing circuitry probably can be integrated with the display. This reduces the cost and increases the reliability of interconnecting the display with the rest of the system.

Display failures are frequently caused by problems of interconnection in assembly; placing circuitry on the display panel can increase manufacturing yields of assembled systems by reducing the number of interconnection points. Many current flat-panel displays have as many interconnection points as there are rows and columns on the display. As pixel density increases, this will become an even more important problem for reliable manufacturing. By adding some redundancy to the circuitry on the glass panel and bypassing faulty circuits using lasers, rework costs can be greatly reduced.[22] Another important area of possible cost savings is the integration of testing circuitry onto the display. If displays can become self-testing, and even self-repairing, then yields can be increased and device reliability can be enhanced.

One possible historical analogy for the importance of integrating system circuitry onto the display is seen in the failure of most U.S. consumer electronics manufacturers to use integrated circuits or to speedily reduce the number of circuit boards in color television sets in the 1970s, in stark contrast to their Japanese competitors. The inability of most U.S. producers to take

[21] For a detailed discussion of the IC impacts, see U.S. Congress, Office of Technology Assessment, *The Big Picture: HDTV and High-Resolution Systems*, (Washington, D.C.: GPO, 1990), pp. 63-68.
[22] Rework costs are often a major component in the total manufacturing costs of electronic systems.

advantage of the cost-reducing and reliability-enhancing features of circuit integration and manufacturing simplicity made possible by ICs helped to accelerate their competitive decline.[23]

III.2 Integrated Displays and New Markets

Systems with integrated displays will not only displace systems with plain displays in existing markets: they will open up new markets that did not exist before. Greater portability, low power usage, and compactness will combine with relatively lower production costs to expand demand. Integrated displays will permit individual users to carry around with them general-purpose computers that were previously immobile and special-purpose computers that were not previously economical to build. A range of existing product markets will also be transformed into new market opportunities by the addition of display system capabilities.

The rapid success of laptop and now notebook computers is an indication of the potential size of these new markets.[24] Even before the laptop computer, one can argue that the firms that succeeded in integrating simpler displays with circuitry (as Casio did with watches and calculators) were able to win market share in highly competitive markets. These early integrators may have some advantages in the next round because of their experience with COG, TAB, and flexible circuits.

Currently, several workstation manufacturers are marketing personal workstations with color LCD flat-panel displays on the assumption that people will pay a premium for compactness in highly functional systems. Integrated displays will have a significant impact in this realm as well. U.S. firms are overwhelmingly dependent on Japanese firms for the LCDs that make laptop, notebook, and palm-top systems possible. Japanese firms, therefore, are generally well positioned to take advantage of integrated displays -- in both the component and end-product markets.

Smarter cellular telephones, more functional inventory tracking devices, faster financial telecommunicating devices -- all will become easier and cheaper to make with the development of integrated displays. Many entirely new and unpredictable applications of microelectronics technology are likely to arise with the integration of displays with systems. Not all the things

---

[23] See Jeffrey Hart, "The Consumer Electronics Industry in the United States: Its Decline and Future Revival," *Business in the Contemporary World*, 3 (Summer 1991). p.46-54.

[24] On the rapid growth of the laptop market, see Andrew Pollack, "Japanese Portables Threaten American Lead in Computers," *New York Times*, November 24, 1990, p. 1.

that large systems do will be duplicated in smaller systems -- e.g., the centralized management of real-time, on-line databases for large organizations. Nevertheless, the evolution of more powerful computing devices in smaller packages is likely to make it possible to decentralize anything that now is centralized for reasons of lowering computing costs only.

Many office machines and consumer durables will be using flat-panel displays as visual interfaces in order to make it easier to use the product or to diagnose problems. Examples of this trend can be found in photocopiers, key systems (multi-line telephone systems for offices), laser printers, and fax machines.

The current generation of photocopiers uses LCDs to give users feedback on the nature of the job they are doing and to help them correct a problem in the system (e.g., paper jams and toner refills). The graphics display can make it possible to add new functions to the machine without overburdening the user with problems of learning how to use the machine. It can also probably reduce the tendency of users to call the company to correct minor problems.

In key systems, it is often useful to have a graphic display of the number dialed and of the lines that are currently open or busy. It is for this reason that most key systems now include monochrome LCDs. With the implementation of narrow-band integrated services digital network (N-ISDN) capabilities, new services like caller ID (which gives the user the number of a call originating from outside) can be displayed in the same way. With broadband ISDN (B-ISDN), the capability of displaying a video image together with audio information may be sufficiently valued to justify putting a more advanced display on "telephones." Indeed, perhaps in anticipation of this, AT&T has recently re-introduced the picture phone.

In short, flat-panel displays can enhance the value to users of a wide variety of products. The more difficult the product is to operate without instructions, the greater the need for displays to provide guidance and diagnostics. Thus, displays will become increasingly important for many consumer durables and office machines, even those products that have not previously included displays. Capturing these new opportunities will require timely access to the necessary display technologies at a reasonable price. Such access will become more difficult as the supply architecture becomes even more restrictive.

III.3 Subverting U.S. Strengths: GUIs and Multimedia

Existing U.S. strengths in system architecture and software provide a powerful means of bargaining to attain access to necessary display technologies. This can be seen, for example, in Apple's ability to use control over its graphical user interface (GUI) to lever its portable Mac deal with Sony, and Hewlett-Packard's control over its laser printer driver software to lever its relationship with Canon for supply of the laser printer engine. Nonetheless, integrated display systems and a restrictive architecture of supply will also create challenges to 'soft' U.S. strengths. The stakes can be seen in potential impacts on GUIs and multimedia computing.

Graphical user interfaces (GUIs) are central to the current competition among operating systems for microcomputers and workstations. The Macintosh GUI, for example, is widely recognized as a key to the success of the Macintosh as an office machine because it lends itself to easy training of new personnel. The combination of a high-resolution monitor with a "mouse" (a kind of pointing device) and a relatively standard set of graphical symbols for starting and ending programs (also for editing, cutting and pasting, and drawing) makes the Macintosh operating system easier for novices than those using text-only displays and keyboards for input.

Until the introduction of the PS/2 line in 1981, the IBM PC lacked a credible response to the Macintosh GUI. This also explains the GUI now in the Presentation Manager for OS/2. The Presentation Manager mimics many aspects of the Macintosh GUI -- use of icons or graphic symbols for basic operations and a mouse for pointing to them. The Presentation Manager, like the Macintosh operating system, creates new hurdles for the writers of software to create a friendlier interface for the user. Like the Macintosh GUI, it is aimed at providing friendliness without losing functionality.

The IBM Presentation Manager and Microsoft Windows were both developed by Microsoft Corporation.[25] Windows 3.0, the latest version of Microsoft Windows, is catching on now that there is sufficient power and random-access memory (RAM). Intel's 80386 and 80486 microprocessors have finally made that environment attractive to programmers and users. A sizeable number of standard programs are being converted to take advantage of this new environment. Like the Presentation Manager, Windows also uses symbols to mimic the Macintosh GUI.

The UNIX operating system has been a competitor in the market for operating systems in a wide range of computer systems, but initially lacked a GUI. This hurt the take-up of UNIX, especially by users of smaller systems who were more comfortable with the Macintosh GUI or the relatively less friendly PC-user interface (mainly because of the availability of useful software for the two machines). Firms responded to this sluggish embrace of UNIX by offering new GUIs for UNIX.

The first company to do this was Sun Microsystems, which put its "Open Windows" GUI on Sun workstations.[26] Several other producers of workstations provide UNIX operating systems with GUIs -- Hewlett-Packard has its New Wave, NeXT has a GUI environment called NextStep, Digital Equipment Corporation's Ultrix version of UNIX has a GUI, and Sony has a proprietary GUI for its NEWS workstation. None of these GUIs are compatible with one another.

The move to GUIs in UNIX workstations has led to a number of efforts to standardize them. The Open Software Foundation has invented a GUI called Motif, which is consistent with the X/Open group's GUI specification for UNIX called X Windows. Motif probably has the best chance of any UNIX GUI to become an industry standard. Nevertheless, a single UNIX GUI in the market is unlikely given the inevitable temptation to use them for product differentiation. Since the differentiating utility of GUIs drops sharply in the presence of standards, the outcome of the GUI standardization battles will be an important factor in the future of UNIX-based systems.[27]

In order for GUIs to make computers more accessible and functional, they need to be used in conjunction with high-resolution displays, preferably with color. High resolution permits a great deal of detailed information to fit on the display and allows the computer to work well with a wide range of display sizes. Color helps the user to differentiate between different types of information on the screen. Because of the extensive use of "windows" in GUIs to represent the various tasks that the computer is performing at any given moment, GUI workstations are easier to use when the display is larger than the conventional 14-inch desktop display.[28]

---

[25] IBM took over further development of the Presentation Manager after its introduction to the market.

[26] More recent Sun workstations feature a GUI called SunView.

[27] See Tekla Perry and John Voelcker, "Of mice and menus: designing the user-friendly interface," *IEEE Spectrum*, 26 (September 1989): 46-51; Michael Faden, "An X/Posé," *Unix Review*, vol. 6, No. 6, 14-25; David Chandler, "Fiat Lux, and There Was the Open Software Foundation," *Unix Review*, vol. 6, No. 7, 16-31.

[28] According to Booz-Allen and Hamilton, Inc., *Competitive and Economic Impact of HDS Technologies on the U.S. Electronics Industry*, Final Report, Phase One, American Electronics Association, High Definition Systems Task Force, (February 21 1990) p. 25, 60 percent of the displays sold by DEC are color and 70 percent of the systems sold by Sun have color displays.

GUIs with full-motion video and audio capability -- a combination now increasingly referred to as "multimedia" computing -- may prove to be especially useful for training people who are using computers for the first time and who may be resistant to learning from screens that display only words, numbers, and other static symbols.[29] Video and audio capability will also make desktop machines more functional for advanced users. A mutually reinforcing relationship is thus established between the development of advanced displays and electronic systems manufacturers trying to make their products both easy to use and highly functional. High-information-content (HIC) displays have the capacity to exploit the potential of multimedia computing, and, in the end, the ability of systems manufacturers to produce functional multimedia will depend on the quality of displays they can incorporate.

In short, whatever their 'soft' strengths, systems manufacturers must still have advanced displays in their products. For them, the pending shift in the supply architecture from open to restrictive is hugely problematic: it matters not just how much the displays cost but whether the most advanced displays are available in a timely manner and whether it will be possible to work with suppliers of displays in integrating system circuitry. If the displays are priced higher on the merchant market than they are for internal use, or if the latest displays are not available or do not permit co-design or joint manufacturing to minimize final product costs, then an important advantage will accrue to those vertically integrated firms that manufacture both displays and systems. Almost no existing U.S. or European systems firm manufactures displays. All of their would-be challengers in Japan do.[30]

III.4. The Strategic Bottom Line

Displays in the next few decades may be as pervasive in manufactured goods as semiconductors have been in the last two decades. There will be opportunities to realize reduced unit costs in displays by increasing manufacturing yields, just as there were in semiconductors. In addition, the cost-reducing and reliability-enhancing effects of progressive integration of circuitry in the various generations of semiconductors (IC, LSI, and VLSI) are likely to occur

[29] This claim has been made by Intel in explaining its purchase of the digital video interactive (DVI) technology pioneered by a group at the David Sarnoff Research Center in Princeton. It is also the position taken by John Sculley of Apple Computer, who calls it "P3TV" (Paradigm Three Television).

