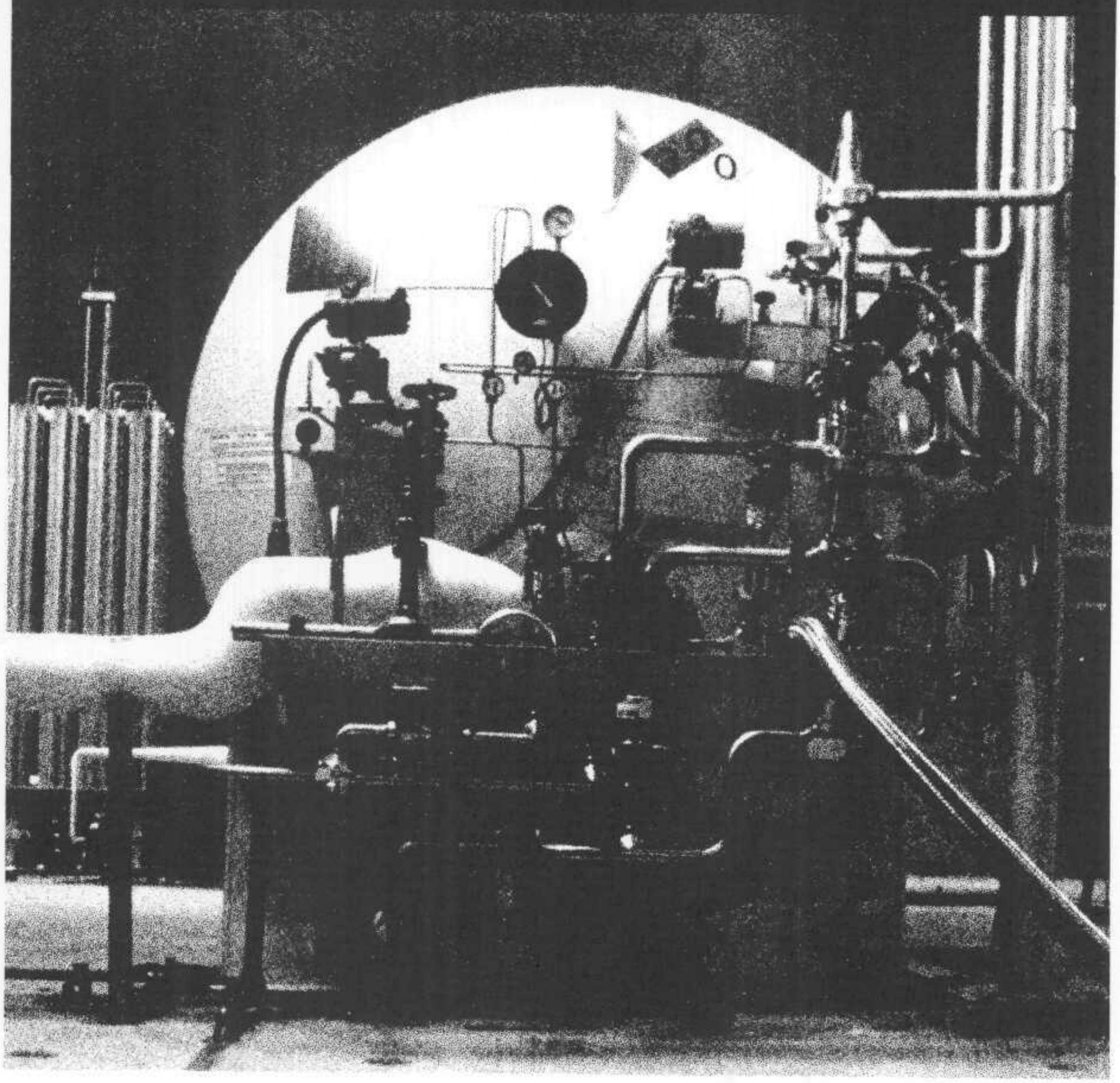
CONGRESS OF THE UNITED STATES
CONGRESSIONAL BUDGET OFFICE

JULY 1990

Using R&D Consortia for Commercial Innovation: SEMATECH, X-ray Lithography, and High-Resolution Systems



A CBO STUDY

CBO Publication
#523

S U M M A R Y

July 1990

CBO STUDY ON RESEARCH AND DEVELOPMENT CONSORTIA

The federal government is now considering policies to promote technology as a way of increasing the competitiveness of U.S.-owned firms. Research and development (R&D) consortia are increasingly suggested as a tool to help channel federal support to industry. A study by the Congressional Budget Office (CBO), *Using R&D Consortia for Commercial Innovation: SEMATECH, X-ray Lithography, and High-Resolution Systems*, prepared at the joint request of the Senate Budget and Senate Governmental Affairs Committees, reports that R&D consortia can be useful in a variety of circumstances. Such consortia complement, however, more than substitute for the research efforts of individual companies and government programs. To be effective, R&D consortia must develop from private sector interests, thus dictating a relatively passive role for the federal government.

The model consortium, SEMATECH, is actively pursuing its R&D program on semiconductor manufacturing technology, concentrating on the equipment used in making computer chips. Its chief accomplishment to date has been to strengthen the working relationships between semiconductor producers and their suppliers of equipment and materials.

The usefulness of R&D consortia depends on specific R&D agenda of the industry where a consortium is proposed. In the case of x-ray lithography, the federal government is already active, and a division of labor exists among the major parties involved in this area. In high-resolution systems for electronic imaging, the technologies involved are so diverse and the competitive factors so different that no single consortium could assist all the firms involved in those markets. Several smaller consortia could, however, target specific supporting technologies, such as flat-panel displays.

The Office of Intergovernmental Relations is CBO's Congressional liaison office and can be reached at 226-2600. For additional copies of the study, please call the Publications Office at 226-2809. Questions regarding the analysis should be directed to the author, Philip Webre, of CBO's Natural Resources and Commerce Division at (202) 226-2940.

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USING R&D CONSORTIA FOR COMMERCIAL INNOVATION: SEMATECH, X-RAY LITHOGRAPHY, AND HIGH-RESOLUTION SYSTEMS

The Congress of the United States
Congressional Budget Office

NOTE

Cover photo courtesy of SEMATECH of Austin, Texas. The photograph shows a node in the gas supply system of SEMATECH's wafer fabrication plant in Austin.

PREFACE

Joint government-industry consortia are increasingly discussed as a means of increasing the competitiveness of U.S. industry. A previous Congressional Budget Office (CBO) study examined the model joint government-industry consortia, SEMATECH, which was founded to do research and development (R&D) in semiconductor manufacturing. Another CBO study, parts of which are incorporated here, assessed the importance of one technology area--high-definition television--commonly discussed in connection with competitiveness and R&D consortia. The current study discusses both the major policy options before the Congress regarding R&D consortia and the major technology areas discussed in connection with R&D consortia. The Senate Committee on the Budget and the Senate Committee on Governmental Affairs jointly requested the report. In keeping with CBO's mandate to provide nonpartisan analysis, no recommendations are made.

Philip Webre of CBO's Natural Resources and Commerce Division wrote this report under the supervision of Elliot Schwartz and David Montgomery. The staffs of the Brookhaven National Laboratories and of SEMATECH provided valuable assistance. The author wishes to thank Christopher Gintz, Jules Godel, Richard Heese, Glenn McLoughlin, Boban Mathew, James Murphy, Murray Ross, Michael Sieverts, W. Edward Steinmueller, George Uriano, and Gwynne Williams for their helpful suggestions. The author wishes especially to acknowledge the comments of the late Dr. Robert Noyce.

Sheila Harty edited the manuscript. Donna Wood typed the many drafts. Kathryn Quattrone prepared the report for publication.

Robert D. Reischauer
Director

July 1990

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The success of foreign high-technology companies in U.S. markets has stimulated debate on whether the federal government should foster new strategies to increase commercial innovation among U.S.-owned firms. One commonly suggested strategy is for firms to pool their resources to form research and development (R&D) consortia. In 1984, the Congress passed the National Cooperative Research Act (NCRA), which made it easier for private firms to engage in collaborative R&D. In 1987, the government, together with industry, began funding SEMATECH, a large-scale R&D consortium focusing on semiconductor manufacturing technology. Some policy analysts argue that the federal government should take a more active role in fostering R&D consortia, including financial support where necessary. Toward that aim, SEMATECH is seen as a model of public/private collaboration.

In this study, the Congressional Budget Office analyzes the benefits and limitations of using federally supported R&D consortia to encourage commercial innovation. The two questions posed are:

- o How do R&D consortia fit into federal efforts to promote commercial innovation?

- o What federal policy and institutional changes are needed to promote the use of R&D consortia?

The study finds that federal support for R&D consortia can be a useful, if limited, tool to support commercial innovation. To be effective, such consortia must develop from private sector interests, thus delegating a relatively passive role for the federal government. Nevertheless, should the government choose to support R&D consortia through direct funding, it must develop institutions to carry that objective out. This study concludes that, regardless of the institutions developed, the relationship among members of the consortium and between them and the federal government will be key to its success.

Beyond generic questions of overall federal policy on R&D consortia, the study examines three specific proposals. The applicability of SEMATECH as a model for future policy is explored first, and then the potential role of R&D consortia is examined for specific technological areas, such as x-ray lithography for integrated circuits and high-resolution display for electronic systems.

PUBLIC PURPOSES FOR FUNDING R&D CONSORTIA

Collaborative R&D now receives public funding for several reasons. Most commonly, the collaborative effort produces a product or technology, which some federal agency intends to purchase, or involves an area of the public interest, such as health. Only recently has discussion begun on federal funding for collaborative R&D where the research results would be put to private use by the members, such as in SEMATECH.

Many reasons justify federal funding for R&D in general. Private markets tend to fund less R&D than is best for the national interest. In high-technology industries, a national security aspect in R&D is often involved. R&D can also build up the science and technology infrastructure by producing knowledgeable people.

Reasons for federal support of consortia devoted to commercial R&D center on the advantages of collaborative work. By supporting R&D consortia, the federal government may achieve many of the same results that private firms do in joint ventures. A consortium may contain firms with complementary strengths. It may also transfer the best existing technology within an industry to firms with average technology. Alternatively, it may establish an industry standard that results in a larger potential market.

Even though a consortium may fulfill a public purpose, the interests of private members of a consortium are not the same as the goals of public policy. The risk is that firms may apply consortium-developed technology in ways the Congress did not intend--for example, to move production or subsequent R&D overseas.

Even among proponents of R&D consortia, major difficulties emerge in deciding which types of collaborative research the federal government should support. One view of commercial innovation suggests that the government should support basic science research and sometimes support applied research for developing new technology with broad potential. As the technology comes closer to the marketplace, commercial innovators are more able to secure the benefits of their R&D, decreasing the need for federal support. This view of commercial innovation is often called the "pipeline" model because science resources go in at one end and products come out at the other.

A different view of commercial innovation, however, suggests that the process of developing technology is not as linear as the pipeline model implies. The interactions between the different phases of R&D--basic, applied, and development--may flow both ways. Sometimes gaps in basic theory are revealed in the development phase, as are solutions to generic problems. For example, by supporting the work of the first producers of integrated circuits, the federal government helped find solutions for all subsequent producers of integrated circuits. This alternative view, sometimes called the "chain-linked" model, opens the possibility for federal support in areas denied by the pipeline model because all stages of commercial innovation are recognized as producing public knowledge. If the government felt commercial innovators were greatly advancing the state of scientific or technical knowledge through their design development, it might justifiably support such research.

LESSONS OF SEMATECH

Direct translation of the SEMATECH experience into other industries is limited. Several factors are unique to SEMATECH, although some general lessons have been learned. SEMATECH's principal contribution so far has been in strengthening the lines of communications between producers and users of semiconductor manufacturing equipment. Producers better understand the plans of their most likely clients, while users better understand the capabilities and problems of their suppliers as well as the problems of other users. This knowledge gained from the SEMATECH experience has already improved the allocation of research resources for some equipment producers.

A closely related implication is that R&D consortia can agree on a work plan when engaged in activities that affect competition among their suppliers. Increasingly, SEMATECH is providing contracts to suppliers of semiconductor manufacturing equipment to improve their products. While R&D contracts for equipment may be noncompetitive for semiconductor producers, they clearly affect competition among producers of semiconductor manufacturing equipment. Thus, SEMATECH has engaged in R&D that does not directly affect competition for the bulk of its membership but does affect the supplier industries.

Whether the use of federal funds by SEMATECH for such R&D is warranted depends largely on how commercial innovation is viewed. Believers in the pipeline model might view such support as an unwarranted subsidy by the federal government. By contrast, such support is consistent with the chain-linked model of commercial innovation.

SEMATECH is not the solution for all the R&D problems faced by the semiconductor industry. SEMATECH, like other R&D consortia, has limited goals--in this case, improving manufacturing technology that will come into use within five to eight years. Thus, while federal support for R&D consortia may be worthwhile, it does not substitute for a wider program of federally sponsored research.

POLICY OPTIONS

If the federal government were to encourage more R&D consortia for commercial innovation, some policy options would emerge. The government can act indirectly through antitrust policy. The Congress can also mandate direct federal support for R&D consortia through one or more federal agencies. Direct support raises two types of concerns: those common to all federal efforts to foster R&D consortia, and those arising from the government's choice of agency to carry out this policy.

Antitrust Relief For Joint Manufacturing

Some policymakers have proposed that the Congress should extend the protection of the NCRA to joint production ventures, making them exempt from private treble-damage lawsuits but still liable for single-damage suits. A central argument behind this proposal is that the risks in bringing new products to market should allow firms engaged in new product development to combine their efforts for production, thereby spreading the costs and reducing the risks. As U.S. high-technology industries are characterized more by small firms than are the foreign industries against which they compete, allowing antitrust relief to these smaller U.S.-owned firms may increase the capital available to them by permitting them to join forces.

Antitrust laws, as currently interpreted by the courts, do not constitute a barrier for most common types of joint manufacturing. Despite widely repeated assertions regarding problems with U.S. antitrust laws, surveys of joint ventures in the past 15 years have concluded that joint production ventures are announced on the average of nearly one per week. While more joint ventures might develop in a looser environment, their current numbers suggest that the law was no constraint. In fact, the U.S. business culture, which stresses adversarial roles, is a more likely constraint.

Nevertheless, discouraging industrywide efforts might be desirable. A strong potential for collusion does exist. Even if a joint production venture is initially subject to international competition to curb price increases, orderly marketing agreements or other government constraints on competition might give the joint production venture substantial power in the domestic market. If this were to occur, not only might U.S. consumers pay more, but also the member firms might become less competitive in the absence of international pressure.

Encouraging Federally Funded R&D Consortia

Using federally funded R&D consortia to promote commercial innovation raises common concerns, irrespective of the institutional tool chosen. These concerns include program priorities, program funding, and program operations.

The program priorities for applied research are now set by how the research affects the mission of the federal agencies involved: the National Institutes of Health by how it affects health, and so forth. R&D efforts to promote commercial innovation have no such criteria. Most proposals specify that federal efforts are intended to advance generic technology, meaning research that could be used by many industries. This definition limits the agency charged with fostering technology. Many important areas of technology are concentrated within a specific industry because of their current or practical applications and, thus, cannot be considered strictly generic. For instance, the authorizing legislation for the Advanced Technology Program of the National Institute for Standards and Technology (NIST) specifies that it should advance x-ray lithography. Yet, the only industry that directly needs x-ray lithography is the semiconductor industry.

If federal R&D were to support only truly generic R&D, it may miss many technological opportunities. Furthermore, political favoritism may also distort the process of setting research priorities. Certain technologies may become politically favored and receive a disproportionate sharing of funding for their contribution to national productivity and competitiveness. Consequently, the government has to decide how much discretion to provide in choosing technologies and projects.

Policies to support R&D consortia may preempt or stall other means that the federal government has to increase commercial innovation. For example, such consortia may distract from efforts to improve the technical capabilities within U.S.-owned firms. Since only about 1 percent to 2 percent of industrial R&D involves interfirm collaboration, decisions on the allocation of resources within firms are more likely to affect commercial innovation than would research collaboration among firms. Furthermore, if the federal government were to join a consortium, it would have to decide what to do, if anything, about R&D on competing approaches to the same technology that the consortium may have rejected or that lie outside its mission.

Improved communications between suppliers and their customers are the clearest benefits of R&D consortia. The result is increased coordination without the need for integration though ownership, as well as decreased risk and uncertainty for all concerned. Federal agencies responsible for R&D consortia devoted to commercial innovation should encourage membership from supplier and customer industries in addition to membership from the industry in question. Assisting these relationships may be the most important role of federal agencies.

Program funding and cost sharing are difficult to apportion. The Defense Advanced Research Projects Agency (DARPA) within the Department of Defense can often take the initiative because it is well funded and has the flexibility to reprogram its funds quickly. DARPA has roughly $500 million to spend on dual-use technologies, although most of that is not for supporting R&D consortia. Unless a new funding agency has enough funds and enough flexibility to take advantage of opportunities, the agency will have a hard time overcoming the passivity delegated for the federal role in private consortia.

The 50/50 cost sharing for federal involvement in SEMATECH created a precedent for R&D consortia and established that the industry was seriously interested. Other industrywide consortia may also be able to draw on substantial private contributions. Industry is not likely to create an irrelevant research agenda if its own money were at stake. This incentive system is even more important in consortia devoted to commercial innovation. Discriminating among interesting technologies requires detailed knowledge, which is usually located in private industry. If the private sector has its own funds and experts involved, the research is more likely to be relevant.

Program operations in R&D consortia will have to rely fundamentally on private sector partners for success. For example, SEMATECH was organized largely at private initiative, despite that the federal government provided moral and financial support and DARPA provided organizational help. To a large extent, the government will be delegating its authority to private initiative, both during and after formation of any R&D consortium.

Failure is a common result in the development phases of new technology. The "right level of failure" will be hard to determine for any federal agency supporting commercial innovation through R&D consortia. To continue support in the face of failure will also be hard for the Congress. One way of ensuring the right level of failure is to separate the reputation of federal support efforts from that of any single major project. Rather, by supporting many smaller technology developments, the federal government could pursue a broad portfolio of technologies, some of which would have commercial potential and, therefore, would not discourage additional funding.

Organizational Alternatives

Many observers have questioned the appropriateness and advisability of having a defense agency like DARPA fund many of the federal government's civilian commercialization efforts, such as SEMATECH, x-ray lithography, and high-resolution systems. If the federal government wants to encourage the creation of federally funded R&D consortia devoted to commercial innovation, several options exist: DARPA can continue with its present assignment; DARPA's mission can expand to include civilian technology; the Advanced Technology Program at NIST can be used; and/or a new technology agency can be created.

Continue DARPA's Current Mission. DARPA's long history of assembling and supporting teams to perform mission-oriented research did not include funding projects where the initiative was outside federal hands. SEMATECH is the exception. If R&D consortia become a more popular way of advancing technology, DARPA may have to change. The Congress recently expanded DARPA's flexibility in dealing with industry. DARPA can now enter collaborative research agreements and joint ventures with small R&D firms. The "New Agreements Authority" calls for DARPA to allocate $25 million a year over two years to a revolving fund from which it could finance joint ventures with industry.

Expand DARPA's Mission. Advocates of expanding DARPA's mission to include developing civilian technology argue that in many areas of technology national security is just a fig leaf for DARPA's real purpose: improving competitiveness. Proponents argue for a straightforward approach, making DARPA responsible for developing civilian technology. The trade-off here is the extent to which policy weighs civilian versus military technology development.

NIST's Advanced Technology Program. The 1988 Omnibus Trade Bill set up the Advanced Technology Program within the reorganized NIST. The intent of the program is to accelerate commercialization of new technology by encouraging U.S. companies to form joint R&D ventures, such as consortia, by providing support offices, technical assistance, and, under limited conditions, minority funding for up to five years. NIST, formerly the National Bureau of Standards, has a distinguished history of developing new standards and their infrastructure. Supporting R&D consortia risks diverting NIST from its central mission. Furthermore, NIST's strong ties to industry might be hurt if NIST became identified with one or another segment within an industry as a result of its work with R&D consortia.

The Advanced Civilian Technology Agency. One proposal receiving substantial attention has been put forth in S. 1978, the Trade and Technology Promotion Act of 1989. This act would set up the Advanced Civilian Technology Agency (ACTA) within the Department of Commerce. ACTA would provide grants and enter into contracts or cooperative agreements to support projects for developing new technology of potentially significant value to the United States. The intent of the legislation is for the ACTA to set up a revolving fund. Projects funded by ACTA that prove successful will pay back all or part of their costs into the revolving fund. The fund will then use those resources for future projects. Setting up ACTA and getting it properly functioning may take some time, delaying efforts to promote R&D consortia. Unlike DARPA or NIST, ACTA would have no history of involving industry.

R&D CONSORTIA FOR ELECTRONIC IMAGING SYSTEMS

An area of technology where U.S.-owned firms are active is electronic imaging systems, such as high-resolution and advanced imaging. U.S.

computer makers are advancing the quality and the technology of graphics in the products they offer; U.S. electronic equipment firms are leading in advanced imaging systems and many of their components. Most of these areas are developing as rapidly, if not more so, than is consumer-oriented, high-definition television (HDTV). For instance, U.S. personal computer makers are already selling graphics systems with roughly the same number of lines on the video display as HDTV. The areas where U.S.-owned firms lag are in television receivers and integrated production equipment and in computer displays.

The substantial participation of U.S.-owned firms in these technology areas both complicates and reduces the need for additional federal activity, most notably sponsoring R&D consortia. The number of U.S.-owned firms in these fields increases the competing interests that the federal government may have to satisfy in defining the appropriate generic R&D. In addition, because the U.S.-owned firms participating in these areas include many of the largest and technologically sophisticated industrial firms--IBM, Eastman-Kodak, Bell & Howell, Unisys, Texas Instruments, Intel, Microsoft, among others--no single federal program may add productively to the roughly $120 million already committed to federal R&D in this area. Some funding, however, could be redirected toward commercial ends. Lastly, because of the diverse interests of the different groups, a single consortium may not serve all market segments. Potential exists for several smaller targeted consortia in narrow fields.

An additional complication is the relationship between domestic and foreign firms. In the areas of displays, U.S.-owned firms can profit from using foreign technology. Already IBM has entered joint development agreements with Japanese flat-panel display producers. Foreign firms have also made commitments to develop and produce high-resolution displays in the United States.

R&D CONSORTIA FOR X-RAY LITHOGRAPHY

Federal support has also been proposed for a consortium on x-ray lithography. Current lithography technology will no longer be appropriate for new semiconductor design by the late 1990s. Semiconductor manufacturers now use light to transfer the image of the integrated circuit from the master pattern (or mask) onto the silicon wafer. As integrated circuits become more complex and incorporate more devices, some other form of illumination will have to be found: x-ray lithography is the leading candidate. A beam of x-rays would substitute for the light used in optical lithography. Other forms of advanced lithography use electron beams or ion beams.

The Congress has been funding research on x-ray lithography, mainly through the Department of Defense and the Department of Energy. These efforts have been closely coordinated with private efforts, most notably IBM. Recently, IBM has suggested that the federal government and other semiconductor producers join it in a larger and more comprehensive program to develop x-ray lithography.