[30] IBM -- an important exception -- is manufacturing AM-LCD displays jointly with Toshiba.

again (although perhaps less dramatically) with the progressive integration of circuitry onto flat-panel displays.

Advanced displays will be used in a wide variety of products, because they will eventually make those products cheaper to produce. They will make it possible to create a large number of entirely new high-volume/high-value electronics products -- based on advantages in compactness and lower power consumption. They will increase the user-friendliness and functionality of systems. They will create demand for a new generation of manufacturing equipment and skills.

The parallels between semiconductors and displays are evident, and so are the parallel impacts: as a few vertically integrated firms come to dominate the resulting opportunities, the supply architecture in displays and other component, machinery, and materials technologies will shift to become more restrictive. Critical technological and manufacturing know-how will shift out of the United States and Europe into Asia (especially Japan). A vast array of new markets will likely be exploited first in Asia. And even existing domestic U.S. strengths in systems architecture, design and software, and integration might be undermined.

In our view, significant participation in this industry needs to be a key priority for any nation wishing to remain on the cutting edge of electronics -- even if only for military applications. But what does significant participation entail? Must U.S.-owned firms actually produce advanced displays? Or is it necessary only that such production be located in the United States? Is it simply a matter of assuring access in a timely manner and at reasonable prices to the integrated display-systems products and technologies produced abroad?- The answers to these questions turn in part on the current state of market competition, to which we now turn.

IV. Japanese Leadership in Advanced Display Markets

The current markets for advanced displays are strongly dominated by Japanese firms. As pointed out earlier, these firms are mostly large, vertically-integrated electronics firms, although a few like Hosiden are smaller and more specialized. They largely control the world market for flat-panel displays, valued at $3.2 billion in 1989. This includes all sorts of flat panels, including the simplest monochrome LCDs. The market is projected to grow to $11.7 billion by 1996. Table 1 shows breakdowns of demand for flat panels by type of end-use. Stanford Resources believes that demand for flat-panel displays will grow more rapidly in the computer industry than in any other end-user industry.[31]

The world market for high-information-content displays (i.e., displays with greater than 100,000 pixels) was around $9.6 billion in 1989 -- about 83 percent of the world display market.[32] Television and high-resolution computer monitors are the two largest market segments in the HIC display market. The flat-panel portion of the HIC display market was around $670 million in 1989 (7 percent) and was shared between LCDs and plasma display panels (PDP) with EL displays accounting for only about 2 percent of the FPD total.

The HIC display market is projected to grow to around $23 billion by 1996. Stanford Resources predicts rapid growth in flat-panel HIC displays to $6.9 billion or 30 percent of the HIC display market by 1996 (see Graphs 1 and 2).[33]

CRT displays currently dominate HIC display markets in midsize televisions and in monitors for desktop computers, dumb terminals, and workstations. Flat-panel displays (FPDs) dominate in laptop computers and LCD televisions -- products that can not be made with CRTs. All current LCD-TVs have small (less than 6-inch diagonal) LCD displays. Over 90 percent of portable computers have either LCD or PDP displays. Most of these are the so-called monochrome "half-page" variety, which are 10-inch diagonal.

In the near to midterm future, advanced displays will be most important in televisions, portable computers and workstations, and military electronic systems. The major television manufacturers in Japan and Europe are developing larger LCD displays. In Japan, the goal of one government-industry research effort is to build a one-meter diagonal active-matrix LCD.[34] Digital Equipment Corporation is currently marketing a workstation with 19-inch high-

---

31 This belief is supported by the projection of Nikkei Business Publications Electronics Group in a November 1989 publication that 24 million of the 40 million personal computers to be sold in 1995 will use LCDs -- 8 million AM-LCDs, 8 million multiplexed color LCDs, and 8 million monochrome LCDs. See TechSearch International, Inc., *Flat Panel Displays in Japan: A Compendium of Abstracts of Published Articles on Japanese Developments in Flat-Panel Displays*, (Austin, Texas: TechSearch International, April 1990), p. 1.

32 In this part of the paper, advanced displays and high-information-content displays are treated as synonyms. There is reason to argue, however, that 1 million pixels rather than 100,000 should be the boundary between advanced and conventional displays, since HDTV-quality video requires that many pixels. VGA monitors for computers are capable of displaying 300,000 pixels, and so would be considered to be high-information-content displays under the Stanford Resources' definition.

33 Stanford Resources, Inc. figures cited in AEA Report, *supra*, pp. 10-11.

34 This effort is part of the Giant Electronics Technology program funded jointly by the Japanese Ministry of International Trade and Industry (MITI) and participating firms.

resolution, monochrome EL display, produced for them by Planar Systems.[35] In the next ten years the demand for advanced flat-panel displays will grow more rapidly than the demand for high-information-content CRTs because of their greater compactness, portability, and lower levels of electromagnetic emissions. Prices of large-area color flat panels will remain higher than those for comparable CRT displays for at least a decade, but for the relatively smaller large-area video projector market LCD projectors may be cheaper in just a few years.

IV.1. Major Japanese Producers

Japan controls more than 90 percent of the world market for AM-LCDs, 69 percent of the world market for PDPs, and 29 percent of the world market for EL displays.[36] In addition, Japan controls well over 90 percent of the world market for multiplexed LCDs.[37]. These strengths in advanced flat-panel display production are based on a solid commitment by at least 10 major firms to invest in display research and production facilities for long-term payoffs.

The top thirteen Japanese producers of FPDs are: Matsushita, Sharp, Optrex, Hitachi, Hosiden, NEC, Sony, Seiko-Epson, Toshiba, Sanyo Electric, Seiko Instruments, and Citizen Watch (see Table 2). Other producers are: Fujitsu, Kyocera, Stanley Electric, Shimatori Sanyo Electric, Alps Electric, and Futaba Electronic Industries. Sharp, Hitachi, and Optrex are the largest producers of high-information-content LCD displays. High-volume production of high-information-content LCDs is still mainly in multiplexed LCDs. Optrex, for example, manufactures only multiplexed LCDs for use in equipment panels and cars. AM-LCDs are still too expensive for most high-volume applications, with the notable exception of hand-held TVs and high-end laptop computers. However, all the major systems firms and few smaller firms have made large investments (in the $100 to $200 million range) in AM-LCD production facilities; it is clearly their intention to shift into high-volume production of AM-LCDs as soon as possible (Table 3).

Japanese firms are approaching the switching of AM-LCD pixels from two main directions: thin-film transistors (TFT) and metal-insulator-metal (MIM) diodes. TFT AM-LCDs are more difficult to make but are probably better suited to faster and higher-resolution color displays.

---

[35] Interview with James Hurd, Planar Corporation, Beaverton, Oregon, July 6, 1991.
[36] Office of Technology Assessment, *The Big Picture,* p.70.
[37] David Mentley, Stanford Resources, telephone conversation, February 24, 1992.

MIM AM-LCDs are easier to produce, and therefore lower in price, but less well suited to color, faster speeds, and higher resolution.[38]

Sharp and Hitachi are clear leaders in TFT AM-LCDs. Hitachi is marketing a very high quality 10-inch color AM-LCD for laptops and portable workstations. Sharp is selling 6-inch TFT AM-LCDs for televisions and 10-inch high-resolution monochrome AM-LCDs for computer applications. Sharp has marketed an LCD projector called the XV-100 (for NTSC signals at around $3,000 per unit), and has announced a second-generation product called the XV-120. The imaging source for this projector is a single, full-color TFT AM-LCD. Toshiba is using its joint venture with IBM to become a player in the AM-LCD area, oriented toward use in laptops and portable workstations. It appears to be considerably behind Sharp and Hitachi in this area, a fact revealed by its use of a Sharp display in its high-end transportable.

Hosiden is a smaller firm that previously specialized in the production of switches and connectors.[39] Hosiden was an early developer of AM-LCD technology, starting its research around 1979 with financial support from the Ministry of International Trade and Industry (MITI). Hosiden's main customers for AM-LCDs in Japan have been Matsushita Electronic Industrial (MEI), Nippon Telegraph and Telephone (NTT), and the Japan Aviation Electronics Industry (JAEI). Hosiden is now the main supplier of AM-LCDs to Apple Computer for use in its portable Macintosh computer. Hosiden supplies AM-LCD's to Apple for the model 170 portable computer, which is assembled in Scotland and costs about $4,000.00. Sony is supplying super-twist STN-LCD's for the model's 100 and 140. These run in the mid-$2,000 range. Hosiden began to produce 10-inch color AM-LCDs in a facility at Seishin designed to produce about 30,000 units per month early in 1990. Hosiden is focusing on the computer market and will not produce consumer products or projection displays. They use custom-made production equipment and are trying to maintain their lead through innovations in process technology.[40] However, Hosiden's considerably smaller scale makes it less likely that the company will be able to keep up with the investment race.

---

[38] TechSearch International, p.11.

[39] See table 2 for Hosiden's place among Japanese LCD manufacturers. Hosiden's current sales average between $50 and $100 million per year (50 billion yen in 1990). David Mentley, Stanford Resources, telephone conversation, February 24, 1992.

[40] See *Japan Company Handbook: First Section Firms*, (Osaka: Spring 1990), p. 692; Etsuro Ogisu, *Liquid Crystal Displays (LCDs): LCDs in, CRTs out?*, (London: UBS-Philips and Drew, October 18, 1989).

While the main Japanese R&D effort focuses on incrementally improving multiplexed LCDs and developing new AM-LCD technologies, a number of firms have invested in alternative flat-panel and projection technologies. Futaba Corporation is the most important player in vacuum fluorescent displays (VFDs). Matsushita and Oki are competitors in the international markets for monochrome plasma displays. IBM uses Matsushita plasma displays in one of its PS/2 portable machines. Matsushita is active in research on ferroelectric liquid crystals for light-valve projectors and on field emission displays. Sharp is the only major Japanese firm in the EL market.[41]

Some of the firms that were initially quite strong in LCDs were watch and calculator firms like Casio, Citizen, and Seiko-Epson. While Seiko-Epson seems to have made the transition to HIC displays, innovating early and successfully in the technologies for integrating driver circuitry on the LCD substrate, Citizen and Casio have not done so well. But Seiko-Epson was unable to deliver as promised a blue-mode HIC display to a small California firm called Dynabook Technologies, so the latter switched to Hitachi.[42] Citizen and Casio have chosen not to develop AM-LCDs.[43]

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. For example, 1)Asahi and Nippon Sheet Glass make glass substrates for flat panels; 2)Nikon makes large-area steppers; 3)NEC Anelva makes dry etching equipment; 4)Nitto Denko makes color filters and polarizers; 5)Dai Nippon Printing and Toppan Printing make advanced printing equipment for large-area flat panels; 6)Japan Vacuum Technology makes Indium Tin Oxide (ITO) films for transparent conductors; 7)Canon makes mirror projection systems; and 8)a variety of firms make fluorescent backlights. Even where Japanese firms are not strong, as in the manufacturing of liquid crystal chemicals, gray-scale drivers, and high-performance glass, foreign firms have located in Japan or formed joint ventures with Japanese firms to service the local market. Examples of this phenomenon include Merck Japan, Texas Instruments Japan, and Corning Asahi Video.

---

41 Sharp briefly funded a small American firm called Amtel Video in its efforts to produce a white-light modulator called "crystal scan" (see section on American firms below).

42 Interview with Dan Evanicky of DynaBook on August 14, 1990.

IV.2. Japanese Government Policies

Japanese government interest in high-resolution displays originally stemmed from a desire to improve existing computer monitors so that they could display legible kanji and kana characters along with the usual ASCII characters. The Pattern Information Processing System (PIPS) program from 1971 to 1981 was the first major government program that included funding for high-resolution monitors and displays. PIPS focused mainly on the problem of electronically representing a sufficient number of easily recognizable kanji and kana characters. This work was crucial, however, for motivating the subsequent research on high-resolution displays. Total funding for the PIPS program was 22 billion yen and most of the work was carried out at the Electro-Technical Laboratory, run by MITI's Agency of Industrial Science and Technology.[44]

With the transition in consumer electronics to high-definition products, the Japanese government has instituted a variety of R&D programs to support the work of the public broadcasting network NHK and manufacturing firms. Two programs are aimed directly at advanced displays: 1)a 7-year $100 million collaborative research program to build a 1-meter diagonal color flat-panel display for HDTV and 2)a similar program to support the development of a high definition LCD projector. The flat-panel project is co-funded by MITI, the Ministry of Posts and Telecommunications (MPT), and the private firms that belong to the Giant Electronics Technology Corporation (GTC). The core corporate members are: Dai Nippon Printing, Hitachi, NEC, Sharp, and Toppan Printing. Government funds derive primarily from proceeds of the sale of NTT shares, tobacco taxes, and motorboat racing fees. As mentioned briefly above, the GTC effort focuses on the use of printing technologies in conjunction with polysilicon processing techniques to manufacture large-area AM-LCDs. In typical and complementary bureaucratic rivalry, the projector project is funded by the Ministry of Posts and Telecommunications (MPT).[45]

The Japanese government understands that the manufacturers are already strong in this area, so the various agencies are not expending large sums of money. Nevertheless, they are trying to

---

[43] Ogisu, p. 4. Citizen is assembling a laptop model, an LTE, for Compaq in Japan; it uses super-twist LCD technology. In the future, it may move to AM-LCDs, or it may use improved super-twist LCDs. Conversation with Dave Mentley, Stanford Resources, Inc., February 24, 1992.
[44] Ezra Vogel, *Comeback*, (New York: Simon and Schuster, 1985), pp. 142-3.
[45] *The Big Picture*, pp. 68-9.

push the firms to develop larger displays so as to make it easier to sell the products associated with high-definition TV (HDTV). The research involved is ostensibly "precompetitive" in that the focus is on generic technological advance in displays and none of the items involved is near immediate commercialization. Again, true high-definition LCD projectors are still several years away from introduction to the market; large-area AM-LCDs are probably 7-10 years away from introduction.

IV.3. Major European Challengers

Despite their established presence in video consumer electronics, the major European electronics players are far behind the Japanese in the development of advanced displays. The major European firms involved in research on advanced display technologies are: Philips, Thomson, Finlux (and its subsidiary, Lohja -- now a division of Planar Systems), Thorn-EMI, AEG, Hoffmann-LaRoche, GEC, Barco, and Olivetti (in a joint venture with Seiko Instruments). Two national laboratories in France, CNET and LETI, have display research teams. In Germany and the United Kingdom, a number of university teams are working in this area as well. The two biggest players are the two consumer electronics giants -- Philips and Thomson.

Philips is using its laboratories in the Netherlands (Eindhoven) and in the United States (Briarcliff Manor, New York) to develop AM-LCDs and driver circuitry for advanced displays. Philips recently demonstrated a 6-inch diagonal diode-addressed full-color LCD. It is not encouraging, however, that Philips has now moved development of small diameter LCDs out of Eindhoven to its Marantz subsidiary in Japan. This move is an acknowledgment of Philips' relative lag in commercialization of advanced displays. Perhaps more important, the move acknowledges that to access the best display know-how, a firm must acquire the skills and supply base now resident only in Japan. This new truth is also born out by IBM's similar venture with Toshiba.

When Thomson purchased the consumer electronics operations of GE in 1987, it also acquired the GE process for making amorphous silicon AM-LCDs. These AM-LCDs developed by GE were designed for military applications rather than consumer applications. Thomson has continued to produce AM-LCDs for military applications and sells them in the United States through a joint venture called Sextant-Avionique. Thomson has pulled back from developing AM-LCDs for consumer products and has put its resources instead into AC-plasma and cold cathode displays, peripheral driver circuitry for AM-LCDs (work done mainly at the David Sarnoff Research Center in Princeton, New Jersey), and improved CRT technology.

There is a Philips-Thomson-Sarnoff research consortium for AM-LCDs under consideration at the present time. The negotiations for this consortium have been underway for over a year. It is likely that the consortium would apply the Thomson-Sarnoff work on peripheral circuitry to Philips' AM-LCDs. It is unlikely that a viable venture will emerge from these negotiations, as both Thomson and Philips are currently suffering financial difficulties. The fact that the negotiations took place indicates that neither Thomson nor Philips is confident about their ability to produce AM-LCDs on their own.

Lohja-Finlux has developed some innovative EL displays. They are apparently working on using a cadmium selenide AM-LCD to drive an EL display. They have also been active in applying atomic layer epitaxy (ALE), a relatively new form of chemical vapor deposition, to the manufacturing of EL displays. Lohja-Finlux was recently acquired by Planar Systems, a small American firm that dominates world markets for EL displays.

The European Community has been funding research in high-definition technologies through the Eureka-95 program--the main participants being Philips, Thomson, Nokia and ITT-Intermetal. Eureka-95 has been dedicated to the production of prototype equipment for European high-definition standards: 1250/50 for production and HD-MAC (multiplexed analog components) for delivery. In a clean division of labor, Thomson is building the front end, Philips the bandwidth reduction and picture improvement electronics; Nokia is building the scrambling electronics, and Intermetal is working on the HD-MAC chip-set. Several pilot high-definition sets have been developed including direct-view CRT's by Philips and Thomson, a rear-projection model by Philips, and a front-projection system by Italy's SELECO. However, the Eureka project has been plagued by several political problems (especially resistance by several European broadcasters to the D-MAC standard) as well as the failure of several participants to meet technical development deadlines (notably Intermetal's problems delivering the promised chip-set). The Europeans are aware of their relative weakness in display technology and are trying to catch up to Japan, but, like the Americans, and as the Eureka troubles indicate, they have a long way to go.

IV.4. U.S. Efforts to Stay in the Game

As Table 4 indicates, the main U.S. firms involved in advanced display technologies are: IBM, Xerox, Texas Instruments, Hughes Corporation, Tektronix, Raychem (including its subsidiary Taliq), Planar Systems, Greyhawk Systems, Optical Imaging Systems (OIS), Plasmaco, Photonics Systems, Magnascreen, Electro-Plasma, Cherry Display Products, Coloray, Amtel Video, Nitor, Hamlin-Standish, and Projectavision.

Except for the first four firms listed, all of these firms are small. The commitment of the larger firms to move to high-volume manufacturing is extremely limited. Of the smaller firms, few have the resources or technical know-how to move to viable volume production. Only Planar Systems, Greyhawk Systems, Hamlin-Standish, and Plasmaco are producing displays in mid- or high-volume facilities. Coloray, Magnascreen, Nitor, Projectavision, Tektronix, and Amtel Video are still working on prototypes. The rest have produced in low volumes for customers with specialized needs, primarily contractors of the Department of Defense.

IBM's effort is primarily in a joint venture with Toshiba, already mentioned in the above section on Japan. Although there have been rumors about IBM's desire to establish an AM-LCD production facility in the United States, these rumors do not seem to be well founded.[46] Xerox is working on applying new poly-silicon fabrication technologies to high-volume production, both in its Japanese subsidiary, Fuji-Xerox, and in an American joint venture with Hamlin-Standish. Texas Instruments is developing a display based on "deformable mirrors". Hughes is attempting to use its light-valve technology, developed for military applications, in commercial video projectors. None of these large firms, however, is involved in even low-volume production of flat panels or projection displays. And major potential customers of all of them (except perhaps of IBM) doubt whether even these larger firms have the corporate commitment and technical skills required to move into volume production if their approaches prove viable.[47]

In addition to these individual corporate efforts, there are several consortia efforts rumored or in progress. The aforementioned activity under European auspices at the RCA-Sarnoff research labs is one. SRI international has been in discussion for some time with a variety of partners, although this effort seems likely to fall short. A consortium effort has been driven by

[46] See Elizabeth Corcoran, "Flat Horizons: U.S. Pursues Research But Little Development of Advanced Screens," *Scientific American*, June 1991, pp. 112-114. Several well-placed sources at IBM have flatly maintained to us that IBM is not establishing such facilities in the United States.
[47] Based on industry sources.

Craig Fields under Microelectronics & Computer Technologies Corporation (MCC) auspices. Given MCC's checkered track record, however, it is reasonable to question whether this effort will succeed. In a related development, Microntechnology bought a small stake in Coloray on January 17, 1992. According to Charles Antony, CEO of Coloray, he now has a chance to get his product out of labs and into the market.[48] In our view, none of these efforts are likely to develop into sustainable, high-volume domestic production capability.

U.S. firms do have some important strengths from which it may be possible to build an advanced display industry. Planar Systems, for example, is the world market leader in monochrome EL displays. If it can develop EL color displays at reasonably low prices, then it might be able to compete with Sharp, its main competitor in Japan. Coloray is developing an innovative approach to manufacturing cold cathode displays, which, if successful, will produce more compact, bright, and energy-efficient displays than those made by AM-LCD producers. Photonics is keeping up with Matsushita and Thomson in inventing color plasma displays. As mentioned before, Tektronix has come up with a method of using gas-plasma to actively address LCDs without using either transistors or diodes to switch the pixels. Greyhawk Systems has a patented system for X-Y laser addressing of LCDs, which can produce very high-resolution images for flat-panel or projection displays. Amtel Video has developed a unique approach to modulating white light for video projection. Nitor will have access to inexpensive red, green, and blue lasers from Spectra Physics. And Projectavision has figured out how to remove the pixel structure from LCD projectors. Each firm has something to add to solving the difficult technological problems of making advanced displays.