Other than making the funding process more secure, it is not clear what more a collaborative effort could do. The federal agencies and private companies are all professionally and institutionally aware of each other's work. The groups active in supporting R&D on x-ray lithography already coordinate with each other. Nevertheless, federal funding for x-ray lithography R&D has been erratic. Formal commitment to a long-term program might increase funding stability and proper planning.

X-ray lithography that uses a synchrotron, a type of particle accelerator, as an x-ray source is one answer to the problems facing lithography, but a half dozen technologies seem promising to semiconductor engineers. Each technology has some problem that is now perceived as insurmountable. Breakthroughs may come in any of these areas. DARPA has investigated how it should support R&D on advanced lithography systems as well as on x-ray. Some changes in its funding commitments may result. The policy objective is to have a portfolio of R&D projects in lithography so that the federal government does not have to guess which lithography system will succeed.

CONCLUSIONS

R&D consortia are often touted as the solution to the problems of competitiveness for U.S. industry. Consortia represent only one of many forms of collaborative R&D, ranging from cross licensing to joint development ventures. R&D consortia can be useful in a variety of circumstances, but they complement more than substitute for the research efforts of individual companies and government programs.

Their principal contribution seems to be in strengthening the relationships between suppliers and their potential customers within an industry without forcing actual merger. The usefulness of R&D consortia depends largely on the research agenda specific to the relevant industry. The existing SEMATECH program seems to be working well. In other areas analyzed in this study--high-resolution and advanced imaging systems and x-ray lithography--the justification for an R&D consortium is subject to substantial qualification.

CHAPTER I

INTRODUCTION

Concerns about the declining international competitiveness of U.S. industry have prompted proposals for additional federal support for research to help U.S.-owned firms bring new products to market. Proponents argue that because federal agencies do not now provide much support for commercial innovation, certain U.S. industries are at a disadvantage compared with similar industries in countries that provide support. Erosion of the U.S. share of the international market in several high-technology industries is often seen as evidence of this problem.

One commonly discussed vehicle for providing support is the research and development (R&D) consortium. An R&D consortium is typically formed when a proposed R&D project poses capital requirements as well as technical and financial risks that are too large for individual firms to undertake alone. European and Japanese firms have a long history of establishing such consortia, often supplemented by financial support from government. Taking their cue from the European and Japanese experience, advocates of greater federal support for commercial innovation have called for assistance from the federal government for industry-formed R&D consortia in a variety of technologies.

The federal government's pending decision on whether to foster R&D consortia will be part of a larger decision on whether to expand federal support of commercial innovation. A general perception is that U.S. universities and firms make many basic discoveries but fail to apply the fruits of this research to produce commercial products as rapidly as some foreign companies do. According to this view, merely increasing basic research will not help because foreign firms may reap the harvest. A more direct approach, such as supporting applied research into new technologies with wide application, is needed instead.

Obviously, government support of R&D consortia is a tool, not a goal. To increase national well-being, such consortia have to be the right tool for the job. This study analyzes recent experience with federally supported R&D consortia to determine what unique benefits they provide and to develop lessons from the experience for federal policymakers. The study also analyzes selected technology areas where R&D consortia have been proposed in order to determine whether such efforts would support the goal of increasing national productivity. Finally, the study examines some of the options available to the Congress should it choose to encourage the use and support of R&D consortia.

JOINT VENTURES, CONSORTIA, AND COLLABORATIVE EFFORTS

Most U.S. industries have substantial experience with collaborative efforts between firms of various kinds. At the lowest level of collaboration are cross-licensing agreements where two firms agree to share certain technology. For instance, Intel and the NEC Corporation each can use the technology patented by the other. One survey suggested that the average U.S. semiconductor firm had over eight such agreements for sharing technology during a seven-year period.[1] Beyond licensing agreements, there are joint development agreements or joint ventures where two or more companies agree to develop together and often to manufacture a product or family of products. For instance, Intel and Advanced Micro Devices (AMD) signed a 10-year agreement--now in arbitration--to develop jointly the family of integrated circuits headed by the Intel 80x86 series of microprocessors that power many personal computers. (See Glossary for definition of microprocessor and other terms.)

It is important not to overstate the extent of collaborative research. Most industrial R&D is still performed singly by private corporations; technical collaborations represent a very modest expansion of total R&D. One recent report suggested that among corpora-

1. Carmela Haklisch, "Technical Alliances in the Semiconductor Industry" (New York: New York University, Graduate School of Business, Center for Science and Technology Policy, February 1986), p. 55.

tions technical cooperation, while growing, represented no more than 1 percent to 2 percent of the research efforts of industrial nations.[2]

Firms establish joint or collaborative efforts for many reasons. They may wish to share the burden or risk in developing products that are especially costly. Reducing the risk seems a straightforward motivation. One firm may believe that another firm's assets or strengths can complement its own. For example, Toshiba, which has expertise in manufacturing memory integrated circuits, has entered technology agreements with Motorola, which has expertise in designing and manufacturing microprocessors.

In other instances, firms may be seeking to establish themselves as the "market standard" by being at the center of a wide net of technology agreements. Intel entered the aforementioned Intel-AMD agreement in an attempt to establish the Intel microprocessor as the industry standard. Intel intended to provide many sources of supply and different variants of microprocessors and related integrated circuits. At present, several firms are using this strategy to establish their microprocessors as the industry standard for use in engineering workstations.

One particular type of collaborative arrangement--the R&D consortium--has been the focus of much attention in policy circles. While there is no formal definition of an R&D consortium, this study will use the term to refer to multiparty collaborative arrangements to carry out research. What distinguishes this type of consortium from other joint arrangements is its open-ended nature. Most collaborative research aims to develop a specific product or technology for sale. Most R&D consortia currently discussed in public policy circles intend to emphasize the process as a means to strengthen more generally the technology base in the United States.

2. Herbert I. Fusfeld, "Significance for Technical Progress," *Technical Cooperation and International Competitiveness: Proceedings of an International Conference*, Herbert I. Fusfeld and Richard R. Nelson, eds. (Troy: Center for Science and Technology Policy, School of Management, Rensselaer Polytechnic Institute, April 1988), p. 272.

The National Cooperative Research Act of 1984

In 1984, the Congress passed the National Cooperative Research Act (NCRA) to encourage R&D collaboration within U.S. industry. The law has two principal components. First, it states that R&D ventures will not automatically be considered illegal as a monopoly or anticompetitive practice but will be judged only after weighing its beneficial and harmful effects. This aspect of the law codifies previous decisions. Second, it reduces potential liability to the actual damages caused by any anticompetitive practice, plus the costs for private antitrust suits brought against joint R&D ventures registered with the Department of Justice. Under most circumstances, a firm could be liable to treble damages if it loses a private antitrust suit.

Since the NCRA was passed in 1984, 150 filings of cooperative research ventures (or consortia) have registered under the act through December 1989. Many of these filings involve the same firms or entities. For example, Bell Communications Research, Inc. (Bellcore), a research cooperative of operating regional Bell companies, is registered. In addition, Bellcore itself has made at least 19 filings for joint research with nonmember companies, other research institutions, and one federal government agency.

Not all of these efforts are attributable to the NCRA. Even before the act, one international survey found over 300 different technical alliances among many different industries between U.S. and Japanese firms during the 1980-1982 period alone.[3] Analysts have suggested that the number of joint ventures and other collaborative agreements is on the rise, independent of the legal environment, as the investment requirements for new products increase and the time frame for capitalizing on new technology shrinks.

3. Cited in statement of Claude Barfield before the Subcommittee on Science, Research, and Technology of the House Committee on Science, Space, and Technology, *The Government Role in Joint Production Ventures* (September 19, 1989), p. 63.

PUBLIC PURPOSES FOR FUNDING R&D CONSORTIA

Collaborative R&D efforts now receive public funding for any of several reasons usually connected with a public goal. The most common reason is that the collaborative effort is performing research aimed at providing a product or a technology that some federal agency intends to purchase. This is the case with military research where a team of several companies undertakes the desired research for a fee: one company may design an airframe, while another firm designs an engine.

Another reason for collaborative R&D is that the technology being developed produces public benefits, even when it is not being purchased directly by a government agency. This is often the case in the standards-setting process. For example, the National Institute for Standards and Technology (NIST) is currently part of a consortium developing specifications to allow exchange of product data in factory automation. In contrast, the type of R&D consortium analyzed in this Congressional Budget Office (CBO) study requires federal funding for collaborative R&D efforts in the private sector where the results would be put to private use by the members of the collaborative, such as in the case of SEMATECH.

The clearest justification of federal funding for private sector R&D is the tendency for private markets to undersupply R&D. This undersupply results because of the inability of any single firm or group of firms to secure the full benefits from its R&D investment. In some industries, a national security aspect is often involved in the R&D. Moreover, R&D helps build up the nation's science and technology infrastructure by building human capital. Thus, R&D produces not only knowledge but also knowledgeable people.

Models of Commercial Innovation

Policy in support of commercial innovation is concerned with creating new products or better products or finding better ways of making old products. In the more traditional view of technological innovation, a new discovery passes through three stages on its way to becoming a product: basic research, applied research, and product development.[4] In basic research, the work is done without a specific application: only the general problem of a knowledge gap is addressed. By contrast, applied research centers on solving specific problems, while product development involves creating concrete solutions for specific problems by using specific tools. In this "pipeline" model, which is linear and sequential, research is at the beginning and products come out at the end. Accordingly, the appropriate place for federal support of R&D is commonly thought to lie near the beginning, where the fruits of the investment are to accrue mainly to the public and where the comparative advantage of any individual or firm is most limited.

While useful, the pipeline model makes several crucial assumptions that limit its usefulness in dealing with commercial innovation.[5] In the real world, substantial interactions take place between the various stages. Gaps in theories and scientific knowledge are often found during the later stages, when theory and knowledge are applied. Furthermore, later stages of innovation often set the research agenda in a specific field of knowledge. Thus, as technology progresses, the important scientific questions change.

The central motivating factor of commercial innovation is not science, as the pipeline model suggests, but rather design. Design of products for sale drives commercial innovation; similarly, research needed to create new knowledge occurs when it is needed to improve design. In the course of advancing specific designs, scientists and engineers discover the aforementioned gaps in knowledge and "go back to the lab" or, in the terms of the pipeline model, perform applied or basic research.

The pipeline model may also limit the government's ability to support technology and learning when the process is driven by commercial innovation. Researchers do not learn abstractly; they learn concretely.

4. For formal definitions of each, see National Science Foundation, *Science & Engineering Indicators - 1989*, p. 89.

5. This discussion is largely taken from Stephen J. Kline and Nathan Rosenberg, "An Overview of Innovation," in *The Positive Sum Strategy: Harnessing Technology for Economic Growth*, Ralph Landau and Nathan Rosenberg, eds. (Washington, D.C.: National Academy Press, 1986), pp. 275-305.

Thus, to learn about a given field requires an object on which to work. In commercial research, that object will often be a specific product. Consequently, in order to advance a given field, the federal government may have to advance the product design of the firm doing the research. During the 1950s and early 1960s, for example, the federal government helped promote the development of the integrated circuit industry. The government was successful, in large part, because it supported research on products that firms within this industry intended to sell. In short, the federal government helped product development.

From an economic perspective, the entire process of commercial innovation is a sequential search for the products or technologies with the greatest economic utility.[6] The first researchers in a field narrow the search, and subsequent researchers benefit from having fewer stones to turn. While scientists doing basic research are conventionally thought to be the first in a field, there is no reason why industry could not be first. Profit as well as the desire to advance science may motivate research. For example, even though the early integrated circuit companies might have gained from federally sponsored research, so too has every subsequent researcher in integrated circuits. (See Box 1 for information on the relationship between these technologies and other electronics industries.)

Because of these limits to the pipeline model, economists have been working on an alternative view of commercial innovation. In this view, design--not science--is the focus. Design is advanced through a "chain of innovation" that may parallel or link with science but is not necessarily led by it. The chain may start with the recognition of a potential market, go through design analysis and refinement, and end in production and distribution. At any point during this chain, innovators may need answers to questions beyond the limits of their knowledge, in which case they will either seek someone who knows the answer or conduct research that draws on the scientific infrastructure,

6. Paul A. David, David Mowery, and W. Edward Steinmueller, "The Economic Analysis of Payoffs from Basic Research--An Examination of the Case of Particle Physics Research" (policy paper prepared for the Center for Economic Policy Research, Stanford University, January 1988), pp. 18-24.

BOX 1
Electronic Products, Parts, and Technologies

Many complex or obscure terms are used in electronic manufacturing and technology within the semiconductor industry. The following examples distinguish electronic products from their component parts and manufacturing processes:

Electronic Consumer and Business Products

- Hand-Held Calculators
- Personal Computers
- Audio Compact Disk players
- Video Cassette Recorders
- High-Definition Television
- High-Resolution Systems

Components

- Semiconductors
  - Integrated circuits (chips)
    - Microprocessors
    - Dynamic random access memories (DRAMs)
    - Application-specific integrated circuits (ASICs)
  - Discrete semiconductor devices
    - Transistors
    - Diodes
- Displays
  - Cathode ray tubes
  - Flat-panel displays
- Other Components
  - Printed circuit boards
  - Magnetic and optical disk drives

Manufacturing Processes and Equipment

- Lithography
  - Optical uses wafer stepper
  - X-ray uses synchrotron accelerator and wafer stepper
  - Both use master patterns (called masks) to transfer image to wafer
- Etching

including universities, scientific personnel, instrumentation, and so forth.

Although the motivation for the question may be a specific design, the answer may be applicable to a wide variety of uses. Thus, research conducted to answer specific design questions is the link between innovation and science as commonly understood. Because of the central chain of innovation and its links with science, this view of commercial innovation has been called the "chain-linked" model.[7]

The two models have different strengths. The pipeline model is straightforward but has to be substantially modified to show how product development can be simultaneous with or even precede applied research. In contrast, the chain-linked model assumes that generic technical hurdles may appear while getting a new product to market; research--called "applied" in the pipeline model--may be done during the process of overcoming these hurdles.

The two models also produce different sets of policy implications. In the pipeline model, the most appropriate role for federal government funds is to enhance scientific contributions that have the most widespread potential benefits. In practice, this role means that the government funds basic and applied research but shies away from product development where private firms can secure the resulting benefits.

In the chain-linked model, the federal government would fund the scientific infrastructure as it does now. In contrast with the pipeline model, however, if the government felt that researchers in industry were advancing public knowledge through product design, it might support such research because all parts in the chain are linked and none is necessarily fully appropriable. Furthermore, because commercial innovation often sets the scientific agenda in the real world, the federal government might become involved in commercial innovation if it felt that the links in a particular case were important.

The competing models of commercial innovation outlined above have different implications for federal support of R&D consortia. The

7. Kline and Rosenberg, pp. 289-294.

pipeline model could be interpreted to limit federal participation in R&D consortia that would concentrate on basic or generic research--that is, cross industry--even if such research is "applied." By contrast, the chain-linked model would permit federal participation in consortia that concentrate on different stages of commercial innovation.

In practice, federal policy vacillates between the two models. On the one hand, the explicit intent is to avoid direct funding of projects that involve product development if the products in question are not for federal use or not of public concern, such as health. On the other hand, federal policy supports private efforts in product development through the research and experimentation tax credit.

Rationales for Supporting R&D Consortia

The reasons for supporting a federal role specifically in private sector R&D consortia center as much on the advantages of collaborative R&D as on whether the pipeline model or the chain-linked model is assumed. By supporting R&D consortia, the federal government may help to achieve many of the same results achieved in private joint ventures. An R&D consortium may contain firms with complementary strengths. It also may be a vehicle for transferring existing technology within an industry, where firms with average technology can have access to the best existing technology or otherwise share experiences. An R&D consortium may also help establish an industry standard, which might create a larger market.

The scale of the R&D program may make a difference in that benefits increase by the size of the consortia. Evidence on economies of scale in R&D is mixed, but some data suggest that a larger R&D effort may justify larger spending on capital equipment, which in turn may help R&D productivity. As more of an industry is represented in an R&D consortium, its member companies are also more likely to secure the benefits created by any innovation--in economists' terms, "to appropriate the returns." This likelihood might encourage more R&D.

R&D consortia may also avoid wasteful duplication of effort. Many firms perform identical research in a race to establish themselves as first to market in order to gain any resulting advantages. Avoiding duplication, while intuitively appealing, may not provide as large a dividend as is commonly thought. In order to understand and make use of the research results, member firms often have to replicate the research and, in any event, to maintain large research staffs and facilities.[8] In this sense, much of the cost-saving advantage of R&D consortia is illusory.

In addition, much of the R&D undertaken by competing firms is not really duplicated. Quite often, competing firms undertake research along different paths to what might ultimately be similar products or processes. Avoiding duplication may lead to a cost saving at the expense of maintaining a more diversified research agenda. Nevertheless, some research has suggested that U.S.-owned firms spend a great deal of effort, compared with Japanese firms, in developing new products based on technology developed outside the firm.[9]

Some analysts argue that collaborative R&D is often unfocused because of contradictory goals of the members. In an atmosphere of multiple agendas, the central focus of the R&D might become diffused and even lost. The tendency may also be to satisfy the least common denominator, which would result in mediocre research projects. If these factors were present, they would result in increased duplication, rather than less, as the more technologically progressive firms not only contribute to the consortium but also pursue their more aggressive and focused research in-house.

Public Purposes, Private Gains

While the public purpose in a federally sponsored consortium may be the more efficient use of national R&D resources, private firms enter

8. The importance of the R&D assets of the firms to which technology is being transferred is discussed in David Mowery and Nathan Rosenberg, *Technology and the Pursuit of Economic Growth* (Cambridge, England: Cambridge University Press, 1989) pp. 6-7 and 79-92. For a more theoretical formulation, see Giovanni Dosi, "Sources, Procedures, and Microeconomic Effects of Innovation," *Journal of Economic Literature* (September 1988), pp. 1130-1135.

9. Edwin Mansfield, "Industrial Innovation in Japan and the United States," *Science* (September 30, 1988), p. 1770.

collaborative relationships because they expect these relationships to be profitable in the long term. Thus, both public and private partners expect to gain from the consortium. But these partners often have different views on how much they are willing to invest and how long they are willing to await success.

What the federal government brings to a consortium is additional funds that permit the members to feel that they are all gaining net benefits. In addition, the government brings its "good offices"--that is, its ability to organize and sponsor or sanction the activity. Federal sponsorship may also help overcome the atmosphere of suspicion that often surrounds collaboration among U.S. businesses.

Even though the consortia being discussed may fulfill a public purpose, they also involve private firms with very different motives. The history of private joint ventures and consortia is littered with examples of failure because the member firms could not agree on the proper allocation of costs and benefits. Firms often do not wish to assign the proper personnel, or they withhold technology for fear of losing their competitive advantage. Coincidence of means is not the same as congruence of ends. Thus, even if a R&D consortium is the right tool for appropriate work, the consortium and its members are not perfect agents of public policy. Firms may use the resulting technology to do things the federal government did not intend--for example, to move production overseas.

Even in the area of competitiveness, R&D consortia may not be the perfect way to achieve the intended policy. Simply stated, actions that make U.S.-owned firms competitive may not make the United States competitive. For instance, many U.S.-owned firms are moving R&D out of the United States.[10] As noted above, R&D increases the abilities of those engaged in it. By moving the R&D overseas, these U.S.-owned firms may have reduced the future potential income of U.S. workers who would have become more skilled by performing the R&D. While the U.S.-owned firms may become more competitive through this action, the U.S. workers may become less so. Yet, the multinational corporations, which are under a great deal of pressure internationally

10. Robert Reich, "Who is Us?" *Harvard Business Review* (January-February 1990), p. 55.

to locate R&D in Europe and elsewhere, often take the lead in developing an industry agenda for the R&D consortium. Excluding these corporations, however, would omit much of the U.S. technical expertise available to any R&D consortium.

DECISIONS REGARDING R&D CONSORTIA

As R&D consortia are tools, not goals, the federal government has to decide whether a given technology area is worth pursuing and whether an R&D consortium is the appropriate tool. Beyond discussing individual cases, the Congress is also debating proposals that would carry out additional decisions on technology by creating a new civilian technology agency or by expanding existing ones. The federal government would give this agency the responsibility for selecting the appropriate technology areas and deciding the best tool for promoting commercial innovation in these areas, whether by supporting private R&D consortia or by providing direct grants and the like.

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CHAPTER II

SEMATECH

SEMATECH, the semiconductor research and development consortium based in Austin, Texas, is widely referred to as the model for a joint government-industry effort in collaborative R&D. Whether or not SEMATECH has fulfilled its goals and expectations is too early to judge. After a lengthy start-up phase centered mainly on internal organization, SEMATECH has begun work within the last year on its goal of improving the technology used to manufacture semiconductor devices, including integrated circuits (or, as they are commonly called, computer chips).

Although substantial discussions preceded SEMATECH's founding, many questions about its design and policy remain unanswered; many of the solutions to anticipated problems conceived during the design phase have proved inapplicable in practice. Policies and plans have evolved since SEMATECH's start and that evolution continues. Nevertheless, sufficient experience has occurred to permit some evaluation of SEMATECH's potential contribution to the semiconductor industry and of its applicability to other situations. At this early stage, the question that is most easily addressed is whether SEMATECH's initial policy decisions are consistent with the initial policy goals approved by the federal government when it funded the consortium.

HISTORY AND GOALS OF SEMATECH

SEMATECH was founded in the spring of 1987 to boost the manufacturing technology of the U.S. semiconductor industry. Since then, 14 U.S. semiconductor firms representing 80 percent of the output of U.S. industry have joined this consortium. The federal government initially approved $100 million for fiscal year 1988 to match the contributions of SEMATECH's member companies. The member companies and the federal government have committed themselves to five years of joint R&D in semiconductor manufacturing technology, each providing about one-half of the annual budget of roughly $200 million. The state and local governments also contributed. In addition to the semiconductor producers and the federal government, SEMATECH was joined by SEMI/SEMATECH, a consortium of 140 producers of semiconductor manufacturing equipment.

The Founding of SEMATECH

The period before the federal government funded SEMATECH was turbulent for U.S. semiconductor producers and the semiconductor industry in general. A worldwide slowdown in computer sales occurred during the 1984-1986 period. Since computers are one of the principal markets for semiconductor devices, such as transistors, diodes, and integrated circuits, this slowdown led to a decline in semiconductor demand. Because demand for semiconductors had grown so rapidly during the previous period, semiconductor producers worldwide, especially in Japan, had made enormous capital investments that came on line just when demand declined. Thus, as demand for semiconductors slowed, supply increased. Excess capacity drove rapid price declines: the cost of semiconductor memory devices per unit of memory fell by 70 percent between 1984 and 1985.[1] The semiconductor industry worldwide lost several billion dollars during this period.