However, each U.S. firm, even the large ones, is quite vulnerable to competition from Japanese firms, which have a lot of experience with high-volume manufacturing, access to patient capital, strength in a broad range of display technologies, and the willingness and ability to predate to preserve their market positions. As the anti-dumping petition indicated, none of the smaller, innovative U.S. firms can match this competition in the absence of correctives to the U.S. business environment. Moreover, given the asymmetrically easy access major Japanese firms have to the domestic U.S. technology supply base, it is easy to envision Japanese firms acquiring or becoming predominant partners with any of the smaller firms whose technological

[48] John Carey with Robert D. Hof, "Meet Silicon Valley's New Screen Hopeful," *Business Week*, February 3, 1992, p.32.

innovativeness would threaten established Japanese market position. Indeed, several of the U.S. firms with innovative approaches, like Amtel, have been being funded by Japanese firms wishing to hedge the risks of their own development efforts.

As a result of entrenched Japanese competition conjoined with the lack of domestic skills and resources, most U.S. systems firms have simply abandoned the advanced display industry. Table 5 lists the U.S. firms that either closed a flat-panel production facility or sold one prior to 1990. The list includes many large systems firms: e.g., AT&T, Control Data, Exxon, GE, GTE, Hewlett-Packard, IBM, NCR, and Texas Instruments. Individually, each of the involved firms provides apparently reasonable justifications for their abandonment of this market. Common justifications include, among others, the belief that advanced displays are not central to the strategy of the firm, calculation that capital requirements for world-class manufacturing are too large a proportion of the total capital investment of the firm, and simple fear of Japanese competition eliminating profitability.

Most often, however, these firms are motivated by one or both of the following beliefs: 1) advanced displays can be purchased on the open market at reasonable prices without fear of delays or interruptions in supply -- i.e., that an open and accessible merchant supply architecture in displays will exist; 2) the firm can cut for itself a defensible and reliable supply deal with a major Japanese supplier, even if other firms will be victimized.

These perceptions on the part of the managements of many major U.S. firms are individually legitimate. They smack, however, of similar justifications heard time and again in other industries, beginning with consumer electronics producers like GE and RCA who became dependent on their Japanese competitors for similar, apparently justifiable reasons. We believe these justifications are shortsighted because they do not fully take into account the ambitions of Japanese firms to compete in a wide variety of markets for electronic systems and the historical record of Japanese competitive strategies in semiconductor and other supply-base markets. Moreover, even if their actions work for individual firms, *there is no guarantee that the domestic U.S. economy will retain the advanced display know-how and production activities necessary to assure domestic capabilities for defense and other needs in this critical area of rapid, cumulative technological advance.*

In our view, then, systems firms in both the United States and Europe will grow increasingly dependent on the supply of high-value-added components from their Japanese competitors.

They will fail to exploit a host of new maret opportunities and are likely to lose market share in products that share manufacturing know-how and scale economies with integrated display systems. Defense agencies in both regions will be unable to purchase inexpensive advanced displays from locally-owned vendors and will have to choose between higher average procurement costs for military electronic systems or greater dependence on Japanese vendors for components. Furthermore, U.S. and European electronics manufacturing, particularly in the areas of semiconductors and systems assembly equipment, will continue to erode.

V. American Responses: What Is To Be Done?

American national security and international economic competitiveness have depended in the past -- and will continue to depend in the future -- on maintaining a leading position in advanced electronics. In our view, that will be an increasingly difficult task because of the shifting architecture of supply of underlying components, materials, and machinery technologies -- illustrated here by our analysis of the advanced, high-resolution display industry.

As the architecture of supply shifts from relatively open to closed, from competitive to oligopolistic, from dispersed to concentrated, there are two primary effects on the U.S. position in electronics. Technological production activities and the associated electronics know-how are moved out of the U.S., thereby eroding the competitive potential
architecture shifts, will become zero-sum. Foreign competitors now increasingly dictate the terms of access to advanced technologies, the timing with which U.S.-based producers can incorporate those technologies into advanced products, and the price U.S.-based producers pay for the privilege.

As the U.S. position in electronics erodes, the United States loses far more than a major source of jobs and wealth. America is ceding to competitors abroad a defining characteristic of its national economy in the 20th Century: the ability to shape its own technological destiny. Reversing this potentially dire constraint will not be easy. Here, we can at best suggest the outline of the necessary response.[49] There are two components, an external focus aimed at maintaining an open and internationally accessible global supply base in electronics and other high technologies, and an inward effort aimed at maintaining leading-edge production activities

[49] However, we hope to develop this conclusion at length into a separate paper in the near future.

and know-how within the borders of the domestic U.S. economy. We briefly examine each in turn.

V.1. Ensuring Access Abroad[50]

Ensuring access to the electronics supply architecture that increasingly resides abroad will require fundamental changes in the post WWII U.S. approach to trade policy. The reason lies in the contradictory aims and actions of those who increasingly control the supply base, especially in Asia. In principal, every economy wants access for its firms to markets, technology, and investment opportunities in partner economies. But many Asian economies, and especially Japan, also want considerable control over foreign behavior in their domestic markets. That control may come by government restriction as in Korea, or, as in Japan, by sharp limits on the ability of outsiders to buy into existing groups or participate in market privileges. The desire for unrestricted access abroad while maintaining restrictions on foreign practices at home can only be maintained so long as Asia's trading partners tolerate the game.

This problem lies at the heart of the contemporary U.S.-Japan disputes over trade and investment. It is crucially important to emphasize that the disputes are not about the formal principal of freedom of access -- which has been the focus of U.S. trade policy toward Japan for close to three decades. Rather, the disputes are about the impacts and meaning of domestic Japanese policies and business practices that are not transparent and that implicate desires for national and regional autonomy in development. For example, domestic Japanese policies to accelerate productivity by supporting technological innovation are difficult in practice -- perhaps impossible -- to distinguish from strategies to create market advantage. Policies to promote the domestic diffusion of technology easily emulate mechanisms that support domestic producers at the expense of imports. In technology industries characterized by scale and learning economies in which costs drop dramatically as volume increases, Japanese forward pricing strategies are indistinguishable in practice from dumping.[51]

---

[50] This subsection is partly drawn from Michael Borrus, Wayne Sandholz and John Zysman, "Epilogue," in Sandholz, Borrus, Zysman, et.al., *The Highest Stakes: The Economic Foundations of the Next Security System*, (New York: Oxford University Press, forthcoming, 1992).

[51] Forward pricing occurs when a firm prices below current costs in anticipation of generating sufficient demand to push actual production costs down below the price target. Dumping is selling below a fair market value.

Judging whether such domestic practices and policies are simply idiosyncratic or are illegal barriers to trade requires inquiry into intent and effect. Three decades of fruitless trade negotiations have revealed that the current U.S. approach to trade cannot adequately cope with either the inquiry or its effective resolution. It is time to move beyond the typical U.S. focus on transparent and fair processes, imposing legal constraints on administrative discretion, and eliminating practices that differ from U.S. norms. The past decade has shown that the only trade policy that works with Japan is a results-oriented policy -- one that focuses on negotiating substantive outcomes that are precisely specified, like specific import market shares in particular industries or specific investment targets.[52] That such an approach works has been demonstrated at least in part by the Semiconductor Trade Agreement, the opening of foreign procurement by Nippon Telegraph and Telephone, the reservation of Japanese radio spectrum for Motorola products, and the granting of retail licenses to Toys R Us.

Resolving the access problem, then, will require a managed solution with at least two features. The United States needs 1)to insist on strict reciprocal access to regional markets, investment opportunities, and supply base technologies; and 2)to delimit international standards for appropriate industrial practices and policies. First, reciprocal access to markets, investment opportunities, and underlying technologies is the only possible policy in this area: when know-how and markets for new technology cluster regionally and progress is driven by scale and learning, whoever has the broadest access to all three regions will likely end up dominant. Or, to put it another way, if we have access to three-thirds of the world's storehouse of technologies relevant to our industry and you have access only to two-thirds, we are likely to win over time. Reciprocity of access permits as much openness as each regional economy can tolerate politically and forces compromises in domestic practices that impede access whenever domestic industries seek foreign market opportunities.

Second, however, the principal can only be enforced by reaching some degree of agreement over which domestic business and policy practices are appropriate international conduct. Multinational codes of behavior are very difficult to negotiate and historically problematic to execute and enforce. Rather than itemizing individual industrial behavior, it will probably be

---

[52] On this point, and for a coherent argument in favor of managed trade, see BRIE's Laura D'Andrea Tyson, *Who's Bashing Whom*: *Trade Conflict in High-Technology Industries*, (Washington D.C.: Institute for International Economics, forthcoming, 1992).

necessary to limit the impacts of disruptive foreign access practices by directly negotiating the interests involved. That is, wherever access-impeding practices are alleged and proved, resulting market shares of the advantaged industry ought to be limited by agreed rule of thumb. For example, at least half of domestic consumption, but no more than 50% of global production, ought to be produced locally (with full local value-added). Foreign direct investment, monitored to assure compliance, would be the vehicle to adjust market shares. This would bring significant local production back into the economy that had been disadvantaged by the restrictive practices of its trading partner, would still reward innovating industries, but would simultaneously help to harmonize foreign disruptive practices with U.S. norms of behavior.

Gaining such reciprocal concessions abroad will require further changes in U.S. practices. Consider that we would never have negotiated for arms control the way we currently negotiate for trade concessions -- by adhering only to abstract principle and disarming in pursuit of it. Instead we engaged in a massive arms build-up and then reciprocally negotiated concessions. The same approach is likely to be the only effective approach in the current trade climate. Only by engaging in some systematic practices to create domestic advantage will we be sufficiently armed to reciprocally bargain away practices and policies abroad that disrupt the functioning of an open world economy. Indeed, it was precisely the mutual concession of reciprocally lowering tariff barriers that drove the success of the first 6 rounds of tariff reduction in the Multilateral Trade Negotiations (MTN) under GATT auspices through the 1960s. In the 1970's and 1980s, the MTN floundered as interventionist practices accelerated abroad only because the U.S. had few such practices to concede in return for the concessions it wanted from others.

V.2. Redevelopment at Home

Managed external access will thus prove ineffective -- indeed, may not even be achievable -- without continuing strength backed by activist policies at home. There is a surprising amount of agreement among analysts of all political persuasions as to what needs to be done at home. The normal catalogue includes: stable fiscal and monetary policies; encouraging productive investment and savings over consumption; favoring long-term financial holdings over short-term financial transactions; and massive reinvestment in infrastructure and education.[53] Slightly more controversial, but endorsed here, are targeted policies to: 1)assure cutting edge development of technology and best industrial practices at home; 2)develop the mechanisms for the diffusion of advanced technology and practices throughout domestic industry; and 3)provide a capacity to absorb technology and best practices developed abroad.

In addition to continuing to fund new technologies developed at home, we can effectively ensure that leading-edge technologies and know-how reside in the United States in only two ways: by redeveloping what has been lost or by repatriating what has gone abroad. Several existing U.S. policies, from those aimed at aggressive technology development at DARPA and NIST to regaining chip leadership via Sematech, aim at redevelopment of the capabilities of *U.S.-owned* enterprise. That route is necessary, if merely to keep *foreign-owned* suppliers honest in the market. It is, however, an extremely expensive route for an economy burdened with severe budgetary constraints and debt. There is also no guarantee that U.S. firms can acquire in a reasonable time-frame the relevant know-how that has been developed abroad through decades of continuous re-investment and learning. As a result, the United States also needs to think about ways of re-patriating into the domestic economy foreign technologies and best practices.