Also during this period, most U.S. integrated circuit producers withdrew from the dynamic random access memory (DRAM) business--only Texas Instruments, Micron Technologies, and the International Business Machines Corporation (IBM) remained as substantial producers. Despite the withdrawal of U.S.-owned firms from the DRAM market, the majority of the decline in U.S. production during this period was the result of the worldwide reduction in demand and not of the increase in Japanese production.[2]

1. Integrated Circuit Engineering, *Status 1989* (Scottsdale, 1989), p. 3-49.

2. See Congressional Budget Office, *The Benefits and Risks of Federal Funding for Sematech* (September 1987), referred to hereafter as *Benefits and Risks*, pp. 15-16 for calculations.

Since DRAMs are the most popular single type of integrated circuit, often leading other integrated circuits in manufacturing technology and design density, many groups viewed this withdrawal with alarm. There are two common explanations for why U.S.-owned firms abandoned this market. Some industry observers argue that U.S. producers were pushed out by the predatory actions of Japanese producers, which were large integrated firms able to cross-subsidize their semiconductor operations from the sales of electronic equipment, such as television receivers, video cassette recorders (VCRs), and computers. Other observers point out that U.S.-owned firms often had better investment opportunities in microprocessors and other proprietary integrated circuits where unit prices and profits were much higher. The two theories are not mutually exclusive; the decision of any given firm may have had elements of both.[3]

Following their withdrawal from the DRAM markets, U.S. producers sought relief from Japanese pressure, first through legal action. Then, in September 1986, the U.S.-Japan Semiconductor Accord set minimum target prices for DRAMs and some other popular integrated circuits produced in Japan.[4] DRAM prices in the United States tripled overnight, much to the consternation of U.S. producers of computers and other electronic equipment. International prices were still reputedly below the target prices, putting U.S. equipment makers at a continuing disadvantage.

In April 1987, following months of increasingly acrimonious negotiations, the federal government imposed tariffs on imports of Japanese electronic equipment in retaliation for Japan's alleged failure to enforce the accord. The government of Japan responded by forming a special unit within the Ministry of International Trade and Industry to enforce the accord and to monitor DRAM production in Japan. The result was the largest increase in unit memory costs, ris-

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3. For one study combining both factors, see David C. Mowery and W. Edward Steinmueller, "Government Policy and Industry Evolution in the U.S. Integrated Circuit Industry: What Lessons for Newly Industrializing Economies?" (Stanford: Center for Economic Policy Research, January 1990), pp. 26-52.

4. Analysis of the accord and its effects are largely based on Kenneth Flamm, "The Impact of National Policy/Politics on the Semiconductor Industry," Presentation to the Semiconductor Equipment and Materials International's Twelfth Annual Information Services Seminar, January 15-18, 1989 (Newport Beach, Calif.: 1989).

ing by over 40 percent between 1987 and 1988 and restoring the Japanese semiconductor industry to profitability. Thus, federal consideration of funding for SEMATECH in the spring and summer of 1987 came during a period of heightened friction over semiconductor trade between the United States and Japan.

SEMATECH received support from many different quarters, often for very different reasons.[5] The semiconductor industry wanted the federal government to help restore the market share it enjoyed before the Japanese made massive investments in semiconductors. In addition, a widespread perception existed that the U.S. industry lagged in manufacturing technology and that government support for this technology could overcome the handicap. The Department of Defense (DoD) also supported SEMATECH on the grounds of national security, although only 3 percent of DoD computer chips surveyed were imported.[6] Finally, many analysts, both in and out of federal government, argued that this industry still had the potential to contribute disproportionately to the national well-being through technical advance and to have spillover effects both within the industry and throughout the economy. For these individuals, SEMATECH was one more incentive for the U.S. semiconductor industry to continue its history of unparalleled technical advance.

SEMATECH Plans and Early Accomplishments

SEMATECH was intended to have three phases, corresponding to integrated circuit designs with minimum feature size of 0.8 microns, 0.5 microns, and 0.35 microns. (A micron is a millionth of a meter. See Glossary for other technical terms.) Phase I was focused on state-of-the-art technology and was intended to establish a common baseline from which SEMATECH efforts could proceed. Phase II is now in the prototype stage and should be in the manufacturing stage by the end of 1990. SEMATECH's intent is to have this 0.5 micron technology in the

5. For a general discussion of the rationales for supporting Sematech, see Congressional Budget Office, *Benefits and Risks*, pp. 26-37.

6. Department of Defense, Defense Science Board, "Report of the Defense Science Board Task Force on Defense Semiconductor Dependency" (February 1987), p. 63.

hands of member companies in 1991. SEMATECH officials claim that the 0.35 technology of Phase III is on schedule for delivery during 1993.[7] While these phases are designed to first match and then surpass the leading Japanese technology, they will not necessarily or immediately be implemented by U.S.-owned firms, which have often lagged in manufacturing technology in preference to concentrating on design and other areas. (See Box 2 for a description of semiconductor manufacturing technology.)

Since the federal government first funded SEMATECH in December 1987, SEMATECH has accomplished a great deal, primarily in internal organization. SEMATECH rapidly organized itself and established industry consensus around a core R&D program. Most notably, SEMATECH assembled a staff of 550 people, one-half of which are scientists and engineers assigned for up to two years by the member companies. SEMATECH claims to have made every effort to ensure that members assigned competent persons with the result that the SEMATECH staff has a strong reputation. It built a state-of-the-art facility in Austin, Texas, in 32 weeks, a remarkable feat in itself; it then transferred software, designs, and expertise to the member companies on how they might go about building a similar facility. In essence, SEMATECH provided the best consensus for the industry on the tricks, tips, and traps of building a state-of-the-art facility.

EVALUATING CURRENT POLICIES AND EFFORTS

In its previous analysis of SEMATECH, the Congressional Budget Office contended that the value of SEMATECH depended on the answers to a series of questions and that certain risks were attached to the program.[8] Answers to some of these questions are still years away, such as whether the technology was best disseminated throughout the

7. Thomas Hayes, "Sematech Today: Cash Dispenser," *The New York Times*, January 4, 1990, pp. D1 and D4.

8. Congressional Budget Office, *Benefits and Risks*, pp. 43-52.

BOX 2
How Are Integrated Circuits Made?

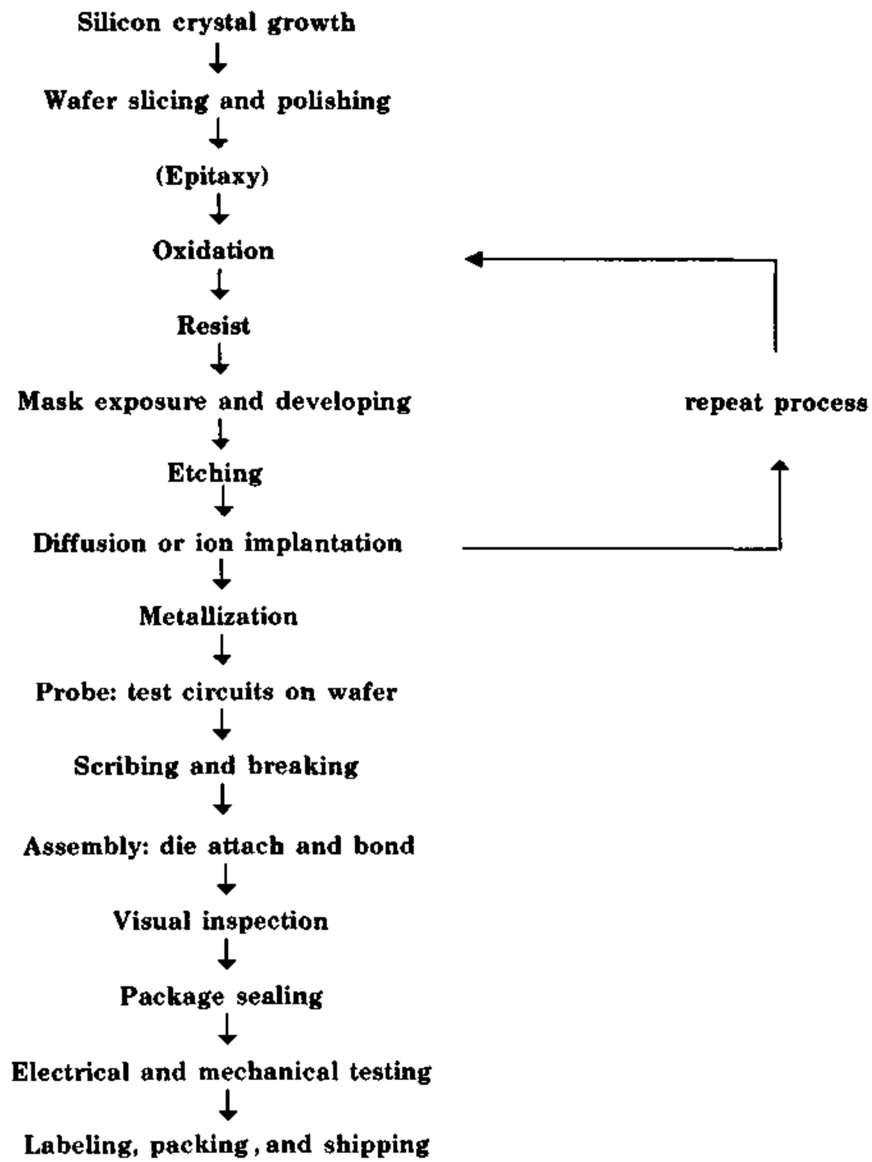
Production of integrated circuits (often called chips) is largely a chemical manufacturing process, rather than a mechanical or electronic process.[1] Most semiconductor devices are produced by taking silicon wafers, usually three to six inches in diameter, and chemically modifying them to create electronic pathways on their surfaces. The process for making logic chips may vary from that for making memory chips, but there are enough similarities that the same production lines are commonly used for both, though not simultaneously. The stages of the manufacturing process for integrated circuits are shown in the diagram.

Manufacturers first take wafers of hyper-pure silicon and grow a layer of silicon dioxide on the top by placing the wafer in an oxidation oven. The oxide layer is then coated with a light-sensitive chemical (called the resist) that makes the wafer like photographic paper. A photographic image of the first layer of the circuit to be manufactured is then projected on one corner of the resist. This process is repeated until several hundred images of that one layer cover the entire wafer. After the resist has been developed, the defined parts of the circuit are washed away, exposing the oxide layer underneath. The oxide is etched away, leaving the silicon uncovered. The silicon is modified by introducing phosphorus or boron into its crystal structure, either through chemical deposition or ion implantation. These impurities create the unique electronic characteristics that give the chip its power. This entire process is repeated for every layer of the circuit. After the silicon layers have been laid down, the manufacturers deposit one or more layers of metal (usually aluminum) to provide interconnections.

The completed circuits, hundreds to each wafer, are then tested. The automated testing equipment holds each wafer and sequentially tests and marks each of the hundreds of circuits on the wafer. After testing, the wafer is sawed into the individual devices (called die). The circuits that passed testing are then packaged and tested again.

1. Discussion taken from David Elliott, *Integrated Circuit Fabricated Technology* (New York: McGraw-Hill, 1989).

The Stages of Integrated Circuit Fabrication



SOURCE: Richard Levin, "The Semiconductor Industry," *Government and Technical Progress*, Richard Nelson, ed., (New York: Pergamon Press, 1982), p. 17.

economy. Other questions are able to be considered, if not answered, at this time, rephrasing the questions to reflect a change in circumstances,

- Does SEMATECH address the right problems in the U.S. semiconductor industry and in a way that also supports national interests?

- Does SEMATECH unduly centralize the nation's semiconductor research?

- Do the private and public participants fulfill their new institutional roles as defined by SEMATECH?

The Focus of SEMATECH Research Efforts

The name SEMATECH is a contraction of "semiconductor manufacturing technology," the improvement of which is its goal. At the risk of oversimplification, this manufacturing technology can be divided into equipment (the tools used to make semiconductors) and technique (how well the tools are used). In the original design for SEMATECH, the R&D focused more on technique. Specifically, it concentrated on the advanced wafer fabrication plant. (Integrated circuits and other semiconductor devices are typically fabricated on a wafer of silicon three to eight inches in diameter, so the manufacturing facilities are called wafer fabrication plants--fabs for short.) In fact, the construction of the plant is an example of this concentration on technique.

SEMATECH was going to build a state-of-the-art semiconductor manufacturing plant, contract out for some even newer manufacturing equipment, improve it, and show U.S. semiconductor producers how to use this plant to its fullest. The overwhelming majority of SEMATECH resources was to be devoted to in-house research in the plant. In the original budget, between 15 percent and 20 percent of the resources were devoted to R&D contracts with outside firms.[9]

Since then, the balance of resources seems to have shifted somewhat. In SEMATECH's 1990 operating plan, 35 percent of its expenditures are devoted to R&D contracts.[10] Outside R&D contracts with semiconductor manufacturing equipment producers have begun to be signed: the first R&D contract went out in the spring of 1989. After a somewhat slow beginning, SEMATECH has picked up the pace of authorizing these contracts. (The complete list, as of June 1990, is presented in Box 3.)

The R&D contracts so far have gone mainly to semiconductor manufacturing equipment or material producers, although one went to the National Institute for Standards and Technology for measurement technology. SEMATECH has also awarded grants to 11 Centers of Excellence for specialized semiconductor research, such as to the University of Wisconsin for x-ray lithography, and entered into agreements or negotiations with two Department of Energy national laboratories for specialized semiconductor research. SEMATECH is committed to spend roughly $10 million per year in these Centers of Excellence.

SEMATECH considers the details of its contracts proprietary and will not divulge information. These remarks on SEMATECH contracts are based on CBO's discussions with industry observers and published reports. Some contracts may be different than the two types discussed here. A joint development contract focuses on new equipment or materials, while a contract to improve equipment focuses on existing equipment. At least one firm got both types.

Both types of R&D contracts, however, are intended for semiconductor manufacturing equipment. Some producers of this equipment are receiving SEMATECH contracts to make their products now on the market more competitive. For instance, one SEMATECH contract to improve equipment is going to Lam Research to improve the

9. *Benefits and Risks*, p. 40.

10. Sematech, "Operating Plan, 1990" (Austin, Texas), p. 12.

BOX 3
SEMATECH R&D Projects for Equipment

Joint Development Projects (JDPs). SEMATECH works with U.S. suppliers on JDPs to develop new equipment, materials, and processes that support manufacturing requirements for future generations of technology. Contracts for JDPs as of June 1990 include:

Supplier	Project
Advantage Production Technology (Sunnyvale, CA)	Wafer cleaning system
AMRAY, Inc. (Bedford, MA)	High-resolution defect imaging and review tool
Applied Science and Technology, Inc. (Woburn, MA)	Advanced plasma-etch technology tool
ATEQ Corporation (Beaverton, OR)	Advanced, submicron reticle, and mask exposure system
AT&T (Murray Hills, NJ)	Deep ultraviolet resist technology
Drytek (Wilmington, MA)	Low-temperature plasma etching
Eaton Semiconductor Equipment Division (Beverly, MA)	Advanced metal deposition system
Gas Supplier Team: Union Carbide Industrial Gases, Inc. (Danbury, CT) Semi-Gas Systems (San Jose, CA) Wilson Oxygen and Supply (Austin, TX)	Total systems approach to gas-related requirements
GCA--Subsidiary of General Signal Corporation (Andover, MA)	Optical wafer stepper
Hampshire Instruments (Marlborough, MA)	X-ray optics
Hewlett-Packard (Cupertino, CA)	Test chips and other devices for manufacturing demonstration
KLA Instruments (Santa Clara, CA)	System to detect wafer defects
Lam Research (Fremont, CA)	Technology for chemical vapor deposition
NCR Corporation (Dayton, OH)	Isolation process technology

National Institute of Standards and Technology(Gaithersburg, MD)	Development of a metrology standard
ORASIS Corporation (Sunnyvale, CA)	System to detect wafer defects
Orchid One (Palos Hills, IL)	Advanced electron beam microscope
Silicon Valley Group (San Jose, CA)	Advanced lithography processing systems
Silicon Valley Group Lithography Systems (San Jose, CA)	Advanced lithography systems
University of Cincinnati (Cincinnati, OH)	Research on advanced plasma-etch technology
Westech Systems, Inc. (Phoenix, AZ)	Planarization equipment and processes

Equipment Improvement Programs (EIPs). SEMATECH attempts to upgrade or modify existing U.S. equipment to meet its manufacturing requirements for current and future needs. EIPs focus on improving the function and reliability of equipment in order to decrease repair time and process costs and to increase the ease of manufacturing the equipment. Programs are conducted at SEMATECH or at the site of a member firm. EIPs initiated to date include:

Supplier	Project
AMRAY, Inc. (Bedford, MA)	AMRAY 1830 scanning electron microscope
Angstrom Measurements, Inc. (Sunnyvale, CA)	Scanline II scanning electron microscope CD measurement tool
Applied Materials (Santa Clara, CA)	Precision 5000 chemical vapor deposition system
GCA--Subsidiary of General Signal Corporation (Andover, MA)	ALS 200 optical I-line stepper
Genus Incorporated (Mountain View, CA)	Genus 8720 chemical vapor deposition system for blanket and selective tungsten films
Lam Research (Fremont, CA)	Rainbow 4600 plasma metal etch system
Silicon Valley Group (San Jose, CA)	Vertical furnace technology

SOURCE: SEMATECH.

capabilities and quality of its Rainbow 4600 system. SEMATECH is also providing contracts to make the next generation of U.S. semiconductor manufacturing equipment more competitive. For instance, SEMATECH is providing GCA, a subsidiary of General Signal Corporation, with a contract to improve the reliability and performance of GCA's lithography equipment that is currently under development.

Currently, SEMATECH will provide no more than one-fourth to one-third of its funds in a joint development effort with an equipment producer; the rest comes from the producer.[11] The equipment producer owns the technology, but it is subject to certain restrictions. First, SEMATECH members have the right to first refusal for the equipment. Second, if the equipment producer fails to deliver, the money may have to be refunded to SEMATECH. Third, if the producer of the equipment is sold to a foreign company, the money may have to be refunded.

To a large extent, SEMATECH has no other choice but to put strict financial requirements in its R&D contracts. The problems with R&D contracting are numerous. If the equipment firm does not have a substantial amount of its own funds at risk, it might pursue R&D that, while technically interesting, might be commercially less feasible. Since SEMATECH's goal is to develop short- to mid-term technology to enhance the manufacturing abilities of the semiconductor industry, SEMATECH's officers wish to keep contractors focused on the needs of that industry. While the precise nature of the split might be debatable, the need to provide commercial incentives is not.

SEMATECH also wants to improve the relationships between producers of semiconductors and the producers of semiconductor manufacturing equipment. As part of this effort, SEMATECH will be purchasing 16 of the GCA wafer steppers and distributing them free of charge among SEMATECH members for site testing.[12] The members will have the option to buy the equipment. This program will give GCA unique market feedback on how its largest clients rate its newest

11. Some information on contract details comes from Report of the Advisory Commission on Federal Participation in Sematech, "Sematech: Progress and Prospects" (1989), pp. 14-19.

12. Peter Dunn, "Sematech to Distribute I-Liners," *Electronic News*, March 12, 1990, pp. 1 and 8.

products during a period when those clients are committing themselves to the next generation of equipment. SEMATECH views all these efforts as part of a total program intended to strengthen the U.S. supplier base.

Why the Focus Has Changed. The late Dr. Robert Noyce, former chief executive officer (CEO) of SEMATECH, explained this shift from research on technique to research on equipment.[13] He argued that, when systematic research began to explore the deficiencies of the supplier industries for semiconductor manufacturing, the situation was much worse than originally envisioned. Consequently, the SEMATECH leadership felt it had to shift resources to areas where they were more crucially needed.

Industry observers are correct in describing the trends in the U.S. semiconductor manufacturing equipment industry as negative, but the absolute levels of output and market share are still quite high. According to SEMATECH's own figures, the U.S. semiconductor manufacturing equipment industry continues to lead the world in overall market share.[14] This continuing strong market position suggests that the acute problems in the equipment industry are limited to specific products, mainly optical lithography. The two U.S. major firms in this area--GCA and Silicon Valley Group Lithography Systems (formerly Perkin-Elmer)--have both experienced major problems in the recent past. Silicon Valley Group Lithography Systems' effort to leapfrog current technology has been more difficult than originally estimated. GCA, which dominated the wafer stepper market in the late 1970s and early 1980s, saw its technology overtaken by Nikon and was unable to mount a challenge.[15]

A recent survey of semiconductor producers, representing roughly 75 percent of U.S. industry output (measured in dollars), indicated that

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13. Dr. Robert Noyce in response to questions before the Industry and Technology Subcommittee of the Senate Armed Services Committee, November 29, 1989.

14. Sematech, "1989 Annual Report," p. 15.

15. For an extensive discussion of the problems of U.S. optical lithography companies, see Rebecca Marta Henderson, "The Failure of Established Firms in the Face of Technical Change: A Study of Photolithographic Alignment Equipment" (Ph.D. Dissertation, Harvard University, 1988), pp. 194-230.

the vast majority of the semiconductor manufacturing equipment purchased for U.S. operations during the 1985-1987 time frame (pre-SEMATECH) was made by U.S.-owned equipment producers.[16] The same semiconductor manufacturing firms, however, did forecast a decline in their purchase of U.S. equipment in the 1988-1990 time frame. Even given this decline, U.S. equipment producers are forecast to hold, in most instances, over 70 percent of the market. The one major area of weakness--optical lithography--represents about 22 percent of total expenditures on semiconductor manufacturing equipment.[17]

One reason for concern is that Japanese firms have moved aggressively into this market. They have taken lower returns than U.S. investors and have capitalized on the mistakes of U.S. industry leaders. While they have suffered many setbacks, Japanese semiconductor manufacturing equipment firms have persisted and thus gained market share. In addition, some observers argue that aggregate market share is not as important as market share in certain "show stopper" technologies, such as wafer steppers.[18] In several of these crucial individual technologies, Japanese firms currently hold the lead. This lead accounts for SEMATECH's determined effort in optical lithography. Lastly, SEMATECH's surveys indicate that among its members the market share of Japanese semiconductor manufacturing equipment is much higher for the leading edge facilities than for the older facilities. U.S.-owned firms hold a comfortable lead in facilities producing integrated circuits with minimum feature sizes of one micron and over; at the submicron level, however, U.S. market share drops substantially below the Japanese.

The shift in SEMATECH R&D efforts might be desirable for reasons that have more to do with its membership than with the problems of equipment producers. Simply put, SEMATECH members may find

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16. Semiconductor Equipment and Materials International, "Results of the 1989 Semiconductor Equipment and Materials Procurement Survey" (Mountain View, Calif.: 1989).

17. Calculated from Joseph Grenier, Dataquest, Inc., "Wafer Fab Equipment Forecast," Presentation to the Semiconductor Equipment and Materials International's Thirteenth Annual Information Services Seminar, January 22-24, 1990 (Newport Beach, Calif.: 1990).