This will likely require carefully targeted policies toward foreign direct investment that encourage foreign producers to transplant the full gamut of their most advanced activities into the United States. So long as the activities are resident in the U.S. economy and the domestic markets are open and competitive, foreign-ownership ought not to matter. This is a strategy that has been pursued effectively by other countries in similar situations in other industries -- notably by the Europeans in the automobile industry from the 1950s on. Conversely, the worst possible policy would be to deny the domestic economy foreign know-how that would otherwise benefit domestic growth and enhance productivity. Yet that is precisely the impact of current U.S. policy. Consider the characteristic remedy that was granted domestic flat panel display producers in their dumping suit against Japanese display firms: an anti-dumping tariff on the display component.

[53] For details, see, among many other sources, Stephen S. Cohen and John Zysman, *Manufacturing Matters*, (NY: Basic Books, 1987) and Michael Dertouzas, et.al., *Made in America: Report of the MIT Commission on Industrial Productivity*, (Cambridge: MIT Press, 1989).

Anti-dumping tariffs raise the price of the display component to U.S. electronic systems firms that produce products incorporating it. The tariff remedy disadvantages U.S. notebook computer firms. For example, since the tariff mandates that U.S. firms pay more than their foreign competitors for the display component, they must therefore charge higher prices in the notebook market (or forego higher profits). Since imported notebooks are not subject to the same tariff on the embedded display component, U.S. firms ultimately lose market position. Similarly, the remedy buys at best a modest amount of time for the struggling U.S. display firms that brought the suit, but it does not even begin to address their real, fundamental needs for substantial investment capital and the know-how to enter high-volume manufacturing. Worse still, by tariffing only the display component rather than embedded displays -- that is, by failing to impose comparable tariffs on imported notebooks containing the display component -- the remedy actually creates an incentive for U.S. notebook producers to move production activities off-shore. They can avoid the tariff by importing the entire notebook computer from off-shore affiliates or sub-contractors, rather than by just importing the display component. The U.S. economy is the ultimate loser: when domestic producers like display firms and notebook computer manufacturers lose market position, the domestic economy eventually loses production operations and comes to rely on advanced activities and know-how that reside only abroad.

What if the remedy had been to bargain with the Japanese defendants, playing one off against the other, to bring advanced display know-how and production into the United States via foreign direct investment from some of the Japanese firms like Sharp or Toshiba? U.S. notebook producers would have benefited from increased local supply without increased component prices (since the tariff would have been avoided). The domestic economy would have benefitted by gaining new productive investment, manufacturing activities, and technological know-how. Even the domestic display manufacturers, who stand the most to lose under this scenario, could have been adequately advantaged. U.S. display firms could have benefitted by acquiring know-how and investment capital if the negotiated form of foreign direct investment was volume production joint ventures in which those display firms were guaranteed some control and participation.

While undoubtedly controversial, this kind of policy is illustrative of what the United States needs to do to regain a measure of autonomy and control over its own technological destiny. The shifting supply architecture (and the asymmetrical access to technologies it portends) is already altering the terms of competition in advanced electronics. In our view, doing nothing or simply muddling along will hasten the day when America's technological future is controlled largely from abroad. Despite its conservative appearance, doing nothing is in fact the most radical alternative because it risks the greatest loss of autonomy. The apparently more radical alternative of taking aggressive steps to safeguard the future is really the conservative thing to do, for it ensures that Americans will continue to control their own destiny.

Appendix A:
Reports on Activities of Specific Firms

This appendix contains reports on site visits and interviews with representatives of the following firms or laboratories: Planar Systems, Greyhawk Systems, Projectavision, Plasmaco, Nitor, Xerox PARC, Coloray, Amtel Video, and the David Sarnoff Research Laboratory.[54]

Site Visit to Planar Systems

Location: Beaverton, Oregon
Informant: James Hurd (President and CEO)
Date: July 6, 1990

Planar is the world leader in sales of electroluminescent (EL) displays. The firm produces around 25,000 displays in 1990 and expects to produce 40,000 in 1991. Total sales in 1990 were around 12 million dollars. Most of the displays sold are used in high-end medical and computer applications. Only about one million dollars (8 percent) of sales are for military applications. Planar EL displays are high resolution, high contrast, low in power consumption, and have a wide viewing angle. As a consequence, customers are willing to pay a premium for EL displays over other types of flat panels.

The majority of the displays sold in 1990 were the 10-inch displays familiar to users of laptop computers. Grey scaling is still primitive for EL. Some military customers of Planar (Norden and CLC) use 16-level grey-scale circuitry to drive the displays they build themselves using Planar glass panels.

Planar was founded in 1985 by James Hurd, who had previously worked for Tektronix (also located in Beaverton). The Oregon Graduate Center provided some equipment and space for the Planar facility in exchange for the benefits that would accrue to the Center in attracting other high technology businesses to the area and in providing students access to leading-edge technologists.

So far, all the displays sold by Planar are monochrome. Technology for displaying color images is still in the experimental stage. Funding from DARPA has made it possible for Planar

[54] These interviews were conducted by Jeff Hart. None of these reports are for circulation beyond DARPA or BRIE personnel.

to set up a small laboratory, of about 3-4 engineers, to work on developing the necessary phosphors for color EL. The main problem seems to be getting a good phosphor for blue (red and green phosphors are already available and acceptable in performance). I saw a working example of the blue phosphor (some calcium salt) during my visit, and it appears that they are on the way to solving this problem.

Prior to the DARPA program on high-definition displays, the main commercial incentives for the firm were pushing them to develop larger and higher resolution monochrome displays. For example, the firm now makes a 19-inch display for Digital Equipment Corporation and has been asked to develop a 24-inch display for Apollo. One of the corporate goals is to produce a 40-inch 2,000 by 2,000 pixel display. Hurd's view was that the demands imposed by developing larger monochrome displays and the risks in developing color phosphors were such that it would have been impossible to fund a color research effort without the kind of long-term perspective that was embodied in the DARPA display effort. When the Bush Administration's began wavering on the DARPA program, Planar was able to get additional financial assistance for its color research from Boeing Corporation and the Department of the Army.

The visit started with a tour of the production facilities. The EL displays produced at Planar begin with contact printing of the lines for the first conductor which is etched on the upper side of the lower glass plate of the display. Then a thin film of dielectric (silcon dioxide) is deposited, followed by a light emitting film (zinc sulfide manganese), followed by another thin film of dielectric and topped by a glass plate with a second conductor (at a 90 degree angle to the first conductor) facing down. All the lithography and deposition is done in a small clean room. All other processing, including coupling of the two glass plates, is done outside of the clean room.

Optical Radiation Corporation of California makes the contact printer in use at Planar, while the deposition equipment (two standard units and one specialized unit) was purchased from a German firm -- Leybold-Heraeus -- and then customized for EL production by Planar. Leybold-Heraeus has specialized in large-area deposition equipment. Many of its customers are in the architectural glass business, but it also sells equipment for manufacturing magnetic disks.

The process for producing the glass plates is highly automated, smaller plates are processed two at a time, and the yield is around 80 to 90 percent. The plates are assembled manually (using two televisions for positioning and a metal clip to make contacts via an epitaxial strip) and then tested for 24 hours before moving on to the next stage of the process -- attachment of the printed circuit board with driver circuitry to the back of the display.

Site Visit to Greyhawk Systems, Inc.

Location: Milpitas, CA

Informant: Dr. Frederic Kahn (Vice President, Physical Technology)

Date: July 17, 1990

Greyhawk Systems is a six-year-old company specializing in the production of very-high-resolution imaging products. Its main products are projection systems for previewing high-resolution computer-generated graphics. Its first commercialized product was the SoftPlot, a rear-projection display, 22 inches by 34 inches. The SoftPlot is capable of displaying 4,000 colors at 16 levels of grey. They began development of this product in January 1985 and showed a demonstration version in May 1986. The SoftPlot originally accepted inputs only in the Hewlett Packard Graphics Language (HPGL) format and allowed users to preview the output of an HPGL file prior to sending it to a hardcopy device. As of 1987, a newer version of SoftPlot could display any type of raster graphics, with 4 million colors (24-bit color). The newer version sold better than the original, although most customers continue to use software in the HPGL (vector) format rather than **raster-graphics** (is this correct) software.

Site Visit to Projectavision

Location: Westbury, New York

Informant: Eugene Dolgoff (President and CEO)

Date: October 16, 1990

Projectavision is a start-up firm which has produced prototypes for LCD projectors which are smaller, lighter, and possibly cheaper than the LCD projectors sold by Japanese firms. Its main contribution to LCD projector technology is maintaining high image quality while eliminating the pixel structure of AM-LCD imaging sources. The firm has additional strengths in optical technologies for concentrating and projecting white light. It is dependent on outside firms for its LCD imaging source, however, which may prove to be a critical weakness. If Projectavision can overcome its vulnerability in this area, it has a chance to become a serious competitor in markets for projection systems.

Projectavision has a very unprepossessing headquarters in a small building on a busy street in a remote part of Long Island. It has a laboratory in the back of the building for testing the ideas of its founder and key employee, Eugene Dolgoff. Dolgoff is an independent inventor who has been working since 1964 in holography and coherent optics. His original goal for displays was to build a laser projector. He used helium-neon, and then argon and krypton lasers to get full color scanned images. He abandoned lasers when he found them to be impractical and dangerous. In the 1970s, he turned to light-valves as a safer alternative. He experimented with lead zirconium, lithium niobite, nitrobenzine, and liquid crystals, and by the end of the 1970s settled on liquid crystals as the best material.

The problem with light-valves was finding a good system for addressing the pixels. Dolgoff worked with electron beam scanning and multiplexing, but it was not until AM-LCDs were available -- around 1984 -- that it was possible to use LCDs as the imaging source for a video projector. Dolgoff built his first prototype in that year using a Seiko-Epson AM-LCD.

In April 1985, Dolgoff tried to negotiate a joint venture with Seiko-Epson to produce LCD projectors. The three representatives that he met with (two Japanese, one American) signed a nondisclosure agreement in order to see Dolgoff's technology. They told Dolgoff: "We don't know about optics, we'll let you know." Six months later, Seiko-Epson produced a prototype LCD projector remarkably like Dolgoff's and took it around the United States looking for a joint venture partner to produce it. Kodak's LCD projector apparently owes its origins to that sequence of events. When they announced the product in September 1988, Dolgoff sued Seiko-Epson and Kodak for violation of the nondisclosure agreement. Kodak stopped selling its LCD projector soon after the filing of the suit. The suit is still pending.