18. The U.S. decline in market share of wafer steppers is largely a decline in GCA's market share. The Silicon Valley Group Lithography Systems was never a major force in wafer steppers.

more common ground in pursuing improved equipment than in pursuing improved technique. Each of SEMATECH's members has a unique manufacturing process, each with its own degree of sophistication. IBM, for example, manufactures integrated circuits with 0.8 micron minimum feature sizes, while Rockwell International uses 1.8 micron minimum feature sizes. Much of the technique and process integration that was SEMATECH's original target might not be transferable to a substantial portion of the membership. Even though the manufacturing techniques might be different, the manufacturing equipment is largely the same. Thus, improving the equipment is a common concern. To a large extent, therefore, SEMATECH has internal pressures to shift its focus from technique to equipment. In addition, pressure has come from the federal partner to increase the level of R&D contracts.

The shift may also reflect a return to a previous period in the relationship between semiconductor producers and equipment producers.[19] In the 1960s and 1970s, U.S. equipment producers and semiconductor producers shared the costs of developing new equipment. For the main part, this sharing was informal: when equipment producers delivered new equipment, it often needed more development to make it truly functional. For this and other reasons, semiconductor producers accounted for the bulk of the equipment and process innovations in semiconductor manufacturing, in contrast to most other industries where equipment producers account for the bulk of process innovation.[20] U.S. equipment producers could afford to force their customers to bear the costs of development because they held a near monopoly position in advanced semiconductor manufacturing technology.

In the 1980s, the Japanese equipment producers began manufacturing advanced technology equipment and, after several faltering steps, began delivering finished products that needed no further refinements by semiconductor producers. This situation forced U.S. equipment producers to absorb all the costs of development; consequently,

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19. This discussion is largely based on Dan Hutchinson, "The State of America's Semiconductor Equipment Industry: Challenges for the 90s" (VLSI Research, November 1989).

20. Eric Von Hippel, "The Dominant Role of the User in Semiconductor and Electronic Subassembly Process Innovation," *IEEE Transactions on Engineering Management* (May 1977), pp. 60-71.

their profits dropped. U.S. equipment producers also lost market share as the reputation of Japanese equipment producers grew. Some industry analysts might view SEMATECH's emphasis on equipment R&D as a return to the situation that prevailed before the mid-1980s when semiconductor producers and equipment producers shared development costs.

The Public Purpose. Whether a focus on technique or equipment at SEMATECH would best serve a public purpose is unresolved. CBO's previous published study on SEMATECH suggested that a central reason for providing support to SEMATECH might be to strengthen the position of producers of semiconductor manufacturing equipment. Simultaneously, the analysis noted a widespread perception both within the industry itself and by industry observers that the U.S. semiconductor industry needed help with manufacturing technique because U.S. semiconductor producers did not use well the equipment they already had. While U.S. semiconductor producers may still, on average, lag in technique, the industry has made efforts in this area. The more advanced U.S. semiconductor producers are considered world class.[21]

The disparity in interests and abilities of SEMATECH members may mean that SEMATECH is more likely to be a success by concentrating on improving the position of the producers of semiconductor manufacturing equipment. While improving technique might be desirable, it might not lead to usable results. For instance, one of SEMATECH's major organizational successes was the rapid construction of the 0.8 micron wafer fabrication plant and the delivery of detailed engineering data on this state-of-the-art facility to SEMATECH members, the bulk of U.S. semiconductor producers. SEMATECH hoped to raise the average level of ability in U.S. semiconductor manufacturing firms by disseminating the best available information.

21. One recent survey indicated that U.S. semiconductor producers had doubled their spending on quality during the late 1980s. Because of the specific nature of semiconductor manufacturing, this increase in quality spending would normally result in increased usable output per unit input and hence lower costs. See National Institute of Standards and Technology, "U.S. Investment Strategies in Quality Assurance" (prepared by Quick, Finan & Associates, Washington, D.C., April 1990), pp. 69-70.

Much of this information, however, is simply not usable by U.S.-owned firms. Some SEMATECH members are not at 0.8 micron manufacturing; by the time they reach this level, the current practice will be obsolete. In other instances, SEMATECH members that do use 0.8 micron processes are committed to different techniques. For example, Texas Instruments is building a new semiconductor memory plant in Italy. The memory manufacturing techniques used by Texas Instruments, however, were developed largely in Japan and are based on Japanese equipment.[22] Nevertheless, SEMATECH planners felt that the 0.8 micron facility could be used for a variety of semiconductor devices and that the cleanroom facility could be adapted to many products and techniques.

SEMATECH's fabrication plant also serves as a central research facility for the equipment producers. Once prototypes of equipment become available, they will be tested at the SEMATECH fabrication plant. Having a source of technical feedback for new pieces of equipment is valuable to equipment producers. Where cooperation exists, such as at the Microelectronics Center of North Carolina, suppliers report that technical feedback coming from sophisticated users is of great value. As part of its effort, SEMATECH holds regular comprehensive debriefings for equipment producers that made losing bids for SEMATECH R&D contracts. The briefings outline areas that need improvement or that are different from the needs of the semiconductor producers that would be their customers. Thus, SEMATECH has served to improve communications between equipment producers and semiconductor producers.

Within the equipment R&D itself, there is an additional tension: improving the current generation of equipment versus producing the next generation. The pressures on SEMATECH are to increase equipment improvement contracts at the cost of joint development contracts. The clearest example of this pressure is the purchase of the GCA equipment and its distribution to SEMATECH member firms. While SEMATECH has funded some R&D into increasing the manufacturability of the equipment, the GCA system was already largely developed. SEMATECH's program of purchases is directed not so much

22. Peter Dunn, "TI's Italian Fab to Use Japanese Gear," *Electronic News*, November 27, 1989, p. 26.

at the technology, but rather at strengthening the ties within the industry.

Normally, the public interest would lie in the opposite direction: the funds tied up in purchasing existing equipment cannot be used to develop new equipment--SEMATECH's expressed purpose. The issue in this case is whether GCA, which is the only major U.S. producer of this type of equipment, could continue without an effort to renew its ties to its potential customers. SEMATECH officers claim that there were substantial institutional barriers and that, without an effort to overcome these barriers, the technology (both the current and the next generation) developed by GCA under SEMATECH's aegis would never come into widespread use. They also state that SEMATECH is unlikely to repeat this effort for other equipment producers.

Centralizing the R&D Agenda

Before SEMATECH was funded, there were concerns that investment in such a consortium would reduce the range of R&D on manufacturing technology being performed or funded by semiconductor producers. Some anecdotal evidence exists that this has happened. Small semiconductor manufacturing equipment producers report that semiconductor firms are less likely to fund R&D independently of SEMATECH and that SEMATECH has an elaborate decisionmaking process that results in only certain firms being funded. In early 1989, press reports alluded to disaffection among some small producers of semiconductor manufacturing equipment. Private firms were also reported to be channeling a great deal, though not all, of their long-term R&D on manufacturing technology through SEMATECH. Furthermore, the SEMATECH R&D agenda is reportedly determined not only by technical criteria but by the perceived ability of the manufacturer to become successful. This added criteria broadens the concern that not only is the research agenda being narrowed but so too might the supplier base.

Considered differently, SEMATECH provides a screening role. Much of the R&D funding by federal agencies, while interesting technically, proves irrelevant commercially. The research results either in products that are too costly or not robust enough for an industrial environment. Problems also often arise when transferring the technology to industry. By focusing less on the gee-whiz aspects of technology and more on the abilities of U.S.-owned firms to deliver the goods in question, SEMATECH does attempt to direct resources to where U.S. industry is perceived weak. Wide agreement exists that U.S.-owned firms are ahead on the technical criteria in many areas of semiconductor technology but often lag in the application of advanced technology for production on the shop floor.

Many industry observers argue that the equipment industry is in need of consolidation and hard decisions on what direction to take. While some interesting technologies may be lost, the resulting financial health of the remaining firms may more than compensate for the loss. In addition, because of the high profile SEMATECH has within the industry, equipment delivered under its aegis is more likely to make its way to the shop floor. This accessibility may have two effects: firms that do receive SEMATECH funds for R&D may be strengthened, and the technology that is developed with federal funds may more likely be used. This latter consideration is substantial as a great deal of federally sponsored technology is simply not used.

SEMATECH is not, however, considering only one firm for each crucial technology. For instance, both Silicon Valley Group Lithography Systems and GCA are receiving SEMATECH R&D funding for optical lithography. Furthermore, each of these firms represents a different approach to optical lithography. Thus, SEMATECH has funded what it considers the two leading firms in the most likely technologies within optical lithography. In other instances, SEMATECH takes firms with novel technology but an unproven track record and provides them with contracts to determine the validity of their claims. This approach allows SEMATECH an early view of the potential of new technology avenues. SEMATECH calls this "management by data."

The process of organizing SEMATECH has provided the industry with a clearly defined research agenda. The formation of SEMATECH was preceded by a series of technical workshops where semiconductor manufacturing technology was analyzed and the improvements needed at every step were discussed. Even though SEMATECH has had to narrow its choices on which of the hundreds of manufacturing steps to focus, the process did make explicit many of the tacit beliefs about technology trends in the industry. This type of market information is quite valuable to firms with only limited access to capital. For instance, some firms could postpone or concentrate R&D efforts because SEMATECH has discovered that current technology will suffice in one or another aspect.

This centralized strategy is not without risks, however. Small firms do sometimes produce items of great value, even if their manufacturing record is slight or nonexistent. By focusing on near-term ability to manufacture, SEMATECH may pass up technology of great potential. To the extent that semiconductor producers channel their R&D funding through SEMATECH, this effect will be amplified. SEMATECH has attempted to reduce these risks by partnering firms--that is, linking a firm with a technically interesting proposal but insufficient business experience to a firm with a more solid business background. SEMATECH officials claim that partnering has helped some, though not all, such firms overcome their weaknesses.

Clearly, the effect of SEMATECH on the concentration of the semiconductor industry's R&D agenda should not be overstated. SEMATECH is not intended to be the source of all advance in semiconductor technology. SEMATECH's role is to provide support for manufacturing technology that will come into widespread use within the next five to eight years. Considering the small size of SEMATECH funding--roughly 5 percent or 6 percent of all semiconductor R&D in the United States and roughly 20 percent of federal semiconductor support--most of the future semiconductor manufacturing technology will be developed outside SEMATECH's aegis.

New Institutional Roles for Private and Public Sectors

When SEMATECH was first proposed, the ability of its members or of the federal government to fit in their required roles was not clear. Many observers argued that semiconductor producers would find sharing information difficult. Others doubted that DoD could play the role of silent partner.

The Role of Vertically Integrated Semiconductor Producers. IBM and American Telephone and Telegraph (AT&T) played a pivotal role in the formation and stability of SEMATECH. The support of IBM was widely understood as crucial during the negotiations leading to the formation of SEMATECH. Since its formation, IBM and AT&T have provided personnel and technology, in addition to their contributions as SEMATECH members. IBM provided the technology most important for manufacturing the latest generation of dynamic random access memory (DRAM), while AT&T provided the latest generation of static random access memory (SRAM). Between these two, SEMATECH had an important technological dowry.

About one-third of SEMATECH members, most notably IBM and AT&T, produce semiconductor devices primarily or exclusively for internal consumption. They compete in the markets that use semiconductors, such as computers and telecommunications equipment and instruments, not in the semiconductor market itself. This situation adds an element of stability and trust to the consortium.

The fact that IBM is not only the largest computer producer but also the largest semiconductor maker further reinforces this stability.[23] IBM's profits are derived primarily from computers, not chips. IBM also has a reputation for wanting to buy one-half of its components and make one-half. This combination of profit plus presence as a buyer in the semiconductor market means that IBM can afford to be generous. IBM views SEMATECH as an opportunity to reduce the costs of its inputs. The perception that IBM and AT&T (to a lesser extent) are footing the bill ensures that other semiconductor producers will gain an advantage in participation. IBM and AT&T may also gain by providing the memory chip technology. If SEMATECH improves the technology, then IBM and AT&T will be in the best position to use those improvements.

The unique position of AT&T and IBM as major producers of both electronic equipment and semiconductor technology makes it less likely that the SEMATECH experience could be repeated in other indus-

23. W. Edward Steinmueller, "Industry Structure and Government Policies in the U.S. and Japanese Integrated Circuit Industries," in John B. Shoven, ed., *Government Policies Toward Industry in the U.S. and Japan* (New York: Cambridge University Press, 1988), pp. 319-354.

tries. Many other industries have vertically integrated producers--that is, firms that produce not only the final goods but also the intermediate goods. In this case, IBM produces the final goods (computers) and the intermediate goods (semiconductors). What makes this unique is that the most technologically dynamic and vertically integrated firms (IBM and AT&T) do not also serve the intermediate goods and markets.

The Role of the Defense Advanced Research Projects Agency. The early fears that the DoD might distort R&D choices of SEMATECH in ways that may be militarily useful but commercially irrelevant have thus far proven unwarranted. Indeed, the Defense Advanced Research Projects Agency (DARPA) is often acknowledged as having played an early and crucial role in helping SEMATECH organize. SEMATECH had great difficulty in finding a Chief Executive Officer, but DARPA kept the pressure on. DARPA officials made SEMATECH officials solidify the original plan of operations: specific technology would be due on specific dates. The increase in outside R&D, which SEMATECH now embraces, was also urged upon SEMATECH by DoD officials.

Whether DARPA will be able to play as central a role in the future is not clear. DARPA currently has one full-time official assigned to monitor SEMATECH. This officer also has other duties, such as being executive director of the National Advisory Committee on Semiconductors. The Department of Commerce also has an officer at SEMATECH who reports to DARPA. The Air Force as well has an individual assigned to SEMATECH.

DARPA has no funds beyond its general administrative budget to oversee SEMATECH: the appropriations are earmarked for SEMATECH. Thus, lacking resources, DARPA will be forced into a more modest role. SEMATECH may not need DARPA guidance as much now that the policies and structure are in place. While major technical issues are to be decided, DARPA may not be helpful in solving them.

Near-Term Prognosis

The untimely death of Dr. Robert Noyce, CEO of SEMATECH, has introduced a new level of uncertainty into SEMATECH's future. Dr. Noyce had already announced his intention to resign, so a search committee was already formed. Given the difficulty of finding a CEO the first time, SEMATECH will be fortunate if it can resolve this circumstance shortly.

From an administrative perspective, however, SEMATECH's prospects are much brighter now than when the first search began. SEMATECH's programs have taken shape in the last year. The technology roadmaps are much more explicit now since being applied to those programs. Many of the priorities have been set, and the R&D contracts have been let. That is not to say SEMATECH 's needs are reduced to a caretaker administration, but the range of choices that the next CEO will have to make has been substantially narrowed. Furthermore, more people within SEMATECH now have a clearer perspective on exactly what the goals are. Given Dr. Noyce's reputation as a manager who led by building consensus and by creating an environment to sustain it, this consensus could carry SEMATECH through the next phase of research.

FEDERAL POLICY OPTIONS

The National Advisory Committee on Semiconductors has recommended that the federal government increase SEMATECH funding by $50 million to be matched by industry members.[24] Without these additional funds, the committee claims, the needs of this segment of the industry cannot be fully addressed. As part of its recommendation, the committee argues that the SEMATECH mission should be broadened to include work beyond 1993. This recommendation would increase both SEMATECH's budget and time frame. SEMATECH currently receives $100 million from the federal government and roughly $125 from member companies and other sources. This proposal would

24. National Advisory Committee on Semiconductors, "A Strategic Industry at Risk," November 1989, p. 29.

increase its budget by 44 percent. In addition, the original proposal involved a five-year (1988-1993) commitment for the federal government.

The committee offers little evidence of the need for additional SEMATECH funding, nor does it pinpoint the areas that SEMATECH is neglecting. The only proof or rationale for this claim is an estimated shortfall of $800 million for R&D in U.S. semiconductor manufacturing equipment over the next three years. Outside of the proposal for increased funding, this recommendation has no clear programmatic element. No specific recommendation is made for either federal agencies or private parties to make up the $800 million shortfall, nor does the committee reveal how this figure was derived. Between the U.S. government and U.S. capital-affiliated firms, roughly $600 million to $700 million is currently spent annually for R&D on semiconductor manufacturing technology. Furthermore, the committee does not make it clear why this spending level is $266 million too low.

The decisions facing the federal government are whether it wants to increase semiconductor manufacturing R&D and, if it does, does it want this increased R&D to fit SEMATECH's near- to mid-term perspective. SEMATECH is concentrating on manufacturing technology that will come into widespread use in the mid-term. Given SEMATECH's active program of equipment R&D, longer-term research into semiconductor manufacturing may be a better investment for the federal government. In fact, some equipment producers have already suggested setting up a federal facility for just this purpose.[25] R&D projects with a long-term perspective might be inappropriate to SEMATECH: either they would receive inadequate attention, or they would divert SEMATECH from its current mission. Thus, SEMATECH may be the wrong institutional tool for a program of longer-term R&D.

The member companies might also not wish to increase the level of their commitment to SEMATECH. Their commitment would be necessary if the 50/50 federal-industry split is kept intact. Early reports,

25. Jack Robertson, "Sen. Gore Hits Bush Inertia on Semicons," *Electronic News*, May 21, 1990, pp. 1 and 4.

however, suggest that the industry may be willing to follow the federal government's lead.

POTENTIAL FOR OTHER R&D CONSORTIA

Direct translation of the SEMATECH experience into other industries as a wider tool of federal policy may be limited. Several features are unique to SEMATECH and are unlikely to be repeated elsewhere, such as: the extent of SEMATECH membership within the semiconductor industry and the semiconductor manufacturing equipment industry; the clearly defined R&D agenda; and the special role of vertically integrated producers. Consortia lacking these features are not doomed to failure, but are likely to be structured differently. Consequently, federal planners should not try to remake them in the SEMATECH mold.

SEMATECH's principal contribution so far has been to strengthen the lines of communication between producers and users of semiconductor manufacturing equipment. SEMATECH has served to reduce uncertainty and risk in this market. Producers of equipment have a better understanding of the directions in which their most likely clients are going; users have a better understanding of the capabilities and problems of their suppliers and the extent to which other users share their own problems. SEMATECH encourages, without actually requiring, some of the beneficial communication and coordination typically associated with vertical integration, such as mergers.

The knowledge needed to reduce such uncertainty is quite detailed. The many assumptions and technicalities about future directions may become explicit only in the context of a research program. This knowledge has already improved the allocation of research resources for some equipment producers. Since SEMATECH members represent 80 percent of semiconductor manufacturing capacity, they have more power to impose solutions on their suppliers. The SEMATECH experience suggests that one important consideration for federal sponsorship of R&D consortia may be in strengthening these vertical ties.

A closely related implication is that R&D consortia can agree on a work plan when they engage in activities that affect competition among suppliers. SEMATECH is providing contracts to suppliers of semiconductor manufacturing equipment to improve their products. These contracts are growing within SEMATECH's budget, relative to those with universities and national laboratories, which are more clearly for noncompetitive R&D. While the R&D contracts for equipment may be noncompetitive for semiconductor producers, they clearly affect competition among semiconductor manufacturing equipment producers. Thus, what SEMATECH has done is to engage in R&D that does not directly affect competition for the bulk of its membership but does directly affect competition for the upstream industries.

Whether the use of federal funds for such R&D is seen as appropriate or not largely depends on how one views commercial innovation. The use of federal funds for SEMATECH contracts might be viewed with skepticism within the pipeline model of commercial innovation. Such an approach is consistent, however, with the chain-linked model. Given the competitive nature of both the equipment and the semiconductor industries, many of the benefits of SEMATECH-supported innovations are likely to flow to consumers through numerous electronic goods.

R&D consortia are not the solution for all the R&D problems any industry or sector might have. SEMATECH, like other consortia, has limited goals. In this case, the goal is R&D on semiconductor manufacturing technology for widespread use within a five- to eight-year horizon. Other successful R&D consortia are also likely to have narrow agenda. Thus, while federal involvement in consortia may be worthwhile, it should not be viewed as a substitute for a wider program of research.

Federal agencies have a positive role to play in the start-up phase of consortia. Many business tensions exist then. For example, potential members may fear that their proprietary information could be compromised through membership in a consortium. Federal agencies can help by serving as mediators. Federal agencies may also be useful in organizational matters. Federal agents have no comparative advantage, however, in deciding technical merits of R&D issues and, in many cases, can only complicate technical decisions by backing politically favored technologies.

CHAPTER III

HIGH-RESOLUTION AND ADVANCED IMAGING SYSTEMS

As technology progresses, consumers have come to expect dramatic increases in the amount of information and the quality of images that can be manipulated and displayed electronically. Engineers and scientists now require fast workstations with high-quality display terminals or video screens at their desks. Medical and biological researchers demand better quality displays on their instruments. Publishers and designers are also using advanced technology. Even the household television set holds promise to receive better pictures in the near future.

Although used in different ways, much of the technology behind these display systems is similar. Because of these similarities, a general perception persists that competitive advantage in one area will translate into competitive advantage in all areas. This perception has raised a concern about the ability of foreign firms to use their strength in some areas of high-resolution systems (HRS) to their competitive advantage in areas of traditional U.S. strength, such as computers and communications equipment.

This concern persists despite the acknowledged lead of U.S.-owned firms in many of the more technologically sophisticated markets. The rationale is that foreign firms dominate markets that, although technologically less sophisticated, use mass production and other cost-reduction techniques. These efficiencies then cause U.S.-owned firms to be undercut in the more sophisticated markets. The archetypal product in this analysis is high-definition television (HDTV), which combines television and computer technologies.

The desire for U.S.-owned firms to have substantial market share in the HDTV market has produced a range of policy proposals reflecting diverse views. One view equates HDTV specifically with advanced imaging technology for television receivers. Another view of

HDTV refers to developing low-cost, high-resolution digital techniques to create images for widespread use in medical and scientific instruments, computers, and consumer products. In this broader view, consumer products are not the first or the most likely uses for the technology in a mass market. An earlier Congressional Budget Office study analyzed the forecasts that used the first definition.[1] This chapter focuses attention on the second definition in order to analyze current and future developments in high-resolution and advanced imaging systems and markets as well as possible roles for the federal government.

Unlike HDTV, which refers to television receivers, the terms "high resolution" and "advanced imaging" refer to systems covering a wide array of technologies, uses, products, and markets. In fact, the definitions are so expansive that the different uses and markets and needs of each are obscured. This CBO study will follow the general definition of HRS as a density of the display approximating 1,000 or more lines along the vertical axis of the video monitor. Advanced imaging technologies use a computer to recognize, create, store, or manipulate these high-resolution images. (Figure 1 presents an outline of the markets for these electronic imaging systems.)

Unlike consumer television, U.S.-owned firms are active in many areas of HRS and advanced imaging technologies. U.S. computer makers are improving the quality of the graphics in the products they offer; U.S. electronic equipment firms are also leading in advanced imaging systems and most components. Most of these areas of electronic imaging are moving as rapidly as HDTV, if not more so. The areas where U.S.-owned firms lag are in television receivers and most integrated television production equipment and in computer displays, both cathode ray tubes and flat-panel displays.

The substantial participation of U.S.-owned firms in these markets both complicates and reduces the need for additional federal activity, most notably sponsoring consortia beyond generic research and

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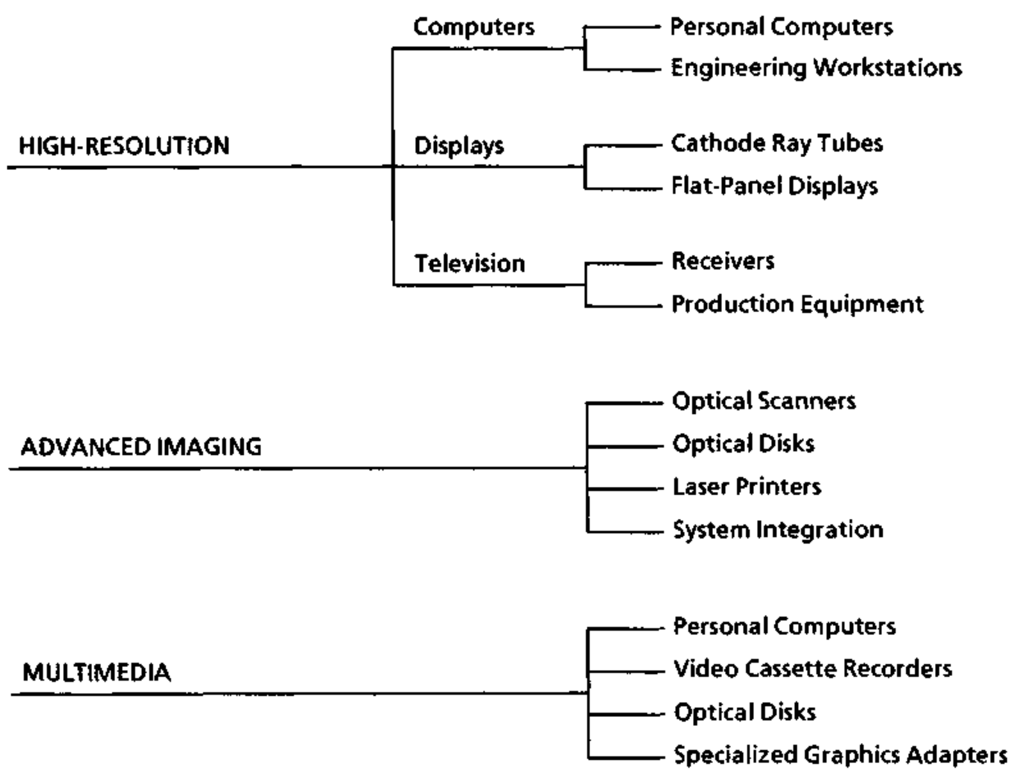
1. See Congressional Budget Office, "The Scope of the High-Definition Television Market and its Implications for Competitiveness" (July 1989). See also Testimony, Statement, and Response to Written Questions of Dr. Robert D. Reischauer in *Prospects for Development of a U.S. HDTV Industry*, Hearings before the Senate Committee on Governmental Affairs, 101:1 (August 1, 1989).

development. Because the U.S.-owned firms participating in these areas include many of the largest industrial firms--the International Business Machines Corporation, Eastman Kodak, Bell & Howell, Unisys, Texas Instruments, Intel, Microsoft, among others--it is not clear whether any single federal program could productively add to the U.S. resources that are already committed in this area. In addition, the diverse interests of these groups make it unlikely that a single consortium could serve all market segments. There may be potential, however, for several smaller targeted consortia in narrow fields. In the area of displays, U.S.-owned firms can profit from using foreign technology. Already IBM is making substantial efforts to develop flat-panel display technology together with a Japanese firm.

Figure 1.
Electronic Imaging Systems



SOURCE: Congressional Budget Office.

MARKETS AND TECHNOLOGIES

This section outlines the major high-resolution and advanced imaging systems. It also discusses a related electronic display technology called multimedia. Within each technology, an analysis of the market competition for each major component is presented, stressing the position of U.S.-owned firms.

High-Resolution Systems

HRS can be divided into its internal and external components--the electronic circuitry that makes such systems possible, and the video displays on which the pictures are exhibited. Because much of the public policy concern has focused on personal computers and workstations, the electronic circuitry--called graphics adapters--is discussed first. The section then turns to the displays and ends with a discussion of television receivers and production equipment.

Personal Computers and Workstations. Desktop computers, both for office use (personal computers) and technical use (engineering workstations), are turning to high-quality video displays at a rapid pace. Computer-aided design and engineering often need high-density display systems. Producers of IBM-compatible microcomputers already offer graphics systems with the same number of lines on the vertical axis as currently planned for HDTV. A portion of the computer market may soon be using display systems that resemble HDTV displays.

The U.S.-owned firms that serve most of the desktop computer markets are responding to their customer demands. These firms compete both among themselves and with non-U.S.-owned firms over which will provide the more widely accepted solutions. In the computer industry, success is, to a large extent, cumulative--that is, customers often buy the same brand of computers over the years to avoid the costs of retraining workers and rewriting software. IBM's success, for example, has been largely through such successive sales. This gives firms an added incentive to satisfy their customers initial graphics needs. Any satisfied customer is likely to become a repeat customer, if the computer producer can keep up with advances in the technology. Since high-resolution display systems are thought to be a growth area, no firm wants to yield to another. Two areas of special interest are personal computers and engineering workstations.

Currently, two U.S.-owned firms are fighting to set the next "standard" for graphics adapters in the IBM-compatible **personal computer** market. IBM and Texas Instruments each have a graphics "architecture" that will allow software to display higher-density screens than permitted by the latest standard--the Video Graphics Array (VGA). VGA, as introduced by IBM, permits a computer to display 480 lines along the vertical axis. Currently, the industry is trying to develop a super-VGA standard at 600 lines of vertical resolution. Beyond that, some equipment vendors are trying to develop a standard for what is referred to as the 1K VGA. Depending on the number of colors available and the adapter chosen, the 1K VGA will display either 768 or 1,024 lines along the vertical axis.

IBM has introduced a graphics architecture (the 8514/A) targeted to the 1K VGA market. Several electronic equipment producers have followed IBM's lead and are selling equipment that uses the IBM standard. Similarly, Texas Instruments has introduced a line of integrated circuits (the TMS340 family of graphics coprocessors) that is also capable of producing this level of display resolution. As with IBM, some electronic equipment producers, including makers of IBM-compatible personal computers, have produced products using Texas Instruments' line of integrated circuits. Most notably, the NEC Corporation, a Japanese firm with a substantial position in the high-end display market, introduced its latest offering of display products for personal computers using one of Texas Instruments' microcomputer chips. One market forecast suggested that 600,000 graphics boards, based on the standards of IBM or Texas Instruments for personal computers, would be sold in 1990.[2]

At this point, whether IBM or Texas Instruments will gain the major share of the market is not clear; each seems to have inspired the loyalty of a different segment of graphics users. Some analysts argue that IBM will lead in the markets for low- and mid-range personal

2. Eric Render, "Post-VGA Graphics Emerge," *PC World* (April 1990), p. 62.

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computer applications; Texas Instruments, with its inherently more flexible solution, will dominate the markets for high-end personal computer and engineering workstation applications. Despite the intensity of the struggle, the bulk of personal computer users may very well remain with the current VGA standard for the time being and migrate upwards to the super-VGA standard only as it becomes much more cost effective.

In addition to these efforts at creating mass markets for high-density computer graphic systems, many small U.S.-owned firms have for some time been offering proprietary personal computer-based graphics systems of very high quality. Limited at present to users with specialized needs, such systems often offer 1,024 and even 1,280 lines of vertical resolution in full-color systems.[3] These efforts are different from Texas Instruments' and IBM's, however, in that the latter are attempting not just to create advanced graphics capability but also to create a mass market through the personal computer.

These high-end graphics systems also expand semiconductor memory technology. Because the display systems need rapid access to the memory, the industry has developed new integrated circuits called video random access memory (VRAM) devices. Unlike the dynamic random access memory (DRAM) devices, VRAMs can transmit video data and receive data from the processor simultaneously. At present, few display devices for personal computers use VRAMs because their cost is several times that of the more popular DRAMs. Some analysts have suggested that HDTV receivers will also be major users of VRAMs. U.S.-owned firms are not major actors in DRAM's, nor are they likely to be in VRAMs.

The display technology used by computers in **engineering workstations** is highly sophisticated because these computers have technical uses, such as computer-aided design and computer-aided engineering of integrated circuits. Often, these computers also create three-dimensional images and rotate them. Producing such effects requires intensive computation. Thus, engineering workstations are often at the forefront of computing and display technology. Work-

3. Tom Manuel, "Moving Beyond VGA," *Electronics* (July 1989), p. 70.

stations have been using display densities of 1,000 lines for some time. High-end workstations have even more display capabilities: they might start with 1,280 lines wide by 1,024 lines high and range up from there.[4] Last year, Sun Microsystems, a leading producer of workstations, announced a new computer board using the Texas Instruments' line of integrated circuits as its graphics coprocessor.

U.S. computer producers dominate the worldwide market for technical workstations: the top four U.S. producers alone account for over 75 percent of world sales.[5] U.S. semiconductor companies are also actively producing the graphics products for the workstation market. Texas Instruments has or will soon release several higher performance versions of the integrated circuits already mentioned, which will be designed to fulfill workstation needs. Similarly, the Intel Corporation has a new microprocessor, which is targeted at the workstation market and has integrated high-resolution graphics within its functions.

Display Terminals. Industry sources estimate the worldwide market for video display terminals of all types will total $14.5 billion in 1990.[6] Systems based on cathode ray tubes account for roughly 75 percent of the total value. Displays are one area within HRS where firms have been able to use their expertise in consumer electronics to achieve a substantial position in the computer market. For example, Sony Trinitron displays physically sit on top of Sun Microsystems workstations. The consumer display market is so large that preeminence in consumer displays may mean preeminence in displays. Between 70 million and 90 million television receivers are sold worldwide each year, compared with roughly 30 million computer monitors and terminals. Displays are probably the area of greatest competitive weakness of U.S. industry in the high-resolution area. These markets are usually divided into those for cathode ray tubes and those for flat-panel displays.

4. Jack Shandle, "HDTV: Looking Good as a CAD/CAM Standard," *Electronics* (June 1990), p. 70.

5. Bernard Levine, "PC, Workstation Firms Face Off," *Electronic News*, June 26, 1989, p. 30.

6. David E. Mentley, Stanford Resources, Inc., "The Flat Panel Display Industry in the U.S.: An Overview," Presentation to the U.S. Department of Commerce Joint Industry/Government Meeting on Flat Panel Displays (Washington, D.C.: February 15, 1990).

The United States imports most of its computer monitors containing **cathode ray tubes**. According to the Department of Commerce, 8.9 million monitors, worth a total of $1.9 billion, were imported in 1988. In contrast, 2.5 million monitors, worth $2.5 billion, were produced in the United States. Of these, 1.1 million, worth $1.1 billion, were exported. In other words, the United States exports a little more than one-half as much as it imports. In effect, the United States imports cheap computer monitors (average selling price $214 per monitor) and exports expensive monitors (average selling price $975 per monitor).

The United States imports so many computer monitors because, in part, it is the largest computer market in the world. In 1989, apparent U.S. consumption of data-processing equipment was $51.3 billion.[7] The next largest single market, at $24 billion, was Japan. That same year, total world consumption of data-processing equipment was $125.3 billion. Many of the imported monitors are integrated into products with significant value and then reexported elsewhere. This is true of flat panels as well.

South Korea and Taiwan together provided almost one-half of total U.S. imports. Japanese firms furnished most of the higher-end color monitor imports, including many of those used by the graphic systems for personal computers and engineering workstations described above.

One technology frequently mentioned in connection with high-resolution systems is the **flat-panel display**--a thin, flat video screen. Providing large but lightweight portable, color, low-power displays has long been an electronics industry goal. Industry sources estimate that the panel display market will total $3.8 billion in 1990.[8] Consumer

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7. Department of Commerce, International Trade Administration, *U.S. Industrial Outlook 1990*, Chapter 30, p. 9. For statistics showing a similar pattern, including equipment leasing and servicing, see Computer and Business Equipment Manufacturers Association. "1989 Information Technology Industry Global Market Analysis" (prepared under contract by the Center for Economic Analysis, Washington, D.C., 1989), pp. 74 and 80.

8. David E. Mentley, as previously cited.

products account for about 44 percent of flat-panel displays. Computer applications account for 29 percent.[9]

Three flat-panel technologies are commonly considered the leading candidates for replacing the cathode ray tube in high-resolution displays: liquid crystal displays (LCD), which account for 58 percent of panel sales; plasma display panels, which account for 12 percent of panel sales; and electroluminescent displays with 1 percent of panel sales. (Vacuum fluorescent displays and light emitting diodes, which account for the rest of panel shipments, are currently not thought to have the capacity to produce high-resolution displays.) Japanese firms now account for 75 percent of LCD sales; by contrast, less than 1 percent are made in the United States.[10]

Most of the flat-panel displays are not high resolution; in fact, a leading industry observer has estimated that only 15 percent of all flat panels are "high information content displays."[11] Hitachi's small television receiver, which uses an LCD, has only 240 lines along the vertical axis. Others, such as those designed for personal computers, have much higher vertical densities. Generally, they track the display density of the personal computer graphics market. In addition, many of the future uses of flat-panel displays currently being discussed--for example, automobile dashboards--do not require high resolution; other characteristics, such as lighting requirements, may be more important. Similarly, although the potential for large displays receives much attention, many of the short-term markets--again, automobile dashboards--do not require it.

Unlike the DRAM business, which was a market created and then relinquished by U.S.-owned firms, a U.S. flat-panel industry never existed. The U.S. industry largely moved out of solid state displays while they were still relatively simple. The Japanese firms took over this market by making simple consumer displays. These firms have

9. Statistics on industry sales are taken from Dave Bursky, "U.S. Braces for a Desperate Flight in Flat Panels," *Electronics* (December 1988), pp. 39-43.

10. David E. Mentley, as previously cited.

11. Stanford Resources, Inc., cited in David Lieberman, "LCDs Make the Leap to Display of Choice for Low-Cost Portables," *Computer Design* (July 1988), p. 80.

since largely been responsible for the slow and difficult progress that has been made. U.S. R&D, however, is often responsible for the technical breakthroughs. Although IBM has adopted the role of imitator in this market by cooperating with a Japanese firm to develop new displays, other U.S.-owned firms may not be as willing to play that role. In fact, several U.S.-owned firms have begun exploring the possible formation of a cooperative program to develop LCD technology.

Although government efforts, both foreign and domestic, have received a great deal of attention, private efforts are more likely to play a crucial role in developing this technology. First, the scope of the Japanese government-funded Giant Technology Corporation, whose aim was to develop a flat panel measuring one meter diagonally, had its budget reduced from $400 million over five years to $20 million over the same period. Second, if the panel market enjoys the R&D share of sales that is typical for high-technology industries--over 5 percent--then private interests worldwide should be spending roughly $200 million annually on R&D.

A recent arrangement between Toshiba and IBM is evidence of the interest in this technology by the largest electronics firms. IBM and Toshiba have agreed to develop jointly LCDs for personal computers. Given the difficulty that producers of flat-panel displays experience in scaling up to full production, manufacturing experience is likely to be the leading driver of technology. Government funds cannot substitute for this experience.

Third, the federal market for high-resolution, flat-panel displays is small relative to other such markets, further reducing the federal leverage in this technology. For example, while the laptop personal computer market is for over one million units per year, the high-resolution display market for government aircraft is forecast to be 76,000 units.[12] In fact, the largest Department of Defense market for displays is the data entry/word-processing market, which is expected to be 220,000 units. Needless to say this market can be served, for the most part, by existing commercial technology.

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12. Defense Advanced Research Projects Agency, presentation to the Electronic Engineering Times Conference on High-Definition Television (Washington, D.C.: October 1989).

Television Equipment. The high-resolution television technology and its industry can be divided into two product areas: television receivers (and other home entertainment products), and production equipment. Only the former product area has received a great deal of public attention.

Some analysts believe that **high-definition television receivers** will be the next major successful consumer electronics product.[13] In HDTV, the television broadcast signal received is digitized, processed, stored in memory, and then displayed roughly 60 times per second. The number of lines per television screen will double the current U.S. standard, or between 1,050 and 1,260 lines. The HDTV system will also include digital-quality sound. Each frame will have roughly four times the information of the current television screen. For this reason, an HDTV receiver may need as much as 32 million bits of memory and corresponding digital-signal processing. In addition, HDTV will require new production and broadcast equipment as well as a greater allocation of the broadcast spectrum.

HDTV receivers may be introduced in the United States in the mid-1990s. At stake are both the markets for HDTV products and the markets for electronic inputs--in particular, semiconductors--and other associated electronic products. The belief that HDTV will be a very important market has led to a wide range of proposals that federal agencies provide support to U.S.-owned firms to develop HDTV. This section analyzes three major private forecasts of the market for HDTV through two questions:

- o Will there be a large consumer market for HDTV sets? and
- o Is this market critical to the competitiveness of the U.S. electronics sector?

The answer to the first question depends on many variables. The sales forecast in the market studies that were analyzed seem to be at

13. This section is largely drawn from a Congressional Budget Office Staff Working Paper, "The Scope of the High-Definition Television Market and its Implications for Competitiveness" (July 1989).

the high range of the industry's likely sales.[14] The answer to the second question is clearer. Even the most optimistic market growth would be unlikely to affect the competitiveness of other electronics industries to the extent that proponents of HDTV suggest. In reviewing the claims for HDTV made in the market forecasts, CBO found, in general, that either the markets were unlikely to be big enough to have the forecasted effects, or the sequence of events assumed by the studies were not sufficiently developed to warrant the conclusions drawn.

No one can foresee how successful HDTV will be. The success predicted by private market forecasts may be justified by the larger prices consumers pay for color television over black and white and by the recent rapid growth of the premium television receiver market. Whether consumers will value the incremental benefits of HDTV as highly is unknown, especially if there were intermediate types of advanced television from which to choose. Evidence from consumer surveys suggest that viewers' preferences for HDTV vary with the program's subject matter, distance from the set, and other factors (including the picture quality of their existing TV sets).

The success of HDTV in the shorter term will depend most likely on how it is brought into the consumer marketplace and on other variables that market studies have not addressed. As has been shown in product after product, consumers place emphasis on features usually unforeseen by the "experts." The introduction of high-technology consumer products is usually followed by a lengthy trial period in which consumers, producers, and providers of other support services, such as retailers or broadcasters, grope toward an acceptable standard for the product. In contrast, the market forecasts reviewed in this study see HDTV as an instant success--an event that eluded some of today's most popular consumer electronics products, such as video

14. Electronic Industries Association, "Television Manufacturing in the United States: Economic Contributions--Past, Present, and Future" (produced under contract by Robert R. Nathan Associates, Washington, D.C., February 1989); American Electronics Association, "High Definition Television (HDTV): Economic Analysis of Impact" (prepared by the Advanced Television Task Force Economic Impact Team of the American Electronics Association, Santa Clara, Calif., November 1988); and Department of Commerce, National Telecommunications and Information Administration, "Economic Potential of Advanced Television Products" (prepared for National Telecommunications and Information Administration by Darby Associates, Washington, D.C., April 7, 1988).

cassette recorders (VCRs) and microwave ovens. Thus, some skepticism about the timing, if not the size, of HDTV's eventual market success seems warranted.

Forecasts about the effect of HDTV on other electronics markets seem clearer. If the HDTV market reaches a substantial size, most HDTV receivers would probably be produced in the United States regardless of whether foreign- or domestic-based manufacturers become the dominant suppliers. The possible introduction of flat-panel televisions at the premium end of the market, however, might reduce the U.S. manufactured content somewhat. Television receivers are produced in the United States primarily because of the bulk and fragility of many of the components, particularly the television tube and the cabinet. Even if domestic firms become the dominant suppliers, however, some components (semiconductors, in particular) would probably still be imported. For example, U.S.-owned firms dominate the personal computer market but buy many of their semiconductors from abroad.

Even the optimistic forecasts of the potential size of the HDTV market are small relative to other markets in the electronics sector. Thus, HDTV is unlikely to play a pivotal role in the competitiveness and technological development of the electronics sector as a whole. U.S.-owned electronics manufacturing firms may gain or lose market share in the next 20 years, but they already have many incentives to maintain their competitiveness and a large enough market in which to enjoy economies of scale.

Exactly how the HDTV market would change the competitiveness of U.S. producers on the whole is unclear. The entire world market for electronic equipment is forecast to grow by $60 billion in 1990 to reach $733 billion.[15] The world market for HDTV receivers and VCRs is forecast to be less than $30 billion (in 1988 dollars) by the year 2010. It seems counterintuitive to suggest that a small market, which may or may not exist in the future, is a more important force behind economies

15. Bruce Rayner, "Economy Drifts Down; Electronic Markets Follow," *Electronics Business* (January 8, 1990), p. 60. Other forecasts of world electronic sales are within 15 percent of this level.

of scale, technology, and competitive success than is growth in the present market.

This asymmetry of size and effect (where a small HDTV market has a significant influence on markets much larger than itself) is clearly seen by comparing forecasts of the personal computer market with those of the HDTV market. Figure 2 compares the American Electronic Association's forecast of personal computer sales with those for HDTV receivers and VCRs. Not only is the overall sales forecast much higher for personal computers, but the growth is nearly 10 times as high. The HDTV market and related VCRs are forecast to grow by $28 billion, while the personal computer market is forecast to grow by $266 billion, from $48 billion in 1990 to $315 billion in 2010. Yet, according to the American Electronics Association analysis, success in the HDTV receiver market will determine success in the much larger personal computer market. Given the higher growth in the personal computer market and the greater technical sophistication, this result is unlikely.