In early 1986, Dolgoff had built a second prototype. By 1987, his third protype was ready. The second and third prototypes were financed by Dolgoff out of his personal funds. He showed the third prototype in 1988 to Marvin Maslow, who was then an Executive Vice President at Schlumberger. Maslow wanted to fund Dolgoff's further efforts. He became CEO and Chairman of the Board of Projectavision. Maslow brought in Martin Fife, a member of the board of a number of Dreyfus Funds. Fife was the first private investor with an initial investment of $100,000. Fife became Vice Chairman of the Board, and head of the Executive Committee of the firm. Howard Ladd, former CEO of Fisher and later Chairman of the Board of

Fisher-Sanyo after the merger of those two firms, joined the Executive Committee of the Board of Projectavision in 1989. He will be handling consumer marketing for the firm.

The management of Projectavision approached a brokerage firm to raise more capital and succeeded in procuring a million dollar private placement, most of which was used to build the fourth prototype (Model IV). Rosenkrantz, Lyon, and Ross managed Projectavision's recent initial stock offering just before the onset of the crisis in the Persian Gulf. This ISO raised $4.2 million in July 1990.

When the DARPA Broad Area Announcement was mentioned in the *New York Times* in December 1988, Dolgoff put in a blind call to DARPA for more information. He managed to get through to William Bandy, one of the main assistants to the Director of DARPA, who asked him to come to Washington to demonstrate Model III. The DARPA people were delighted to see that an American firm had a working prototype projector and responded accordingly when Projectavision filed a proposal for funding of its display efforts.

DARPA has been an important backer of Projectavision beyond the decision to grant the firm funds under the display project. Projectavision was the first company to receive DARPA money in 1989, initially taken out of the agency's internal funds because of the delays in Congressional and OMB approval of the high definition project. When the DARPA funds were frozen by Bush Administration opponents in 1989-90, Projectavision joined the American Electronics Association in order to help get the funds released. In 1989, DARPA personnel introduced the executives of Projectavision to the principles of Alphasil, in order to find out whether Projectavision had the funds to purchase Alphasil's AM-LCD operations from Honeywell. But Projectavision did not have the funds, and Honeywell decided to sell the facility [see reports on Coloray in Appendix A and Alphasil in Appendix B]. After he left DARPA in May 1990, Craig Fields agreed to be on Projectavision's Board of Directors. One of Fields' deputies, Michael Marks, became an Executive Vice President of the firm in the summer of 1990.

Projectavision recently was granted a U.S. patent for its liquid crystal video display system, although it is still waiting for an issue number. The most important part of the patent includes some unique methods for converging the separate red, green, and blue dots from the LCD imaging source into a single dot on the screen (this was referred to earlier as eliminating the pixel structure) and making it impossible to see the black matrix that surrounds the AM-LCD pixels on the screen. The patent deals also with the methods of concentrating light, electronically biasing pixels to counteract effects of LCD heating, stepping LCD cavities to get a pure black, cooling the display, and using dichroic mirrors instead of color filters to get colors. Patents have also been granted in Spain, Trinidad and Tobago. Patents have been applied for in Japan and 40 other countries.

Projectavision's next patent involves polarizers that use a new optical element that reduces the loss of brightness in the projected image. Dolgoff is also working on a method to reduce the noise from cooling fans that goes with most projector systems and to maintain constant pixel sizes as the LCD imaging source gets warmer.

I was shown the newest protype, Model V. This projector uses an AM-LCD with 320 by 285 pixels. The AM-LCD was supplied to Projectavision by MCC in Austin, Texas. It looks rather unimpressive at first because it is in a laboratory-like metal box with a large lens similar to those on 35mm slide projectors and a cutaway that shows a TV tuner obviously scavenged from a Japanese miniaturized television product of some sort. But the box weighs only 12-13 pounds and projects a very bright image. This compares very favorably to the XV-100 LCD projector now being marketed by Sharp (which does not include an audio or TV tuner) which weighs in at 31 pounds and is considerably larger. Dolgoff projects an initial selling price for the projector of around $1,500. The Sharp projector is selling at a discounted price of around $3,000.

Manufacturing of LCD projectors for NTSC is the initial goal of the firm, and given the quality of image, size, and projected price, this looks like a good bet. Nevertheless the firm is very vulnerable to anti-competitive tactics on the part of potential competitors who are also likely to be the major sources of AM-LCD imaging sources. Dolgoff did not mention when and where an LCD-imaging source with HDTV capabilities might be available to him. Dolgoff said that the firm was negotiating with both U.S. and Japanese firms for AM-LCD supplies. Two U.S. firms have also been approached -- Optical Imaging Systems and the former management of Alphasil (in case the AM-LCD effort of that defunct firm can be revived).

Even if Projectavision fails to reduce its vulnerability in AM-LCDs, it has some very impressive advantages in the optics of LCD projection and may do reasonably well by licensing its technology or by forming joint ventures with AM-LCD producers. The downside risk, however, is that the optical advantages are not sufficient to overcome the advantages of size and technological sophistication of the larger Japanese electronics firms which are likely to be its competitors in projection systems.

Site Visit to Plasmaco

Location: Highland, New York

Informant: Larry Weber, Senior Vice President

Date: October 16, 1990

Plasmaco was incorporated in August 1987. It was founded by James Kehoe, formerly program manager of the IBM plasma facility in Kingston, New York, and Larry Weber, a professor from Illinois University. Kehoe brought with him approximately 19 million dollars of equipment from the Kingston plant and exclusive licenses for all he patents and manufacturing know-how connected with the IBM operation. Weber had invented a method of reducing the number of drivers needed for the plasma display, called independent display and address (ISA).[55] This method is embodied in patents owned by the University of Illinois but licensed from them by Plasmaco.

IBM developed the plasma display technology in 1971. It was designed initially for 3290 terminals and the 3295 information panel. IBM's plasma was an AC device; many of the competing plasma firms, especially Matsushita and Oki in Japan, use DC plasma. The advantage of AC plasma over DC plasma is twice the brightness and contrast for equivalent power and no flicker.

IBM decided to get out of plasma displays in 1987 because they needed room to expand their mainframe production at the Kingston facility but did not have the authorization from top management to hire more people or to create new plants. The plasma facility at Kingston required 100,000 square feet of plant space and 120 people to operate it. They produced a large display with 960 by 768 pixels which required 20 watts of power.

The display itself was somewhat poorly designed. It put extraordinary burdens on software writers -- knowledge of an unusual driver chip architecture was required to write good software. There was no way to get around the display's inability to provide whole-screen images

---

[55]. L.F. Weber and K.W. Warren, "A 512 x 512 Independent Sustain and Address Plasma Display," *Japan Display*, 1986, pp. 496-9; David Mentely, "Plasmaco, A New Flat Panel Display Supplier," (San Jose, Calif.: Stanford Resources, Inc., November 1988).

-- all images had to be presented in four equally sized "tiles" (nonoverlapping windows) on the display. The IBM display was not well suited, therefore, to the emerging personal computer market for displays.

Plasma display sales were not as profitable as mainframe sales, so the firm decided to end the plasma effort after four years of production.

Plasmaco has two products on the market now -- both are ten inch diagonal computer displays (for laptops). The first is a 640 x 400 display called the P33; the second is a 640 x 480 display called the P315. Besides the higher pixel count in the P315, that display has four levels of brightness control which allows the display to emulate EGA and VGA color displays better than the P33. The demostration displays I saw were very sharp, had no flicker, and had a very wide viewing angle. Power usage of the display is low enough at about two watts to permit battery operation for as long as 2.5 hours (depending on usage of power hungry peripherals like disk drives).

Both of Plasmacos products use "chip on glass" (COG) technology. Here COG means the fixing of unpackaged die on the glass substrate of the display and connection of bond wires from the die to conductors on the edge of the display. The saving is in avoiding the packaging of the die and the greater compactness that results. The chips on the periphery of the display are drivers containing high-voltage transistors (address-drivers), shift-register logic, a clock, and a few other functions. These chips are purchased from an outside supplier. A standard automated wire bonder with a vision system is used for attaching the bond wires.

The driver circuitry on the back of the display is very compact and leaves roughly half the area available for additional circuitry. The core of this circuitry is a VLSI programmable gate array made by Xilinx together with a ROM chip that allows Plasmaco to change the logic of the driver circuitry for different products and customers. As volume goes up, Plasmaco will replace the gate array with an ASIC of its own design.

The Plasmaco factory is in an old apple juice plant. It has two clean rooms: 1) a small 1,000 square foot room used originally for prototyping and pilot production now used only for off-contact photo exposure of glass plates and 2) a 10,000 square foot space of class 100 clean room used for 600 degree Centigrade belt furnaces which melt the dielectric onto the glass substrate. Evaporators which coat the glass and dialectric with a layer of magnesium oxide, which prolongs the life of the display by protecting it from the neon gas are not in the clean rooms, nor are the ovens which evacuate the air from between the two glass panels of the display (separated by a distance of only 3 mils) and replace it with neon.

The factory has the capacity currently to produce 50,000 units per year; as demand picks up, it will be possible to expand capacity to 250,000 units per year by simply connecting up equipment that is on the factory floor but not yet in use. At the moment, demand is heavy, and little effort is being made to get new customers because of difficulties in filling existing orders. Here are the numbers of pieces of equipment and their approximate unit costs:

Type of Equipment	Number	Unit Price
off-contact photo exposure system	1	?
magnesium oxide evaporators	9	600,000
evacuation oven	1	250,000
belt furnaces	3?	350,000
10,000 sq. ft. clean room, class 100	1	?
1,000 sq. ft. clean room, class 100	1	?
equipment for testing finished panels	20?	?

In addition to the above, Plasmaco purchased a very large Pfeiffer/Balzers evaporator from AT&T (never used) which will allow them to make larger panels in the future.

Yields at the Plasmaco plant have not reached the 70 percent level attained by IBM in Kingston. This may be the main reason why Plasmaco pricing has not been particularly aggressive. When asked about this Larry Weber said that Plasmaco did not wish to use forward pricing aggressively until it had to match a competing product -- suggesting that Plasmaco's unit production costs are still pretty close to their prices.

Let us turn to the issue of financing, because this may also be playing a role in Plasmaco's pricing strategy. The initial financing for Plasmaco was a small amount of seed money simultaneous with incorporation in August 1987 -- two months before the October crash. The next round of financing was to be a nine million dollar private placement arranged by a large Wall Street investment house which shed 595 of its 600 employees after the October crash. This financing was supposed to come through around March 1988, but was delayed until August 1989, causing the firm to lose much valuable time in bringing production on line.

The Plasmaco principals approached about 100 venture capital firms during the 1987-9 period with no success. Apparently they were all frightened off by the prospect of competition with the large Japanese firms.

Plasmaco chose not to apply for DARPA funding because it needed to focus on getting its monochrome production going. Weber argued that the demand for monochrome displays, especially for computers, would remain strong. A majority of all CRT displays sold currently are monochrome, he argued. The DARPA funding would have required diversion of scarce engineering resources away from monochrome toward color. Photonics has done this, but Plasmaco preferred to work toward large pixel counts first. They will start producing the 970 x768 displays that IBM used to produce first, then move to 1024 x 768.