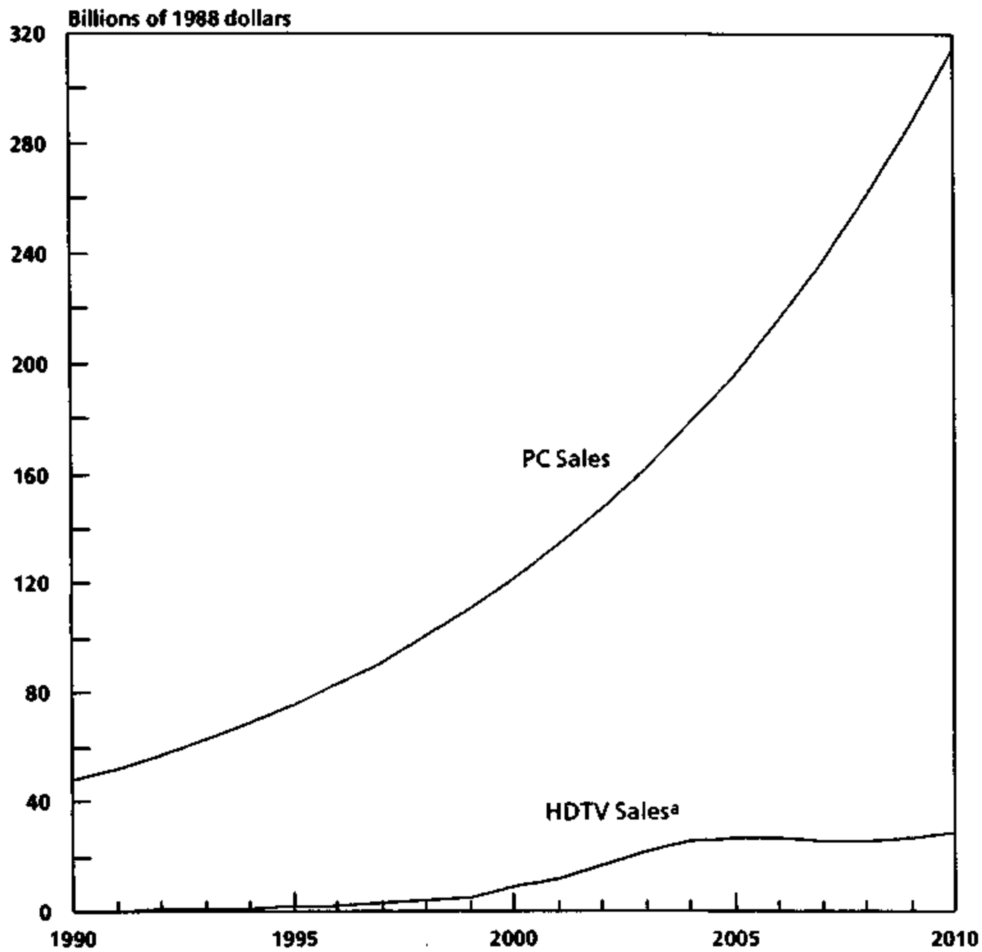
The market for **television production equipment** to produce and broadcast television shows is a small part of the overall communications equipment in the United States. Broadcast and other video production equipment represented $2.0 billion of the $67.2 billion worth of communications equipment shipped in the United States in 1989.[16] According to Dataquest, an electronics market research firm, world shipments of such equipment just exceeded $4 billion in 1987 and grew to roughly $4.5 billion in 1988.[17] Studio video equipment was the largest single category within this market and accounted for roughly $1.5 billion worth of sales worldwide in 1987.

U.S.-owned firms have major positions in almost every segment of this market. Only one, Ampex, is a major broad-line supplier of different categories of equipment; the rest are primarily Japanese or Euro-

16. Electronic Industries Association, *Electronic Market Data Book: 1990* (Washington, D.C.: 1990), pp. 33-35.

17. Dataquest, "High-Definition Video Technology: The Collision between Television and Computers" (October 1989), p. 3-14.

Figure 2.
Comparison of High-Definition Television (HDTV) and Personal Computer (PC) Sales



SOURCE: American Electronics Association, "High Definition Television (HDTV): Economic Analysis of Impact" (prepared by the Advanced Television Task Force Economic Impact Team of the American Electronic's Association, Santa Clara, Calif., November 1988).

a. Includes both HDTV receivers and video cassette recorders.

pean firms. U.S.-owned firms sell industrial video tape recorders, including those supplied by Ampex and a Tektronix subsidiary. Aside from the camera, other parts of the production equipment markets tend to be specialized and fragmented. A large number of U.S.-owned firms operate within these segments. Like the personal computer industry, this portion of the production equipment industry is characterized by rapid innovation and small firms. Recently, a Japanese firm, Matsushita, introduced an automated system that integrated many previously distinct pieces of equipment. The U.S. industry is at a real disadvantage in the camera market, which Japanese and German firms dominate.

In contrast, U.S.-owned firms largely serve the U.S. transmission equipment market--whether for conventional broadcast, satellite, or cable. The Harris Corporation is the largest U.S.-owned firm providing regular broadcasting equipment. Scientific Atlanta and other U.S.-owned firms service the satellite market. Cable systems, whether fiber optic or coaxial cable, are very similar to telephone systems where U.S. equipment producers are strong.

Advanced Imaging

One important technology using many of the components described above is advanced electronic imaging. Electronic imaging uses computers and other electronic technology to reproduce, store, manipulate, and display documents, drawings, and other images normally put onto paper. U.S. corporations produce over one billion pieces of paper a day.[18] Electronic imaging attempts to automate the use of this paper by converting it to computer images: 95 percent of this conversion has not yet been accomplished. Government, insurance processing, and financial services account for almost two-thirds of the total $4.4 billion imaging market.[19] If current growth rates continue, product sales for electronic imaging are projected to approach $13 billion within the

18. Much of the information on imaging needs and uses derives from Samuel Weber, "Imaging," *Electronics* (July 1989), pp. 61-64.

19. Market size estimate cited in Michael Sullivan-Trainor, "Study Divines Image Tech Future," *Computerworld* (June 26, 1989), p. 94. Market share data taken from Samuel Weber, previously cited, p. 62.

next five years. Only one-fourth of the overall imaging market, however, is for electronic equipment ($800 million); the rest is for microfilm, software, and services.

Imaging systems typically consist of input devices (text or line scanners), computers (software and hardware), mass storage devices (often optical disks), and output devices (display terminals and printers). The input devices turn documents into electronic signals somewhat like photocopying equipment. The computers--usually advanced personal computers built by U.S.-owned firms--turn the digital images into words and letters in order to manipulate the data. The computers also compress the signal. The documents are then put on magnetic disks for short-term storage. Longer-term storage increasingly uses a device descriptively termed "write-once, read many" (WORM) optical disks. As the name implies, these disks can only be written on once. Their high-density capacity--up to 1 billion 0s and 1s on each side of a 12-inch platter, equivalent to about 18 file-cabinet drawers of documents per side--allow them to store vast amounts of information. The larger systems have "jukeboxes" of optical platters, which can handle as many as 150 disks. Once stored on the optical disks, the information can be accessed and displayed (as either text or image) on personal computers and terminals through computer networks, then printed out as necessary. Like most personal computers, these imaging systems are "open architecture"--that is, they are composed of equipment and software provided by different vendors with one firm usually serving as an integrator of the system.

Ironically, these systems are often applications of technologies developed for other purposes. Optical scanners developed from facsimile (or fax) machines. Certainly, the personal computer developed independently. The high-resolution monitors, storage devices, computer network, and laser printers were also developed independently. Success in this market is achieved by putting together an architecture of system management that best serves the users' needs.

Successful firms, depending on their market position and expertise, will "mix and match" components produced internally and externally in order to provide its segment of the imaging market with the best "total package." Consequently, no one firm is expected to dominate the market for every component but rather to show both strengths and weaknesses.

Advanced imaging systems range in cost from $35,000 to several millions of dollars, depending usually on the volume of documents to be handled. Different U.S.-owned firms have targeted different segments of the market, defined either by size or by end user. Many major U.S.-owned firms are involved in this market: IBM, Unisys, Eastman Kodak, Digital Equipment Company, Wang, Xerox, and Bell & Howell. In addition, many less well-known U.S.-owned firms are involved in providing the systems and hardware involved.

Scanners. Scanners are machines that take a printed page and convert the text, drawings, and pictures on the page into a form readable by the computer. The scanner market can be divided into two parts: those for text and those for drawings. This division is largely based on the size of the documents to be scanned. Technical drawings are typically much larger than the standard letter- or legal-sized documents, which are the material generally read by text scanners.

Industry sources estimate that the desktop scanner market approached $230 million in 1988.[20] Many U.S.-owned firms offer scanners for sale. Xerox Corporation has several subsidiaries that do. Apple Computer and Hewlett-Packard also offer scanners and have substantial market presence. Unlike Xerox, they buy the optoelectronic components, which read or convert light into electronic signals, from Japanese firms, which largely dominate the component market on the basis of their presence in the larger facsimile and copier markets.

Whether the Japanese companies will be able to use their component expertise to move into this rapidly growing market is as yet unclear. Tailoring the human interface portions of hardware to the needs of scanner users is at least as important for market success as the ability to make the reading components. If sufficient growth in this market creates one or more hardware standards, then manufacturing

20. Paul Kinnucan, "Scanners Capture a Brighter Image," *Computer Graphics Review* (November 1989), p. 28. This estimate seems high relative to the previously discussed estimate for an $800 million imaging market.

ability might become more important. Japanese companies, however, have been unable to turn their manufacturing ability into market dominance in the much larger laser printer market. (See the discussion of laser printers below.)

The scanner is only part of the story. Often, a controller or type of printed circuit board attaches to the personal computer that controls the scanner. This controller, usually U.S.-made, is sometimes more expensive than the scanner itself. Lastly, an optical scanner for computers has two categories of components--hardware and software. The latter component is the more constraining in being limited in its ability to read different types of text and to recognize pictures. Thus, provided they can buy quality hardware, U.S.-owned firms might be better off concentrating on software where their advantage and profit margins may be higher than competing with foreign companies in producing the lowest cost hardware. U.S. software is quickly becoming the standard for scanning, both for regular scanning and the more advanced optical character recognition.

Optical Disks. The U.S. market for optical disks can be divided into two users--consumer and computer. Optical compact disks, for example, have already replaced phonographic records as a preferred medium for music. The issue is what portion of the $70 billion magnetic memory market for computerized information will be replaced by optical disks. Currently, the three types of optical disks in descending order of market size are: read-only memories, write-once, read-many (WORM) memories, and read-write memories. The market for computer optical memory is still small; one industry source estimated that the market for optical computer disk drives would total less than one million units in 1990.[21] Estimates of optical disk sales vary substantially, but none of the alternative sources changes the overall trends. At present, the imaging market mostly uses WORMs for archival purposes, although as the read-write systems become more widely available they might supplant WORMs.

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21. "Optical Disk Sales Seen Hitting $2B (sic) in 1992," *Electronic News*, August 14, 1989, p. 20. For an analysis of optical storage, especially IBM's potential role, see Electronic Trend Publications, "Optical Technology's Impact on Paper, Microform, and Magnetic Disk and Tape Storage" (Saratoga, Calif.: 1988).

Many issues remain unsolved in WORM disk technology, especially in the area of standards, compatibility, and conversion. Disks designed for one computer system often cannot be run on the disk drives of other systems. For example, platter size varies. At present, the WORM market is generally divided into 12-inch platters and 5.25-inch platters; one U.S.-owned firm, Eastman Kodak, uses a 14-inch platter. The 12-inch platters are used by the larger systems, while personal computer-based systems use the 5.25-inch platters. As with magnetic disks, the technology has been progressing in access and storage density. Some U.S.-owned firms that participated in the 12-inch markets have already indicated that they will not be moving forward into the smaller sizes or the higher densities.

The early position of Japanese firms in the read-only memory market does not necessarily translate into a commanding position in the WORM market. Position in the compact disk market for music is an obvious advantage but may be limited by the difference between the two markets and the two technologies. Music listeners appear to be cost sensitive, while computer users care more about error rates.

Success in one technology area, however, may not translate into success in an associated area. For example, U.S.-owned firms dominate the magnetic fixed disk market, which exceeded $7 billion in 1989 and holds a substantial majority of the world market.[22] While commanding the magnetic fixed disk market, U.S.-owned firms are in a much weaker position in the much smaller magnetic floppy disk market. Thus, U.S.-owned firms may play no role in read-only memory disks, while having a substantial role in other types of optical disks.

Laser Printers. Without the ability to produce high-quality copies of their graphics, high-resolution and advanced imaging systems would lose some of their value. Laser printers are currently the technology of choice in producing inexpensive high-quality copies. Of the roughly $11 billion worth of monochrome printers sold for data-processing purposes in the United States in 1989, $5.5 billion were nonimpact--that

22. "1989 World Market Report," *Electronics* (January 1989), p. 57; and "U.S. gets a Fresh Crack at Floppy Disks," *Electronics* (August 1988), p. 73. The U.S.-owned firms, however, often import components, such as the disk itself, and subassemblies.

is, either laser printers or ink-jet printers.[23] This part of the printer market grew by over 23 percent in 1989; forecasts are for another 15 percent in 1990. According to industry sources, nonimpact printer sales have grown from 900,000 units in 1985 to over 2 million in 1989.

Two U.S.-owned firms, Apple Computer and Hewlett-Packard, are the industry leaders in this field. These firms can hold commanding positions in marketing the final product without manufacturing the active optoelectronic components. These components are often manufactured by Japanese companies and reportedly account for no more than 10 percent to 15 percent of the cost of a printer. Texas Instruments has recently announced a new integrated circuit that would substitute for most of the optoelectronic engine in some laser jet printers. If popular, this device might further decrease the Japanese presence in the printer market.[24]

The active optoelectronic components made by Japanese firms are often controlled by integrated circuits manufactured by U.S.-owned firms. Motorola, a U.S. semiconductor firm, produces the most popular microprocessor used to control laser printers. Its major rivals in this market are also largely U.S. semiconductor producers. U.S. semiconductor firms also produce many of the logic devices and erasable programmable read-only memory used in these printers. The read-only memory and DRAM integrated circuits are largely produced by Japanese firms. The printer software is all U.S.-produced.[25]

Systems Integration. This is a high-profit area and the forte of U.S.-owned firms. The profit margins on software systems and their integration are substantially larger than the profit margins on most product manufacturing. According to industry statistics, 45 U.S.-owned

23. Statistical information for this section is largely derived from Bernard Cole, "Nonimpact Printers Transform the Office," *Electronics* (March 1990), pp. 58-60.

24. See J. Robert Lineback, "TI's Flashy Mirror Chip," *Electronic Buyers' News*, March 19, 1990, p. 2.

25. See Bernard Cole, "Nonimpact Printers Transform the Office," *Electronics* (March 1990), pp. 58-60 and Bernard Cole, "AMD Ups the Ante in the PLD War," *Electronics* (March 1990), p. 75.

firms currently provide systems for electronic image management.[26] Most such systems worldwide are installed in Japan where this technology was first developed (the Japanese language itself is image-based). The vast bulk of the Japanese systems, however, are low-volume, filing cabinet-type systems. Japanese firms have much less presence in the mid- or larger-volume systems. In fact, the top two U.S.-owned firms, FileNet and Wang, account for 40 percent of existing high-volume systems. Even at the low volume end, U.S.-owned firms, such as Eastman Kodak and Laserdata, have a substantial presence in both hardware manufacturing and complete systems delivery. Computer network and systems integration is an area where U.S.-owned firms still enjoy a strong market share.

Multimedia

Electronic companies are currently attempting to combine television technology with personal computer technology to provide systems with aspects of each. This union is currently being called multimedia. Such a system might allow a user to connect a personal computer with a VCR to allow interactive video for training purposes. Dedicated simulators, such as those the armed services use for aircraft training, already do this but at enormous cost. Multimedia technology is intended to provide this capability for a few thousand dollars, just the way the personal computer brought the capacity of a mainframe computer down in cost.

Currently, most personal computers cannot show full motion video, the way ordinary television receivers can. The digital video signal used by personal computers requires too much information, relative to a conventional television signal. Using conventional digital technologies, a standard video disk would provide less than a minute of full motion video on a personal computer.[27]

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26. The data on the systems integration market is largely derived from Dataquest, a market research firm, in "Electronic Image Management Systems--Market Review," April 1989, pp. 1-18.

27. Dwight Davis, "Intel and IBM Share their Multimedia Vision," *Electronic Business* (November 13, 1989), p. 30.

Recently, computer and semiconductor manufacturing firms have developed techniques to bring near-full motion video to the personal computer by using special processors and compression techniques. Convinced that multimedia will develop into a major market, the major international electronic companies have begun to position themselves with R&D and products to serve a portion of the market. Indeed, the list of names reads like a Who's Who of the personal computer world: Apple Computer, IBM, Intel, Microsoft, NEC, N. V. Phillips, Fujitsu, and Sony.

Two strategies compete for dominating the multimedia market: one is based on the business computer market, and one is based on the consumer electronics market. Three U.S.-owned firms--Apple Computer, Intel, and IBM--are the leading producers of the former strategy, while several foreign firms--most notably Sony, N. V. Phillips, and Matsushita--have joined together to lead in the latter. Each strategy strives to become the "industry standard"--that is, the system to which the bulk of the applications will be written. If the popular applications are written to one or another standard, then the providers of that standard will presumably enjoy higher sales. The U.S.-owned firms, which have substantial strength in personal computer technology, are using a personal computer-based strategy; foreign firms, which have a stronger presence in compact video disk technology, have a compact disk-based strategy.

A third product-based strategy, however, is not often discussed in the same context but, some analysts argue, may prove successful: video games.[28] After booming in the early 1980s, video games then declined to less than 10 percent of their former sales. Now video games have one of the highest percentage growth sales in consumer electronics.[29] Factory sales of video games exceeded $1.7 billion in the United States in 1989. Video games are also growing in electronic sophistication. In late 1989, several video game manufacturers introduced players that processed information 16 bits at a time, rather than the 8 bits previ-

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28. John C. Gale, Information Workstation Group, "Micro Multimedia" (Alexandria, Va.: March 1990), pp. ix- 5 and ix-6.

29. Wesley Iversen, "Everyone's Waiting for a New Star," *Electronics* (January 1980), pp. 74-75. See also Joseph Pereira, "For Video Games, Now It's a Battle of Bits," *The Wall Street Journal*, January 1990, pp. B1 and B5.

ously. There is talk that if sales stay high, game producers may introduce 32-bit machines in the near future. Furthermore, the cost discipline that producers face is brutal. These systems often retail under $100. Even the 16-bit systems sell for $150.

Analysts who believe that video games will dominate multimedia argue that the cost discipline, plus the familiarity and ubiquity of the machines, will enable Japanese producers to move out of their niche and provide a wider range of software and service. Video games could soon dominate the electronic home information center. Video games are kept inexpensive, however, by making them inflexible. Unlike personal computers, which are mostly based on commercially available microprocessors usually manufactured by Intel or Motorola, these video games have proprietary microprocessors, which are generally more limited in ability. Whether video games can remain inexpensive while accomplishing a wider range of tasks is unlikely.

CURRENT POLICIES AND EFFORTS

Federal agencies sponsor R&D on both advanced imaging and high-resolution systems and purchase such equipment as part of their missions. While the role of the armed services is more obvious, other agencies--such as the Veterans Administration, the Federal Aviation Administration, the National Archives, and the Post Office--are major purchasers of many such systems.

How much federal R&D programs are spending in the area of advanced imaging is difficult to determine. In essence, advanced imaging is as much a particular application of existing technology as it is a new technology. Thus, part of the budget for a supercomputer may be used to create images; the part used for imaging, however, would be indistinguishable from, and indeed be part of, the budget for a supercomputer used to design nuclear weapons.

Similarly, one use of signal processing is graphics. Given the large military investment in signal processing, the portion of the military R&D effort devoted to imaging is difficult to identify separately. In addition, many of the imaging programs are highly classified and not explicitly reported in the budget. Finally, many of the mission agencies--the National Aeronautics and Space Administration, most notably--might sponsor specialized advanced imaging R&D as part of their mission, yet count it as part of their mission research and not as imaging R&D. Recognizing these limitations, nevertheless, the Administration estimated that spending for federal R&D on advanced imaging, including R&D on HRS, totaled $118 million in fiscal year 1990.[30]

The largest single category of federal R&D spending in this area is for the military. The armed services generally sponsor R&D to develop sensors that spot potential enemies or targets and digital-signal processors that interpret the information coming from the sensors. Much of this work, such as night vision equipment, has limited application to the commercial world. In addition, the armed services want displays that will work in ships, tanks, and airplanes. The size, weight, and power limitations make many of these displays similar to those being developed for laptop personal computers and other consumer uses. This similarity suggests that there may be spillovers to the civilian market. The small size of the military market, relative to its civilian counterpart, however, suggests that the military could easily be a net user rather than a supplier of technology.

FEDERAL POLICY OPTIONS

The Office for Science and Technology Policy has testified that it might view generic work in HRS as appropriate. As Dr. Bromley testified, because HDTV, computer workstations, and personal computers may soon be using much of the same technology, work on high resolution as the underlying technology would be an appropriate role for federal agencies.[31] Presumably, in Dr. Bromley's scenario, the task of applying this technology to a specific product--whether an HDTV receiver or a personal computer graphics adapter--would be the responsibility of individual companies.

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30. *Budget of the United States Government*, Fiscal Year 1991, pp. 85-86.

31. See the questions and answers of Dr. Bromley beforethe Subcommittee on Technology and Industry of the Senate Armed Services Committee, November 27, 1989.

The desire by many in the policy community for U.S.-owned firms to have a substantial market share in the high-resolution market has produced a range of policy proposals. At one end, the Congress has appropriated $30 million in fiscal year 1990 to the Defense Advanced Research Projects Agency for research into technologies with potential military use that relate to HDTV displays, including flat-panel screens. At the other end, the National Advisory Committee on Semiconductors (NACS) has recommended establishing the Consumer Electronic Capital Corporation to ensure, among other things, that U.S.-owned firms would have sufficient capital to enter consumer electronics markets. Presumably, these markets would include manufacturing HDTV receivers.[32] The federal financial sponsorship of this corporation is as yet unspecified.

These proposals reflect the previously noted divergence of views regarding HDTV. The narrow view of HDTV equates it with advanced technology television receivers. A more expansive view, however, refers to the development and widespread use of low-cost, high-resolution digital techniques to create images for uses in medicine, scientific instruments, computing, and consumer products.

The policy prescriptions following this divergence of views also differ. The narrower view of HDTV centers on the success of U.S.-owned firms in manufacturing and selling television receivers. Consequently, the bulk of the federal financial support in the NACS proposal is devoted to providing capital funds for manufacturing. By contrast, the DARPA request would develop generic technologies that would find widespread use in a variety of advanced imaging products.

The broader view of the market ironically presents less freedom of action for the federal government. In the narrow view of high-resolution technology, referring only to HDTV receivers, only one U.S.-owned major television receiver producer is left--Zenith. If the federal government wants to favor U.S.-owned firms over foreign companies, but remain neutral among U.S.-owned firms, the field is relatively open for federal intervention. In the wider field of high-

32. National Advisory Committee on Semiconductors, "A Strategic Industry At Risk," November 1989, pp. 23-24.

resolution and advanced imaging systems, plenty of U.S.-owned firms are competing. Any action by the federal government in favor of one U.S.-owned firm may easily hurt its competitor, which may also be U.S.-owned.

Consequently, to remain neutral among U.S.-owned firms, federal agencies must move with circumspection. Furthermore, the national interest in many of these competitive battles is neither on one side nor another. For instance, in the battle between Texas Instruments and IBM over the next high-resolution standard for graphics adapters for IBM-compatible personal computers, which firm represents the national interest? The same question can be asked of joint ventures between U.S.-owned firms and foreign companies: where does the national interest lie in the competition between the IBM and Toshiba joint venture to develop flat-panel displays and small U.S.-owned, flat-panel companies?

In addition, major investments in one subsector of the market would not necessarily help U.S.-owned firms actively competing in other areas. No single technology is common to all firms in the high-resolution and advanced imaging markets that the federal government could support. This situation contrasts clearly with SEMATECH where all semiconductor producers use the same manufacturing equipment. For instance, how will manufacturing HDTV receivers help U.S.-owned firms sell optical disks?

Overall, U.S.-owned firms of all sizes and histories seem actively interested in participating and investing in this market. Some areas within the high-resolution and advanced imaging markets, however, have fewer U.S.-owned firms, or these firms have less market presence than elsewhere. Consequently, one course of action may support the R&D that underlies whole aspects of high-resolution and advanced imaging technologies and leave the development and manufacturing of specific applications to the producers. The Administration seems to favor this course.

In some areas, most notably displays and read-only memory optical disks, U.S.-owned firms have relatively weak competitive positions because of either lack of technology or low capital funding. In such cases, federal support for R&D, such as currently funded by DARPA, might be more possible. The Toshiba-IBM deal on LCD, however, suggests that much of the same expertise might also be available from foreign firms with relatively advanced technologies. In fact, the United States has a bias toward attempting to leapfrog foreign technology rather than admitting to being an imitator or trying to catch up with existing competitors.

POTENTIAL FOR AN R&D CONSORTIUM

On the one hand, not much potential exists for a single consortium of all the firms involved in HRS and advanced imaging technology. The range of technologies, products, and markets is simply too diverse. The kind of agreement on a technological agenda, such as that which characterizes SEMATECH, would be unlikely.

On the other hand, potential does exist for smaller targeted consortia in narrow fields. In fact, several collaborative research efforts are currently under way. The standards-setting process for HDTV has produced collaborative research. A joint research laboratory is even testing the standards. In addition, there are private joint ventures in this area. The previously mentioned IBM-Toshiba venture on flat panels is one. There are also reports of a U.S. cooperative for technology development on LCD. Recently, N. V. Phillips and Thompson Consumer Electronics announced a joint venture to develop advanced television receivers, the first step toward HDTV receivers becoming prevalent in the United States.

CHAPTER IV

X-RAY LITHOGRAPHY

A technology currently used in semiconductor manufacturing may no longer be appropriate after the late 1990s. The advancing state of the art for semiconductor design is the impetus behind the proposals for federal support in developing a new process to make leading edge integrated circuits.

Semiconductor manufacturers now use optical (light-based) lithography to transfer the image of the integrated circuit from a master pattern (often called a mask) onto the prepared silicon wafer. As integrated circuits become more complex, their features get smaller. In fact, they approach the limit at which beams of light are no longer sharp enough to draw the circuitry as thin as needed. To manufacture chips at these smaller dimensions, makers of semiconductor manufacturing equipment intend to use ultraviolet light sources and other techniques. (See Box 4 for a description of lithography systems.)

Consensus, however, is that optical lithography using ultraviolet light will become ineffective or "bottom out" as geometries go below 0.25 to 0.3 microns.[1] (A micron is a millionth of a meter.) Transferring images of this size using optical lithography will be like drawing a fine line with a crayon. At that point, some other system will be needed for exposing the integrated circuit images onto the wafer. Still, consensus has often been wrong about when optical lithography will become ineffective. In the early 1980s, many industry analysts thought light could not be used below one micron. For this reason, current opinion should be viewed with some skepticism. Regardless of whether optical lithography can be pushed below 0.3 microns, it is approaching the

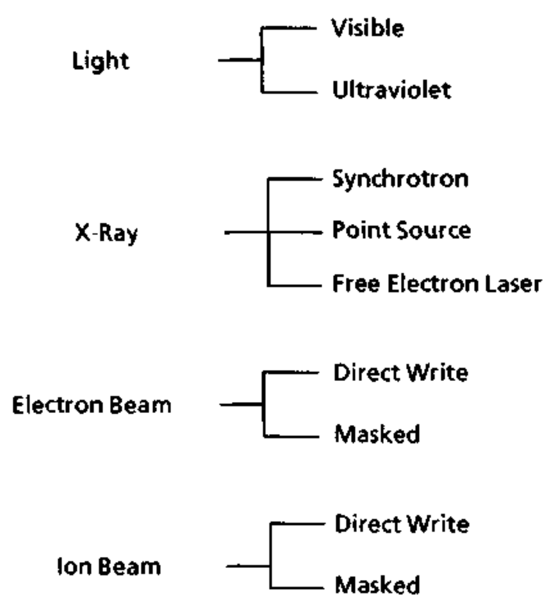
1. Dr. Alec Broers, "Fundamental Versus Surmountable Problems of Lithography (A Technology Forecast)," Presentation to the Semiconductor Equipment and Materials International's Thirteenth Annual Information Services Seminar, January 22-24, 1990 (Newport Beach, Calif.: 1990). See also "Into the Millennium with Ion Beam," *Technology Research Letter* (July 1989), p. 3.

BOX 4
Lithography and Integrated Circuits

Lithography (or photolithography) is the step in semiconductor manufacturing in which the desired circuit image is transferred onto the semiconductor material, usually a silicon wafer. The wafer is first covered with a special photographic emulsion (called a resist) that will retain the integrated circuit image. The image can be transferred by using a master pattern (called a mask) like a photographic negative or by writing the image directly. Several different sources can accomplish the transfer. A lithography system reduced to its bare essentials involves:

- o A source (of light, electrons, x-rays, or ions);
- o A means of creating an image with the beams of light or particles and delivering these to the wafer (usually with a lens or magnet); and
- o A means of positioning the wafer.

Lithography Systems



SOURCE: Congressional Budget Office.

absolute limits of light. Some new form of lithography may have to be devised.

X-ray lithography is the leading candidate among other forms of advanced lithography. In x-ray lithography, a beam of x-rays substitutes for the light used in optical lithography. Because their wavelengths are much shorter than those of ultraviolet or visible light, x-rays can be used to imprint circuit features that are much narrower. The dimension allows faster computer processing and lower costs because the chips can store more information.

The federal government has been funding x-ray lithography research, mainly through the Department of Defense and the Department of Energy (DOE). These federal efforts have been closely coordinated with private efforts, most notably those of the International Business Machines Corporation. These federal efforts, however, have received only irregular and small-scale funding.

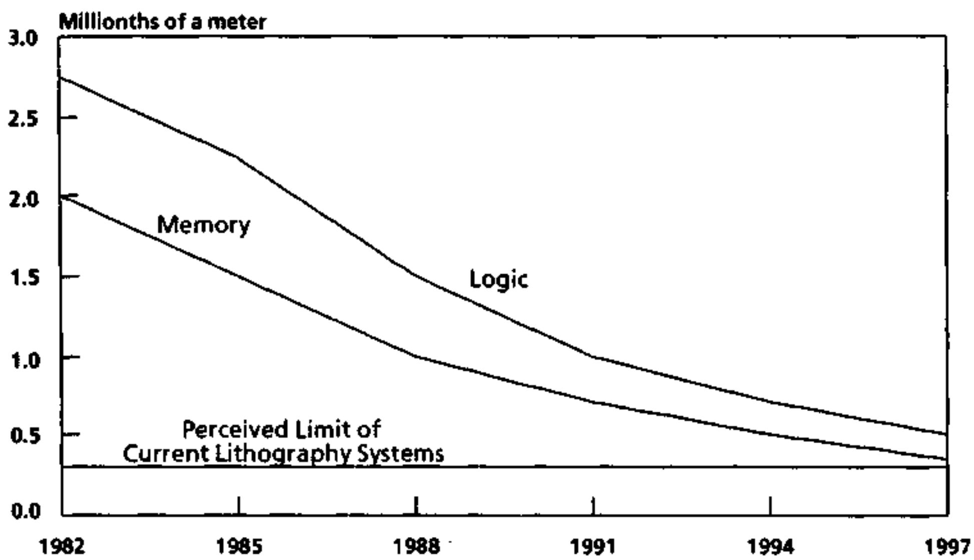
Recently, IBM has suggested that the federal government and other semiconductor producers join it in a larger and more comprehensive program to develop x-ray lithography. Other than securing the funding source, what a more collaborative effort could do is not clear. The federal agencies and private interests are all professionally and institutionally aware of each others' work. The groups active in supporting research and development in x-ray lithography already coordinate with each other to a large extent. Federal funding for R&D in x-ray lithography, however, has been irregular. Thus, formal commitment to a long-term program might increase funding stability and proper planning.

MARKETS AND TECHNOLOGIES

Different types of integrated circuits are approaching the perceived limits of optical lithography at different rates, as Figure 3 shows. Memory producers, most notably firms manufacturing dynamic random access memories (DRAMs), are likely to encounter problems with these limits first. Producers of logic circuits, such as microprocessors, will probably reach the same geometries three to five years later. The leading edge of integrated circuits among Japanese firms are more likely to be DRAMs or other memory devices, while the leading edge devices of U.S.-owned firms are more likely to be microprocessors or other logic integrated circuits. Consequently, these two trends have placed much greater burden on Japanese producers.

The general category of x-ray lithography includes more than one exposure system and more than one type of x-ray source. The most publicized and developed type of x-ray lithography system uses a circular or oval-shaped accelerator, called a synchrotron, to produce beams of x-rays from speeding atomic particles. These beams are then channeled through ports into long tubes called beamlines. At the end

Figure 3.
Minimum Feature Size of Logic and Memory Integrated Circuits



SOURCE: Richard Van Atta, Harold Bertrand, Michael Keller, Joseph Ruzzi, and Sharon Squassoni, "Microelectronics Manufacturing Technology: A Defense Perspective" (IDA Paper P-2097, prepared by the Institute for Defense Analyses, Alexandria, Va., for the Office of the Deputy Under Secretary of Defense for Research and Advanced Technology, April 1988), p. 42.

NOTE: Consensus is that current light-based lithography systems will no longer be useful when minimum feature sizes shrink below roughly 0.25 to 0.3 millionths of a meter.

of the beamline is the equipment that uses the x-ray beams to transfer integrated circuit patterns from the masks onto specially prepared silicon wafers. Other x-ray lithography systems, often called point sources, are more experimental. These systems use plasma or lasers or both as sources of x-rays.

X-ray Synchrotrons

While better understood than point sources, synchrotrons are neither a straightforward nor a cheap way to produce integrated circuits. Synchrotrons are huge, sophisticated, scientific instruments maintained and operated by highly trained physicists who understand the interactions of the particles and magnetic fields in the synchrotron. It is not yet a machine for the factory floor. Experimenters in this field are attempting to advance synchrotron technology in several areas, most notably to make the system more compact and, therefore, more accessible to industry. Efforts to do this are under way in two areas--the magnets and the exposure system.

Synchrotron Magnets. Up until now, most of the magnets for synchrotrons have been conventional electromagnets. In order to reduce the size of these synchrotrons for the factory floor, some physicists have proposed using superconducting magnets. A conventional magnet-based synchrotron might be 10 meters in diameter, while a superconducting magnet-based synchrotron might be as small as 3 meters in diameter. Even if the synchrotron itself were reduced, the size of the total package would likely be much larger than conventional lithography equipment. For example, the beamlines that channel the x-rays to the lithography equipment have to be at least 5 meters to 10 meters long. Furthermore, the synchrotron has to be enclosed behind a radiation-proof structure. Thus, the size of the synchrotron itself is only a fraction of the size of the entire assembly. A single synchrotron, however, can produce x-ray beams for 16 to 20 production stations.

Exposure System. X-ray beams cannot be reflected at large angles like conventional light. Consequently, the x-ray beams must be used in the same plane in which they originate from the synchrotron. If the beams emerge horizontally, they must be used horizontally. Since conventional integrated circuit exposure systems (wafer steppers) project light downward, using a horizontal beam exposure system would entail a major redesign of all the mechanical systems--such as the stages on which the silicon wafers sit. In addition, because the features are so small, the mechanisms that are needed to hold and position the silicon wafers are at or beyond the current state of the art.

Point Sources

As an alternative to synchrotron-produced x-rays, small U.S. companies are attempting to produce x-rays using plasma or lasers. In this case, most of the lithography stays roughly similar to current methods; only the light source is changed. Plasma or laser x-ray sources produce x-rays of longer wavelength (often referred to as "softer") than the synchrotron sources. This allows more conventional photographic emulsions and other materials to be used. Point sources pose less of a potential hazard in terms of exposure to radiation. An additional advantage is that these systems occupy roughly the same floor space as conventional lithography equipment and, consequently, could fit in conventional factories rather than need tailor-made facilities.

These systems must still overcome many technical hurdles in order to become a suitable replacement for conventional lithography. Currently, plasma-based x-ray equipment does not have the capacity necessary to be a tool for mass production. Conventional optical lithography equipment has a capacity on the order of 50 to 60 wafers per hour, while the prototypes of plasma-based x-ray equipment have only a fraction of that, currently about 2 or 3 wafers per hour. Research into improved lasers is intended to raise this rate by an order of magnitude. In addition, the beam of x-rays is not aligned as perfectly as might be needed for fine lithography. Currently, research is under way to reduce the tendency of the beams to spread. This research is also intended to reduce the minimum feature size available from point sources from 0.5 to 0.25 micron.

Potential Market Size

Recent calculations by IBM indicate that, if the technology develops according to the forecast, one synchrotron could produce four quadrillion bits of memory in DRAMs per year soon after the year 2000.[2] By way of reference, the entire world consumed 0.7 quadrillion bits of memory in DRAMs in 1989. DRAM consumption, however, is forecast to rise to 4.3 quadrillion bits of memory by 1993.[3] If DRAM consumption continues to grow at the average rate for the 1980s (82 percent annually), total DRAM consumption will exceed 280 quadrillion bits by the year 2000. These calculations suggest that there might be a sizeable market for synchrotron rings. In contrast, if growth in the demand for DRAMs slows to 40 percent a year, then the market for synchrotrons would be only a fraction of the larger size. (During the 1980s, DRAM growth has never been below 40 percent and has averaged 82 percent.)

Synchrotrons might also be used on other integrated circuits, such as static random access memories, erasable programmable read-only memories, and application-specific integrated circuits. These other markets are much smaller than the DRAM market. Data on production quantities, however, are not as readily available.

CURRENT POLICIES AND EFFORTS

X-ray lithography clearly has the potential to advance semiconductor manufacturing technology. Toward this end, x-ray lithography is being advanced in the United States through several efforts, both public and private. Foreign governments and foreign firms are also making substantial investments.

2. Alan Wilson, IBM Research Division, Presentation to the Fifth Brookhaven National Laboratories Workshop on Synchrotron X-ray Lithography, November 16-17, 1989.

3. Integrated Circuit Engineering Corporation, "Mid-Term Status of the IC Industry-1989" (Scottsdale, August 1989), Chap. 3, p. 45.

Federal Research

Federal agencies are spending, in the aggregate, probably $25 to $30 million a year for R&D on x-ray lithography. Most of the direct funding comes from DoD, but extensive use is being made of DOE facilities and personnel, most notably at Brookhaven National Laboratories.

In fiscal years 1988 and 1989, the Congress appropriated a total of $25 million to construct a conventional magnet synchrotron devoted to x-ray lithography. The synchrotron was to be located at the Louisiana State University Center for Advanced Microstructures and Devices. The preliminary plan and contract have been approved. The project is still in the final design and negotiation phase and, as a result, two years away from completion.

More recently, the Congress earmarked $33 million for DOE to develop an x-ray lithography program but provided no new funds. Instead, the funding was to come from Basic Energy Research Programs. In response, DOE has begun an effort to transfer synchrotron technology to industry.

DOE's proposal, which was bid in the spring of 1990, calls for a two-year program to design, fabricate, and test a "commercially viable" synchrotron. The proposal excludes beamline or semiconductor manufacturing equipment technology necessary for production. DOE proposed that this synchrotron be jointly developed with either semiconductor producers or synchrotron producers. Costs would be equally shared to a cap of $15 million in federal funds. Of this $15 million, $5 million will come from existing 1990 appropriations for the Office of Energy Research; $10 million is being requested from the Congress for fiscal year 1991. The intent of the program is to build a domestic capability for such synchrotrons. To this end, only U.S.-owned firms are eligible to participate in the effort.

The Defense Advanced Research Projects Agency contracted with the staff of the National Synchrotron Light Source at Brookhaven National Laboratory to build a compact superconducting-magnet synchrotron for x-ray lithography. The Brookhaven staff is currently building the accelerator. At present, the Phase I conventional magnets are being built. The five-year cost for this synchrotron and its operation is forecast at $31 million. DARPA is also funding the construction of several beamlines, including the lithography equipment, which will be dedicated to x-ray lithography at the University of Wisconsin synchrotron. The Congress appropriated $30 million for DARPA's x-ray lithography program for fiscal 1990, a $10 million increase from 1989.

In addition, DARPA funds much of the work done by the Naval Research Laboratory. Under contract with DARPA and the Very High Speed Integrated Circuit program at DoD, the Naval Research Laboratory is funding research that mostly (though not entirely) concentrates on areas other than x-ray sources. Specifically, the Naval Research Laboratory argues that developing x-ray lithography will require developing a whole host of support technologies. The Naval Research Laboratory has chosen to concentrate in these areas, most notably making the masks where it will place 65 percent of its funding. Because of the fine-line width needed and the harder impact of x-ray radiation on materials, conventional masks and chemicals cannot be used for x-ray lithography. Currently, the Naval Research Laboratory estimates that its program will cost $120 million over five years. At the end of this period, it hopes to have a national x-ray mask resource facility that can provide the technology base for the semiconductor industry. In addition, the Naval Research Laboratory is funding R&D on x-ray point sources.

Private Research

IBM is funding its own R&D effort on x-ray lithography. IBM has contracted Oxford Instruments, a private firm from the United Kingdom, to build a synchrotron at an IBM site that will be used for research and production. In addition, IBM has conducted most of the private R&D on x-ray lithography at Brookhaven. To date, industry sources estimate that IBM's costs for advanced semiconductor manufacturing for its facility at East Fishkill, Vermont, are approaching $500 million. Within this facility, IBM is having a synchrotron built for x-ray lithography. IBM has indicated that its site may be available

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for outside research on a selective cost-sharing basis. So far, Motorola is the only semiconductor manufacturing company that joined up.

The American Telephone and Telegraph Company has also increased its presence at Brookhaven, although so far it has not signed up with IBM and Motorola. At this time, AT&T is concentrating on x-ray optics technology.[4] AT&T has made an important breakthrough recently that may make x-ray lithography more feasible and may extend its potential range. While this AT&T technology may be useful with both synchrotron sources and point sources, some of the synchrotrons now being built or designed around current x-ray optics technology may not be able to take full advantage of its potential. AT&T officials believe that this technology will take tens of millions of dollars for further development before it becomes commercially available. AT&T is currently negotiating with a U.S. producer of lithography equipment--GCA, a division of General Signal Corporation--on the next phase of research.

Finally, SEMATECH has a small but active x-ray effort. Most recently, SEMATECH awarded a joint development contract to Hampshire Instruments to improve the quality of the x-ray beam in the point source.

Foreign Research

Other governments, most notably Japan and Germany, are actively involved in R&D on x-ray. The Japanese government and industry have several x-ray lithography efforts under way.[5] According to DOE sources, three conventional magnet and three superconducting magnet synchrotrons devoted to x-ray lithography are currently under construction or being commissioned in Japan. By the end of 1990, all the machines are expected to be operational. Most, though not all, of these synchrotrons are designed for lithography. Both the Ministry of Inter-

4. Peter Dunn, "Bell Labs, GCA Optic Division Build X-ray System with 20:1 Reduction," *Electronic News*, April 16, 1990, p. 28.

5. This discussion is largely taken from James Murphy, "Electron Storage Rings as X-ray Lithography Sources: An Overview," presented to the Society of Photo-optical Instrumentation Engineering Symposium on Microlithography, San Jose, California (March 1990).

national Trade and Industry (MITI) and Nippon Telephone and Telegraph (NTT), which have been associated with past major collaborative efforts in Japanese electronics, are involved in the current efforts. Many of the Japanese semiconductor firms have also chosen to participate in one or another of these experimental efforts. While the Japanese do not have the long history of accelerator involvement that U.S. scientists have, they do have the hardware at hand (see Table 1).

At present, experiments in x-ray lithography are being conducted in at least two sites: at SORTEC (the collaborative effort sponsored by MITI) and at the NTT complex. Even where the Japanese synchrotrons are not yet at full power, they are leading the field. At the NTT site, the synchrotron is achieving more than one-fourth of its design current of power. This is much more than any other effort has achieved. The comparable U.S. efforts will not reach this level for a couple of years, at best.

While the Japanese effort has been widely publicized and offered as a justification for a similar U.S. effort, there is substantial reason to believe that a raw comparison of the number of synchrotrons is misleading. First, the Japanese may have built many more synchrotrons than they need for research purposes.[6] Assuming there are 16 beamlines per synchrotron, the 7 Japanese synchrotrons would give over 100 beamlines, each capable of doing x-ray lithography R&D. Only one-half dozen Japanese semiconductor manufacturing companies would be interested in and positioned to do independent R&D on x-ray lithography. The rest of the Japanese companies are net consumers of lithography technology. Assuming that they need only a few beamlines each, like U.S. researchers, two dozen beamlines may satisfy most of the research needs, leaving the Japanese with substantial excess capacity in synchrotron beamlines. Second, some of the synchrotrons are not optimized for lithography; they produce the wrong wavelength of x-ray.

6. For a similar analysis, see Mark Crawford, "Japan's Big Gamble on Synchrotrons," *Science* (December 15, 1989), p. 1383.

TABLE 1. SYNCHROTRON X-RAY LITHOGRAPHY RESEARCH FACILITIES

Name	Location	Size (Diameter in meters)	Date[a]
	Multipurpose for R&D		
ADONE	Frascati, Italy	12m	1969
ALADDIN	Madison, Wisconsin	20m	1985
BESSY	Berlin, Germany	18m	1983
HESYRL	Hefei, China	20m	1989
PHOTON FACTORY	Tsukuba, Japan	66m	1982
SPEAR	Stanford, California	74m	1973
TERAS	Tsukuba, Japan	10m	1981[b]
VUV	Upton, New York	18m	1983
	Dedicated to X-Ray Lithography		
	Powered by Conventional Magnets		
CAMD	Baton Rouge, Louisiana	17m	1992[b]
LUNA	Tsukuba, Japan	6m	1989
NIJI-2	Tsukuba, Japan	4m	1988
NTT-1	Atsugi, Japan	14m	1988
SORTEC-1	Tsukuba, Japan	15m	1989
	Powered by Superconducting Magnets		
AURORA	Tanashi, Japan	3 m	1989
COSY	Berlin, Germany	6 m x 2 m[c]	1988
HELIOS	East Fishkill, New York	6 m x 2 m[c]	1990
NIJI-3	Tsukuba, Japan	4 m	1989
NTT-2	Atsugi, Japan	6 m x 2 m[c]	1988
SXLS	Upton, New York	4 m x 2 m[c]	1993[b]

SOURCE: Congressional Budget Office compilation of data from G.P. Williams, J.B. Godel, G.S. Brown, and W. Liebmann, "Report of the Fifth Workshop on Synchrotron X-Ray Lithography, November 16-17, 1989" (Brookhaven National Laboratory, Upton, New York, 1989), p. 3; and James B. Murphy, "Electron Storage Rings as X-Ray Lithography Sources: An Overview" (Presentation to the Society of Photo-optical Instrumentation Engineering Symposium on Microlithography, San Jose, 1990).

a. Date when scheduled for first operation.

b. Estimated.

c. Oval shaped.

The German efforts in x-ray lithography have not progressed smoothly. After funding the construction of a synchrotron with two superconducting magnets, their research effort plateaued. The superconducting dipole magnets have failed to perform as expected, and no purchasers for the system have been forthcoming. Consequently, the small start-up company that was founded to market these systems has ceased operations.