Site Visit to Nitor

Location: San Jose, CA

Informants: Kerry McKinney (VP) and Frank Gibeau (President and CEO)

Date: July 17,1990

Nitor is a very small firm that proposes to develop inexpensive laser projectors for both industrial and mass consumer markets. McKinney and Gibeau would not tell me much about how they intend to do this because they were concerned about revealing proprietary information. My overall impression was that Nitor was not going to have enough money to do what they said they wanted to do.

Apparently, some of the engineers associated with Nitor have had experience building large laser projectors for the Air Force, probably through a firm called Visulux, but I could not get McKinney and Gibeau to elaborate on this. The Visulux projector is large (16' by 32') and requires large amounts of power. It costs about $250,000 per unit. The Nitor laser projector, according to my informants, would be about the size of a slide projector and would be price-competitive with CRT and LCD projectors. When I asked McKinney about safety problems with lasers at the DARPA meeting in January 1991, she did not provide a convincing answer.

The only funding for Nitor activities so far was the $1 million grant from the DARPA BAA. Nitor received this award in May 1989, but the funds had been frozen by the Bush administration and had not arrived as of the time of the visit. This had obviously hurt the venture badly. Apparently, the Nitor principles had approached a variety of venture capitalists for startup funding, but none were interested. McKinney and Gibeau complained lengthily about the defects of American venture capitalists -- of their avoidance of risk-taking (especially where there was the possibility of Japanese competition), their preference for funding software rather than hardware, and their desire to control the operations of the firm in exchange for their investment. There appeared to be no future prospect of venture capital funding.

The visit took place at the headquarters of Spectraphysics, which will be the main supplier of color lasers to Nitor. Spectraphysics is supporting Nitor during its startup period by providing limited access to its office, but nothing else. Nitor does not have its own offices yet.

Gibeau's main experience was 25 years in manufacturing microcomputer and data storage drives, specifically hard-disk drives. McKinney drafted the Nitor application to DARPA. Both were members of the Defense Manufacturing Board.

In sum, I found this to be a somewhat depressing glimpse into a venture that appeared to be more hype than substance. It left me wondering whether DARPA's funding of Nitor was a big mistake.

Site Visit to the Palo Alto Research Center of Xerox Corporation (Xerox PARC)

Location: Palo Alto, California

Informant: Richard Bruce (Director, Display Research)

Date: July 24, 1990

Xerox is one of the world's leaders in manufacturing processes for amorphous silicon (a-si) and polycrystalline silicon (poly-si) circuitry. A-si processes are necessary for the manufacturing of thin-film-transistor (TFT) active matrix liquid crystal displays (AM-LCDs). Poly-si processes permit the fabrication of power transistors (used for driving displays) and integrated circuits directly on the glass panels used for AM-LCD and other types of flat panel displays. Poly-si processes are crucial, therefore, for the integration of displays and electronic circuitry which we discussed in the body of this paper.

Work on a-si began at Xerox PARC in 1974. At first they did not know how to work with it and little progress was made. In 1980, the first reliable transistors were fabricated with a-si. This permitted them to place all the electronics of a typical xerox copier on an 8.5" by 11" glass panel. Plasma CVD equipment for a-si was developed at Xerox PARC and then used at the Fuji-Xerox facility in Ebina, Japan, to make scanning and printing devices. The major investments in manufacturing began in 1987. While the Japanese factory was being built, the Palo Alto laboratory was developing a 60-foot-long plasma CVD machine.

At the Japanese factory, this machine was used in conjunction with a Nikon stepper and Japanese robotics and handling equipment to make a thin glass electrography element which is about 3/8-inch wide and 12 inches long that replaces a much larger electro-mechanical device in advanced color printers. Xerox recently announced a new integrated color printing system which utilizes this device. All the high-voltage driver transistors and electrical charge wires are integrated on the glass using a poly-si process, thus eliminating some clunky printed circuit boards.

To develop the a-si process, Xerox PARC engineers converted a .8 micron CMOS line to a-si glass lithography. Internally, they had to get experts on a-si (mostly advanced materials researchers) to interact with CMOS experts (knowledgable in manufacturing issues). The materials people were not used to thinking about manufacturing, and the manufacturing people were not familiar with a-si materials. Clean room technology was not a problem: the lithography for the a-si process required only class 5; the rest of the process required class 20. Steppers are a serious constraint to throughput for a-si and poly-si lithography for AM-LCDs. Many passes are needed for lithography, which could be reduced if it was possible to have steppers with variable resolution (TFTs need higher resolution than do LCs and connector/driver lines).

The Xerox management considers the essence of the company to be the development and commercialization of scanning and printing technologies, thus there is very strong support for the a-si research team. Xerox leads the world in laser printer revenues (not volume), thanks to a very successful high-end laser printer line. There is somewhat less support for the application of a-si and poly-si technology to advanced displays, as this is not currently seen to be a strategic area for Xerox.

Nevertheless, the joint research effort with Raychem in advanced displays, funded by DARPA, is an indication of the strong interest of the scientists and engineers at Xerox PARC in displays, as is the more recent joint venture with Hamlin-Standish to produce AM-LCD displays for Xerox PARC internal use. Xerox PARC has a mandate to pursue all technologies which contribute to the "office place of the future." Xerox is willing to do a lot of things in this area to increase their corporate visibility. But so far they have been reluctant to fund high-volume manufacturing of either computers or displays (having been burned badly in their earlier efforts in computers).

The joint research with Raychem had not gone very well. Raychem was responsible for developing a new liquid crystal material (from what he told me I infer that it is a polymerized liquid crystal material which does not require polarizers like the AM-LCDs made in Japan). The advantage of this new material is that more light gets through the AM-LCD and the display can be brighter for a given amount of backlighting or projection lighting. In a typical AM-LCD with polarizers, only 4 percent of the light gets through. In a polymerized LC device without polarizers, 12 percent can get through. Raychem's main task was to develop a material that worked at lower voltages. It was not able to do this; apparently, Asahi Glass was able to do it first.

The joint venture with Hamlin-Standish is to manufacture low volumes of AM-LCDs for Xerox internal use. Hamlin-Standish has strengths in LC technology but not in TFTs. Xerox is contributing its expertise in a-si and poly-si for TFTs and driver/connector circuitry. The actual production will be done at Hamlin-Standish's plant in New York.

The Xerox part of the Raychem-Xerox research was to develop a-si and poly-si circuitry for an AM-LCD display. Special driver chips were designed by Xerox. Xerox worked with National Semiconductor on custom ICs for displays.

The DARPA project was very helpful for Xerox. They made contract through DARPA with a number of people who were innovators in light-valve technology and video processing circuitry. The impounding of DARPA contract funds by the Bush Administration was a cause for concern.

It was Richard Bruce's opinion that the U.S. systems firms are not willing to take on the Japanese firms in displays or other important components. The general belief is that Japan is too far ahead in a-si technology. Venture capital does not do the job here because of the very high initial investments in AM-LCD production facilities -- somewhere around $200 million.

Bruce's unit at Xerox PARC has focused on the use of LCD projection displays to allow people to work in groups. This application requires that the display be large and very high in resolution. The DARPA contract was used to subsidize this research. At the HDDT meeting at DARPA in January 1991, I saw a picture of a laboratory prototype of a full-color, high-resolution (2,000 by 2,000 pixels) AM-LCD imaging source built at Xerox PARC with poly-si processing on glass. This imaging source is exactly the size of a 35mm slide, and is thus suitable for a relatively compact projection system.

Site Visit to Coloray

Location: Fremont, California

Informants: Scott Holmberg (VP for Semiconductor and Process Development), George Proulx (Director, Corporate Programs and Administration, and Chris Curtin (VP, Product Engineering)

Date: June 21, 1990

Coloray is developing a reliable manufacturing process for a flat panel display technology called field emission display (FED) or "cold cathode." This technology was first developed by Stanford Research Institute (SRI) in the 1950s, who continue to hold several FED patents. Coloray was incorporated on February 1, 1990, under the leadership of Charles Manley. Manley was hired by Commtech, the exclusive licensing agent for SRI patents, who also supplied the startup capital for Coloray. Manley hired Cris Curtin and Bob Duboc, as well as other members of the Coloray team.

FED technology has many characteristics in common with cathode-ray-tube technology. Like CRT, FED uses an emitter of electrons to excite a phosphor on the inner surface of a glass display plane. However, unlike the electron guns of CRTs, the FED emitters are very small and are placed very close to the glass panel. In fact, each dot has its own emitter (or cluster of emitters). Thus, the key problem in manufacturing FED displays is fabricating the tiny emitters reliably and getting a uniform distance between the emitters and the phosphor-coated glass panel.

The FED emitters are very small cones of molybdenum. These cones have to be deposited inside a tiny hole etched in a layer of silicon dioxide insulator, which itself is between two layers of metal conductors (the top layer controls the columns, the bottom the rows of the display). So to make the display, here are the necessary steps: (1) the row conductors are deposited on a glass panel, (2) a layer of silicon dioxide insulator is deposited on the row conductors, (3) the column conductors are deposited on top of the silicon dioxide layer, (4) one-micron diameter holes are etched in the column conductor and silicon dioxide layers, (5) molybdenum is deposited in the holes, (6) the molybdenum is etched to form a cone, (7) glass spacers are formed on the almost-completed bottom panel to ensure uniform spacing between the bottom and top panels, and (8) the top and bottom glass panels are bonded together.

The electrons that excite the phosphors come off the tips of the cones. If the cone is not sharp enough or if it gets deformed because of use over time, then the pixel will be defective. For this reason, there needs to be redundancy in cones per pixel. There is some speculation that extra high voltage emissions will occur occasionally that will "kill" a pixel, making the display unusable. The Coloray people say that this problem has been solved.

Another problem still to be solved is the need for lower voltage phosphors. CRT phosphors are being used in current FED displays. These phosphors were designed for excitation by electrons accelerated to 20 kilovolts. FED electron voltages are more in the range of 500-1000 volts.

The Coloray engineers claim that the FED displays will be superior to AM-LCD displays because of lower manufacturing costs, greater power efficiency, better viewing angle, faster response times, less sensitivity to ambient temperature, and cheaper raw materials. They estimate that the FED will cost roughly 70 percent what it costs to manufacture an equivalent AM-LCD. There is no need for backlighting in FED displays. In addition, the FED will be 5-6 times more power efficient than a plasma display. The power efficiency they are aiming at is greater than .5 lumens per watt (which is what the Hitachi 6" by 8" AM-LCD display currently gets).

While I was visiting the Coloray facility, I got a long story about the birth and death of Alphasil. Coloray was founded on the ashes of Alphasil. See the report on Alphasil in Appendix B.

Site Visit to Amtel Video

Location: Palo Alto, California

Informants: Timothy Draper (President and CEO) and David L. Brown (General Manager)

Date: June 21, 1990

Amtel Video is a startup firm working on a form of "white light modulation" -- a generic term for almost any type of projection system. It was formed in 1989 on the foundation of revenues obtained by Draper Associates for licensing some technologies connected with DAT machines. Venture capitalists were approached initially, but were not willing to provide funding in the absence of "proof of concept." The lead member of the venture capital group was concerned about entering the consumer electronics business and did not want to risk getting a reputation for poor judment. When the lend venture capitalists waffled, the rest disappeared. Venture capitalists are more like bankers now, according to Draper.

Amtel applied for DARPA funding after the first BAA was announced, but did not win a grant. Then a small amount of money came in from Sharp Corporation of Japan for a six month period (early 1990) which had expired by the summer of 1990. After the Sharp money was gone, a small amount of venture capital was finally obtained. The firm is currently looking for corporate partners to provide longer term funding of research and development.

Amtel's development efforts are focused on a technology called "Chrystal Scan." A white light is projected through a polarizer and then through a linear modulator or light-valve and scanned across a screen with a scanning mirror. The mirror scans in a triangular wave pattern, not a sawtooth or sinusoidal wave.

No special screen is need for obtaining a clear image. The brightness would be 300 lumens and power consumption would be 300 watts. The contrast ratio would be 170:1 with 256 gray scales. The unit costs for an NTSC display would be around 250 dollars. HDTV displays would be more. Resolution for these displays could theoretically go as high as 5,000 by 5,000.

A working prototype was expected to be completed by November 1990. Six months later, Amtel would have a manufacturable prototype ready.

Site Visit to David Sarnoff Research Center

Location: Princeton, New Jersey

Informants: Dr. Arthur Firester (Director, Applied Physics and Advanced Display Laboratory) and Jack Fuhrer (Director, Television Research Laboratory)

Date: October 17, 1990

The advanced display research at the Sarnoff Center is focused on display-peripheral circuitry using poly-silicon (p-Si) processing techniques. This research is supported primarily by military contracts, and not by high-volume consumer or industrial firms. That appears to be the main weakness of the program. The technical excellence of the work at Sarnoff is its main strength. In the United States, Sarnoff and Xerox PARC stand out as leaders in the development of p-Si circuitry and processes.

The main thrust of the Sarnoff effort is to test designs for driver circuitry on the periphery of the glass substrate for AM-LCD displays. The Sarnoff researchers have demonstrated that p-Si circuits can be successfully placed on a narrow border surrounding an active matrix array. Doing so has the benefit of reducing the complexity and therefore the costs of connecting driver ICs (which previously had to be placed on a separate printed circuit board or on the substrate using chip-on-glass technology) to the display. This makes it possible to make the interface between the circuitry on separate PCBs and the display much simpler and therefore easier to manufacture and test. These benefits are greatly magnified when the pixel counts go up on high-resolution flat panels. However, the p-Si techniques need to be improved in order to make them fully competitive with existing a-Si processes (see report of site visit to Xerox PARC for further discussion of these issues).

Other relevant work at Sarnoff includes the use of the Princeton Engine, a massively parallel computing system, to similute the performance of various proposed high-definition systems. Sarnoff continues to work on improvements in CRT technology and in 3-D imaging. Finally, there is a major effort in psychometric research which may permit hardware designers to take into account the limits of human cognition and perception in designing display systems.

The Sarnoff Center has been managed by Stanford Research International (SRI) since 1987, when Thomson of France purchased the consumer electronics operation of General Electric (GE). GE had purchased the consumer electronics arm of RCA only a year before. Initially, GE had decided to make a go of it with the consumer electronics business and instructed the researchers at the Sarnoff Center to keep up their work on consumer television technologies. GE was making AM-LCD flat panel displays in Schenectady, New York, for its military customers. Thus, the researchers at Sarnoff had access to some excellent AM-LCD research.

However, when GE sold GE/RCA Consumer Electronics to Thomson because it believed the television business would not be profitable, the Sarnoff Lab was cut off from the Schenectady display lab. Part of the deal between Thomson and GE included the sale to Thomson of GE's amorphous silicon (a-Si) active matrix processing technology. Thomson applied this and ancillary technologies acquired from GE to the manufacturing of low-volume military products (the relevant subsidiary is Sextant Avionique).

Thomson has not been interested in high-volume production of AM-LCDs. In France, the main Thomson research effort was in plasma displays, for use in computers. In addition, the need for Sarnoff to become self-supporting eventually under SRI management (it received some funding from Thomson in the form of a portion of the licensing revenues from GE and RCA patents) meant that research had to become more short-term in focus. Thus, Sarnoff increasingly aimed at military contracts to fund the kind of high-risk research they had been doing all along. This was frustrating for Firester's group because they knew the technology they were working on would be more valuable if there were a high-volume application connected with it.

The overall philosophy of Thomson toward high-definition displays is that large flat panel displays would not be available until the late 1990s, and that CRTs and CRT-based projection systems would be used first for high-definition applications. This meant that the Sarnoff people had to find a non-Thomson customer for its non-military flat panel research. They have not been able to do this yet. There was some talk of a display consortium with Philips, but this appears to be off for now. Sarnoff is working with Xerox in some parts of its display research, so there may be an eventual connection with the Xerox-Hamlin/Standish display manufacturing venture. This is purely speculation on my part.

Since the visit, Firester has become the director of the Display Division of the National Information Display Laboratory (NIDL) funded by the Air Force initially but with the intention of becoming self-financing thrugh an industrial membership and affiliation program. Many of the activities that had been done as purely Sarnoff activities will now be conducted under the auspices of the NIDL.

Site visit: Dynabook Technologies

Location: Santa Clara, California

Informant: Daniel Evanicky (Director, Display Development)

Date: August 14, 1990

Dynabook is a packager and manufacturer of advanced portable workstations, using color AM-LCDs produced by others in some of their products. Dynabook does not market its own machines but instead manufactures them for others. The firm's name comes from an idea first expounded by Alan Kay. The Dynabook was a self-contained computer that one could carry around and consult just like one can carry around a consult a book. This idea appealed to Steve Jobs, one of the co-founders of Apple Computer, who bought a company _called Woodside Design in 1985 that made vacuum fluorescent flat panel displays (VFDs). The goal of Woodside Design to make VFDs for real-time video display. Jobs's intention was to manufacture a VFD-based Dynabook at Apple, but when he was ousted from the firm, the idea was pretty much dropped.

The current Dynabook was founded by people who left Apple in 1987. The name Dynabook was adopted, and in September 1989 the firm applied for a trademark under that label in the United States. Unfortunately, Toshiba filed both in Japan and the European Community for the same trademark on the same day, so the firm was not able to use the name in those two places. Toshiba is now marketing a laptop under its Dynabook trademark in Japan which has no relation to the products of the U.S. Dynabook firm.

The main competition in VFDs is from Futaba Corporation and Issei Corporation, a daughter of Noritake. Issei is not doing very well, and has asked Futaba for help in recent years. Futaba products are used in calculators, clocks, VCRs, bathroom scales, and radio controls. Dynabook's product range is much more limited, which is a problem for them. They have tried to diversify their operations away from the original focus on VFDs. Their main business now is the integration of advanced laptops, using a patented black magnesium casing and contracting with other firms to supply advanced displays. This has been a difficult strategy because some its suppliers have not been able to deliver on their promises.

For example, Dynabook contracted with Seiko-Epson to supply a blue-mode AM-LCD with VGA graphical capability. The delivered displays did not meet Dynabook's quality standards (the contrast was too low), and now the firm is trying to return them and to recover $1 million in advance payments. It switched to Hitachi to become the supplier of color AM-LCDs for its latest products. I saw an example of this product which had been manufactured for Unisys(?). The display was very crisp and bright and seemed to be fast enough for computer animation purposes. These displays cost around $3500 per unit, so the final laptop product tended to cost around $10,000. The customer base, therefore, consisted primarily of large corporate users.

Appendix B:
The Exit of U.S. System Firms from Advanced Display Markets

This appendix contains reports on interviews with people connected with now defunct advanced display operations at Alphasil and Kylex.

Interview with Scott Holmberg, co-founder of ***Alphasil***
Date: June 21, 1990

Alphasil was founded by Dick Flask and Scott Holmberg in 1982 with seed capital from Bay Venture of $0.5 million. The initial idea was to build a prototype active matrix display. The first display they produced was a 2" by 2" display on a 4" ground-glass wafer. The wafer was processed on a silicon production line rented from LSI Logic. Alphasil obtained some process patents as a result of this work which they hoped would make additional venture capital available. However, they missed their funding window by about a year, as venture capital for active matrix dried up in late 1982.

Small contracts kept the firm alive until 1986. In that year, Sperry contracted with Alphasil to active matrix supply cockpit displays. Sperry provided the capital for a new plant, and were willing to wait 2-3 years for delivery because they wanted a domestic source. When Burroughs purchased Sperry in 1986 to form Unisys, they decided to get rid off Sperry's military businesses, so they sold Alphasil to Honeywell in late 1986. In the summer of 1986, Alphasil had begun construction of a larger plant, but Honeywell was not committed to pursuing a long-term strategy for displays. Although it loaned Alphasil some money in late 1987, in July 1988 it announced that no more funds would be forthcoming. In addition, it forbade Alphasil from contracting with third parties without Honeywell approval. To be fair to Honeywell, in 1988 it experienced a loss of $400 million, of which $100 million was from military operations.

Thus, Alphasil had to close up shop in 1988. Alphasil had established a very good record on yields for its 4" by 5" AM-LCD panels. Many Japanese firms still struggling to get 10 percent. Honeywell continue to hold the Alphasil patents, especially after Alphasil defaulted on its loans.

Phone Interview with David Davies, formerly with ***Kylex***, now with 3M Corporation
Date: July 20,1990

In 1972-77, Davies managed the laboratory at Westinghouse which was working on active matrix flat panels. Peter Brody -- the originator of the idea of active matrix -- was one of Davies' engineers. The lab had about 25 people funded mostly by money from the U.S. Army. Almost no Westinghouse funds were used. Army Electronics Command wanted electroluminescent (EL) displays because of their utility for night-time viewing. LCD displays were not considered appropriate for military applications. In addition, Westinghouse engineers in the Western Electric Tube Division in Elmira, New York, blocked commercial development of flat panel displays within the company. The money from the government was too little in the wrong place to develop active matrix TFT-LCDs.

In 1977, Peter Brody left Westinghouse to form his own company. Davies also lest that year to form a new company called Kylex. The goal of Kylex was to develop an a-Si TFT-LCD display. The original team for Kylex included Davies, Joseph Castellano, and Gary Stone (a Harvard MBA who Davies grew to dislike intensely). The main source of funds for Kylex came from Exxon Enterprises, a venture capital arm of Exxon Corporation. Exxon wanted Kylex to be a business, but were not willing to invest enough to set up a manufacturing facility. They had a total of $500 million to invest but this had to be spread across over 30 ventures. Exxon Ventures was originally led by Ben Sykes, who was a visionary, and others like him. But the visionaries were replaced by oil executives shortly into the effort. When the oil executives took over they shut down all the projects.

Exxon sold Kylex to 3M. Now the plant is being used to manufacture optical disks. Apparently much of the same equipment that would have been used to make AM-LCDs is also used to manufacture optical disks. 3M uses small displays in some of their products but have not stuck with the idea of high-volume production of AM-LCDs. 3M makes a light-valve, however, for industrial applications. They supply one of these to Greyhawk Systems, for example.