FEDERAL POLICY OPTIONS

The federal government has to decide whether to build yet another synchrotron accelerator for R&D on x-ray lithography. IBM's own R&D efforts are on superconducting magnets, which remain unproven. Some physicists argue that this concentration ignores conventional magnets, which have shown value.

In addition, advanced lithography technologies other than x-ray are on the horizon and, while perhaps not as well developed as x-ray lithography, may prove cost effective. All of these technologies show signs of being able to produce integrated circuits with minimum features less than 0.3 microns. Although x-ray lithography may appear to be the leading candidate, only time will tell which system replaces optical lithography.

Build Another Synchrotron for Lithography R&D

At the most recent Brookhaven workshop on synchrotron x-ray lithography, consensus was that the current capacity of synchrotrons to do x-ray lithography, whether by public or private effort, is as much as the semiconductor industry could absorb.[7] Counting both current and planned capacity, five accelerators exist on which x-ray lithography R&D can be done. The U.S. semiconductor producers that have expressed interest include Motorola, IBM, AT&T, and SEMATECH. Need for x-ray lithography R&D may exist, but those efforts should be

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7. Mark Crawford, "The Silicon Chip Race Advances into X-rays," *Science* (December 15, 1989), pp. 1382-1383.

focused on the nonsynchrotron elements of x-ray lithography technology, such as the masks, lithography equipment, chemicals, and even point sources.

The report of the Brookhaven workshop argued that the aggregate capacity, while sufficient, either was based on yet unproven superconducting magnet technology or was not designed for integration into a semiconductor manufacturing environment.[8] The recommendation of the workshop was that the federal government build, jointly with some private partners, one or more conventional magnet synchrotrons designed for semiconductor manufacturing and integrated with a production environment.

Given the spare capacity in synchrotrons for this purpose and the bulk of relevant R&D performed by individuals employed by private industry--although sometimes with public funding--it is not clear what would be accomplished by building additional synchrotrons at this time. One result may be to divert the funds needed to operate current synchrotrons and to develop complementary technology. Furthermore, IBM and Motorola--two of the more likely clients of such an effort--have already embarked on their own parallel project.

Two questions remain. The first is whether the federal government is willing to increase its commitment to x-ray lithography to the extent of buying an extra synchrotron ring just in case superconducting magnets fail. The second is whether the federal government wants to go in a different direction than two of the most likely clients, or would it rather support the efforts of those clients.

Advanced Lithography Research

Synchrotron x-ray lithography is not necessarily the only answer to the problems facing lithography. A half dozen technologies, each with some technical problem now perceived as insurmountable, seem promising to semiconductor engineers. Breakthroughs may come in any one

8. G. P. Williams and others, "Report of the Fifth Workshop on Synchrotron X-Ray Lithography, November 16-17, 1989" (Brookhaven National Laboratory, 1990).

of these areas. DARPA explored the possibility of supporting R&D into advanced lithography systems beyond its current efforts in x-ray and may incorporate its findings in future plans.

The policy objective in this case is to have a portfolio of R&D projects in lithography so that a federal agency does not have to guess which lithography system will succeed. The federal government may wish to provide support for other lithography systems, in addition to x-ray lithography. Among the systems most frequently mentioned are free electron lasers, electron beam, and ion beam. These last two are particle beams that can be used either to write the integrated circuit pattern directly on the resist or, in conjunction with a mask, to substitute for light in conventional lithography.

Free Electron Laser. A free electron laser is a device that uses a particle accelerator to amplify a light (or x-ray) beam. Some engineers have proposed using a free electron laser instead of a synchrotron as an x-ray source for lithography. Unfortunately, free electron lasers currently share many of the characteristics of synchrotrons as x-ray sources: both are big, expensive, and need many experts to operate them. At present, the Strategic Defense Initiative funds most of the R&D on free electron lasers.

Electron Beam. Electron or e-beams machines are primarily used to write the pattern directly on the mask, which is in turn used to produce the integrated circuits. While e-beam direct-write machines are precise enough to write the fine lines needed in the future, they are very slow because they write directly. Thus, they are used primarily in areas where one-of-a-kind production is important: mask production, prototype production, and production of small lots of proprietary integrated circuits. Over the years, however, e-beam machines have been getting faster--fast enough, some argue, to be moved out of their specialized role in semiconductor production.[9]

In a related development, IBM has been doing research into using electron beams to expose a mask onto a prepared wafer. In this case,

9. This discussion is from David J. Elliott, *Integrated Circuit Fabrication Technology*, 2nd edition (New York: McGraw-Hill, 1989), pp. 508-514.

the electron beam itself is larger than usual (one millimeter square), enabling it to scan a large slice of the mask at a time. Currently, state-of-the-art masks occupy an area of roughly 100 millimeters square.

Ion Beam. In theory, ion beams can be used in a manner parallel to electron beams to accomplish many of the same goals. The difficulties of working with ion beams, compared with the relative ease of working with electron beams, has limited the use of ion beams to this day. Currently, some research is under way to determine the utility of using focused ion beams to repair defects in masks. Some have suggested using ion beams as a tool to write directly.

Alternatively, some have suggested using ion beams to expose a mask onto a prepared wafer. Masked ion beam lithography is a system that has the potential to achieve geometries of 0.3 micron.[10] While certain technical problems need to be resolved (and may never be), this technology has demonstrated its initial feasibility. In masked ion beam lithography, an ion source replaces the light source in a conventional optical lithography device called a wafer stepper. The ion beam exposes the photographic emulsion on the wafer, much the same way ordinary light does now, transferring the image of the integrated circuit from the mask to the silicon wafer. In this sense, it is similar to point source x-ray lithography. Like point source x-ray, however, ion beam lithography still has substantial technical barriers to overcome, most notably with mask technology. Unlike point source x-ray, capacity does not appear to be a problem.

At present, there are two R&D efforts in this technology. The U.S. Navy had funded the R&D for developing this technology. No further R&D is planned at this time, although the prototype may be transferred to a U.S. university for further work. In addition, a small development project on masked ion beam lithography is under way in Austria.

10. See John Bartelt, "Masked Ion Beam Lithography: An Emerging Technology," *Solid State Technology* (May 1986), pp. 215-220.

POTENTIAL FOR AN R&D CONSORTIUM

IBM has invited the federal government to join it in a major R&D effort to bring x-ray lithography to its commercial stage. Alternatively, the federal government could allow DARPA, the Naval Research Laboratory, and DOE to continue their individual efforts, supplementing their requests as the budget allows. The joint industry-government investment of $300 million on x-ray lithography over the 1988-1994 time frame would be government-led but industry-designed. The largest shares would go to mask-making technology (34 percent) and process integration and device demonstration (29 percent); further shares would go for further synchrotron and lithography equipment development (20 percent) and chemicals and point source R&D (13 percent).

Is an x-ray lithography consortium necessary? SEMATECH and most U.S. semiconductor producers believe that the limits of optical lithography can be stretched until some time after the year 2000. Furthermore, they find the synchrotron ring concept unappealing: the investment requirements, size, and risk of a synchrotron system do not fit within their current production processes. For example, assume that a synchrotron costs $20 million to $25 million. The 16-wafer steppers positioned around the ring cost $2 million each. The beamlines each cost $750,000 to $1 million. Add another $10 million to $15 million for peripheral equipment, the radiation shielding, and the building. Thus, the cost of the lithography equipment and the space to accommodate it could be $75 million to $85 million. Furthermore, failure of just one instrument--the synchrotron--would stop the whole lithography system and, shortly thereafter, the entire fabrication plant dependent on it.

Rather than build a system that primarily benefits producers of semiconductor memories, U.S. producers would rather concentrate R&D on systems with more modular investment possibilities, like point source x-ray lithography. This logic suggests that U.S. producers of semiconductor memories could buy Japanese-developed synchrotrons, if that were the only way. If successful, a synchrotron x-ray lithography project may accelerate tendencies towards vertical integration in the industry. The pieces of equipment developed by this effort are likely to be expensive and to be geared toward mass production. They will be of most benefit to well-capitalized producers of integrated circuits, such as memories, with very large markets.

Thus, synchrotron-based lithography may do little to strengthen the hand of the middle-sized U.S. producers of integrated circuits, which produce a broad range of integrated circuits for many smaller markets rather than for a few large ones. If anything, synchrotron-based lithography should strengthen the bifurcation of the industry into large vertically integrated and usually captive producers and producers who serve special markets or niches. Vertically integrated producers have large internal markets that can guarantee use of synchrotron x-ray lithography machines at full capacity and, thus, ensure profitability; niche producers rely on their design and not on their manufacturing strength.

Synchrotrons, however, may prove useful for devices other than memories. For instance, certain semi-custom integrated circuits, called gate arrays, are fabricated identically except for the last few steps, which give each integrated circuit its specific functional identity. Worldwide shipments of gate arrays are forecast to exceed $4.6 billion in 1990.[11] Thus, gate array producers may be able to use the productive capacity of a synchrotron. Other producers of semiconductor devices may find that they can indeed use high-output lithography machines as they rethink their lithography needs. How a new piece of capital equipment will be used is hard to forecast.

To a large extent, the federal government is already involved in collaborative R&D in x-ray lithography. A division of labor, for example, has existed among Brookhaven National Laboratories, DARPA, the Naval Research Laboratory, and large semiconductor producers. The DOE provides the location, trained labor, and the synchrotron. Other federal agencies have concentrated on supporting technology, while the large semiconductor companies concentrate on the semiconductor manufacturing technology. The major public and private interests know each others' work and, to some extent, coordinate their research. Neither the coordination nor the funding process has run as

11. Jack Beedle, In-Stat, Inc., Scottsdale, Arizona, "The 90's--An Ear of Change," Presentation to the 1990 Semiconductor Equipment and Materials International's Thirteenth Annual Information Services Seminar (Newport Beach, Calif.: January 22-24, 1990).

smoothly as a systematic program should, however. Membership in a formal consortium with secure funding would certainly improve the process, but a substantially larger amount of work may not result, especially since the major private interests have begun to work on their own projects.

While a portion of the industry is interested in developing x-ray lithography with the government, industry has much less interest in developing other forms of advanced lithography. Current R&D primarily exists at start-up firms or with small numbers of individual investigators in major laboratories interested in the questions of advanced electron beams or ion beam lithography. Because of the long time frame before these technologies are needed, the alternatives have had a hard time getting private funding. Even the federal funding sources have been irregular. Thus, the federal government will be unable to find cosponsors for such research if it were to fund a portfolio of advanced lithography efforts.

CHAPTER V

POLICY OPTIONS

If the federal government were to adopt a policy of using consortia for research and development to promote commercial innovation, it would face three important decisions: how much funding to allow, what legal framework to use, and what organizational structure to apply. Most important to the last decision is where to place responsibility for such a policy within the federal government. Also under discussion are the indirect tools the federal government can use to promote R&D consortia: the antitrust limitations in taking these consortia past the R&D stage and into production, and the tax treatment of R&D consortia.

Federal policies in support of R&D consortia, however, are only one element in the broader policy goal of how best to foster commercial innovation. Policies that increase the health and strength of U.S. consortia may not, in all cases, be the same as those that promote rapid commercial innovation. Such a case would be policies that encourage consortia but neglect the technical expertise that is needed within individual firms to benefit from the resulting discoveries.

REFORM OF ANTITRUST LAWS

The Administration recently recommended amending the National Cooperative Research Act of 1984 to include joint ventures for production along with those currently allowed for R&D. Under these amendments, potential liability would be limited to damages (plus attorney's fees) caused by any anticompetitive behavior, as judged by the courts, rather than treble damages, as normally the case in private antitrust actions. The Congress has been considering legislation--specifically, H.R. 4611 and S. 1006--to accomplish many of the same aims.

One central argument behind the proposed changes is that bringing new products to market is difficult and risky. Firms engaged in

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developing new products should be allowed to combine their efforts for production, thereby spreading the costs of development and reducing the risk of failure. Innovation is difficult because new factories are expensive and beyond the means of many firms.[1] Innovation is also risky because less information is available on consumer preferences, competitors' reactions, and market conditions in general.[2] These problems are compounded because the U.S. high-technology is concentrated more in small firms, in contrast to the foreign industries against which they compete. Given the capital constraints under which U.S.-owned firms operate, they often have a hard time breaking out of their market niches to merge into the mainstream.

Another justification for the proposed changes is that while NCRA made R&D exempt from certain legal challenges, it drew the line at production. Thus, firms participating in an R&D consortium might have to part company when trying to apply or transfer their newly acquired knowledge. Transferring newly developed technology is often difficult: SEMATECH, for example, has had to make special efforts to ensure that transfer occurs. To build up a collaborative R&D organization and then require it to break up before the knowledge is applied seems inefficient. Without application, R&D is academic. Some analysts argue that, if the federal government is going to foster R&D consortia to help U.S.-owned firms become more competitive, it may also have to allow firms easier use of the technology developed by those consortia.

The changes in the NCRA, proposed in the bills under Congressional consideration, would still not allow complete integration of the activities of the member firms. The amendments do not remove the NCRA's exclusion on sharing sales, distribution, and marketing information from the permissible activities of a registered consortium.

1. For this argument, see Office of Technology Assessment, *Making Things Better: Competing in Manufacturing* (February 1990), pp. 226-227.

2. Thomas Jorde and David Teece, "Competition and Cooperation: Striking the Right Balance," *California Management Review* (Spring 1989), pp. 26-28.

Are Antitrust Laws a Barrier to Joint Manufacturing?

Antitrust laws, as the courts currently interpret them, do not constitute a barrier for the most common types of joint manufacturing. This conclusion is reasonably clear, despite widely repeated assertions regarding problems with antitrust laws in the United States. One recent informal survey concluded that joint production ventures are being announced on the average of nearly one per week.[3] A different survey suggested that this pattern has held since the mid-1970s.[4] While more joint ventures might have been formed in a looser legal environment, that so many joint ventures were formed suggests that the law was not a major constraint; if firms wanted to form a partnership, by and large they could. In fact, the U.S. business culture with its accent on adversarial roles is as likely, if not more so, to constrain firms from joining together.

The principal argument in favor of changing the laws on joint manufacturing ventures is to codify current law in this area. Applicable law is now found not only in statutes, but also in bits and pieces of judicial rulings and in antitrust policies embraced over the last decade and a half by the Department of Justice. By codifying the law, the federal government would reduce business uncertainty about renewed antitrust restrictions. Such clarification was the principal argument in favor of the NCRA in 1984.

Most joint ventures allowed under current law involve a few firms in an undertaking of limited scope. Such a venture was recently announced between Intel and a Japanese semiconductor producer (NMB Semiconductor) to manufacture dynamic random access memory (DRAM) integrated circuits. Thus, the joint ventures of small numbers of firms, sometimes involving firms with substantial market presence (such as General Motors and Toyota), do not seem hampered by current antitrust policy. What may be discouraged by antitrust laws are industrywide efforts toward joint production ventures.

3. James Rill, Assistant Attorney General, U.S. Department of Justice, in response to questions before the Subcommittee on Science, Research, and Technology of the House Committee on Science, Space, and Technology, *The Government Role in Joint Production Venture* (September 19, 1989), p. 45.

4. Kathryn R. Harrigan, *Strategies for Joint Ventures* (Lexington, Mass.: Lexington Books, 1985), pp. 7-13.

Even in the case of industrywide consortia, business environment and culture may play more central roles than antitrust legislation. For example, U.S. Memories was intended as a production consortium for manufacturing DRAMs. During 1989, both U.S. semiconductor producers as well as U.S. computer manufacturing firms were invited to invest in U.S. Memories. U.S. Memories failed to attract sufficient investors not because of antitrust laws, but rather because the DRAM market had excess capacity. Furthermore, the potential business partners could not agree on terms: Hewlett-Packard, for example, objected to IBM only providing the four megabit DRAM technology and no funds.[5] Other potential investors raised different objections. In the end, common U.S. business practices, not law, defeated U.S. Memories.

Industrywide Production Ventures. One type of venture that may be discouraged by current antitrust laws is industrywide production ventures. These ventures involve more than a small subset of firms in one industry. Good reason exists for discouraging such ventures. First, a strong potential for collusion exists. While U.S. Memories was a small effort in a large internationally competitive industry, that will not always be the case. The changes in the laws being discussed go far beyond the specific case of U.S. Memories, and so joint ventures in vastly different circumstances might be allowed. Second, while international competition might initially cause a joint production venture to curb price increases, later changes in international trade--such as orderly marketing agreements or voluntary restraining agreements--might give the venture substantial power in the domestic market. If this were to occur, not only would U.S. consumers pay more, but also member firms might become less competitive in the absence of international pressure.[6]

One central issue in industrywide manufacturing consortia is whether the Department of Justice can control the actions of any con-

5. Robert Ristelhueber, "U.S. Memories: End of a Cashless Society," *Electronic News*, January 22, 1990, pp. 1 and 4; and Robert Holf, "This Will Surely Come Back to Haunt Us," *Business Week*, (January 29, 1990), pp. 72-73.

6. For an analysis of the debilitating effects of weak antitrust laws on the competitiveness of British firms, see David C. Mowery and Nathan Rosenberg, *Technology and the Pursuit of Economic Growth* (Cambridge, England: Cambridge University Press, 1989), the chapter on "The Organization of Industrial Research in Great Britain, 1900-1950," pp. 59-97.

sortium once the notification process is over. In the case of U.S. Memories, behavior appropriate in the DRAM market might not be as appropriate in the closely related static random access memory (SRAM) market, which is not as dominated by foreign competition. Even if no antitrust statute were violated, a production consortium that could expand into related activities might shift from areas where there is a public interest (as in DRAMs) to areas where there is not (as in SRAMs). The case for special legal treatment is dissipated as a consortium moves away from R&D and into competition with other U.S.-owned firms.

An example of this movement can be found in the history of the Microelectronics and Computer Technology Corporation (MCC). MCC was initially founded to counter the Japanese Fifth Generation Computer Project but has shifted its focus over the years. Its initial case for public purpose was based on using R&D in international competition. As yet, the Fifth Generation Computer Project has proven unfruitful. MCC is now involved in producing software that competes with U.S. start-up companies in engineering software markets currently dominated by U.S.-owned firms.[7] MCC disputes this, arguing that its products are much less well developed and serve only as the core for products of client companies.

In the original policy debate over the NCRA, all innovation was assumed to be in the public interest because of its potential contribution to national welfare. In production, there is no such assumption. Once production is begun, consumers will buy from either firm A or firm B. Assuming they can buy the same product at the same price from both firms, consumers are no better or worse off regardless from whom they buy. With R&D, the hope is that something new and useful will be produced and consumers will be better off. Thus, applying the same criteria in this situation seems inappropriate.[8] Furthermore, the evidence regarding economies of scale in production is mixed, existing

7. See Statement of David R. Coelho, Vantage Analysis System before the Subcommittee on Economic and Commercial Law of the House Committee on the Judiciary, September 28, 1989.

8. This discussion is largely based on Michael E. Porter, Statement before the Senate Committee on the Judiciary, *Competitiveness and Antitrust*, Hearings on Modifications of Antitrust Law or Enforcement Policies with Respect to Distressed Industries (May 7, 1987), pp. 160-171.

in some places but not in others. As a result, one cannot always assume that big is better.

Successors to R&D Consortia

As noted above, one common justification for relaxing the antitrust constraints involves the inefficiency of creating an R&D consortium and then breaking it apart when the time comes to apply the resulting technology. This justification for antitrust exemption for joint production ventures rests partly on assessments of the Japanese experience. The often-cited Japanese efforts in cooperative R&D only rarely and less successfully involve joint production. At the end of the R&D phase, each firm launches its own production as it sees fit.

The more important argument against relaxation of antitrust laws is that analyses of joint ventures suggest that many are in areas of competitive weakness, not strength, or in areas of secondary importance.[9] For example, SEMATECH concentrates on semiconductor manufacturing equipment where none of the competitive strength of U.S. semiconductor producers is found. SEMATECH avoided research on the design of specific integrated circuits--the U.S. strength--as this would have caused the consortium to dissolve. Similarly, once the initial competitive battles over becoming the industry standard for microprocessors were won, Intel ceased licensing its microprocessor technology (its principal strength) to any firm, except IBM, with which it had a special relationship.

To move from R&D consortia to manufacturing consortia would increase the commitment of the member firms in areas where they may not be strong. Private firms will decide where their competitive strength lies. It is not clear, however, whether the role of policy should bias these choices by providing special antitrust legislation when these firms act in concert but not when they act alone.

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9. For different emphasis on many similar difficulties, see David C. Mowery and Nathan Rosenberg, *Technology and the Pursuit of Economic Growth* (Cambridge, England: Cambridge University Press, 1989), pp. 244- 248; Michael E. Porter, "The Competitive Advantage of Nations," *Harvard Business Review* (March-April 1990), pp. 73-93; and Michael E. Porter, *The Competitive Advantage of Nations* (New York: The Free Press, 1990), pp. 612-613 and 635-637.

One clear consequence of these amendments is that many U.S.-owned firms would attempt to register their activities as joint ventures and, thus, to exempt themselves from ever facing treble-damage lawsuits. By allowing firms an exemption from such lawsuits, the federal government might effectively be repealing the treble-damage provisions of antitrust law. These provisions have been quite controversial over the years. If the federal government wishes to repeal these provisions, however, it should be done in the context of antitrust law and not as a side effect of legislation on a different topic.

Foreign Ownership and Joint Ventures

One bill (H.R. 4611) amending the NCRA limits the amendments to joint ventures where 70 percent or more of the shares are held by U.S-owned firms.[10] (The Senate version of the bill does not have this provision.) The proponents of this limitation argue that foreign firms often operate in much looser antitrust environments and, consequently, do not need this encouragement.

Opponents of this provision point to its lack of connection to clear policy goals. The provision does nothing to encourage production and employment nor the performance of R&D in the United States. By explicitly exempting foreign firms, opponents argue that the limitation may discourage firms from setting up production ventures in the United States. For instance, two European firms (Thompson Consumer Electronics and N. V. Phillips) have discussed joint development of high-definition television receivers for the U.S. market. Even though these firms currently produce in the United States and would presumably continue to do so in a joint project, they would still be liable for treble damages if any joint manufacturing agreement into which they entered found them guilty of anticompetitive practices.

10. The bill was amended to include Canadian-owned firms.

THE RESEARCH AND EXPERIMENTATION TAX CREDIT

The National Advisory Committee on Semiconductors recommended that the federal government enact legislation to extend the tax credit on incremental research and experimentation (R&E) to cover the costs of collaborative research, including R&D consortia.[11] By reducing the cost of joining such consortia, the committee believed that further participation in cooperative efforts would be encouraged.[12]

Under current law, members of many collaborative R&D efforts may already be eligible for the credit. If the joint venture is not a separate legal entity and the R&D is performed by employees of the member companies, then--assuming that all other tests for the R&E credit are met--company members would be eligible. If the R&D consortium is organized primarily as a vehicle for promoting basic research in a specific field, such as the Semiconductor Research Cooperative, then payments to the consortium are eligible under the University Basic Research Credit, which also provides 20 percent credit.[13] In fact, the promotional literature for prospective members of the Semiconductor Research Cooperative highlights this aspect of membership. If the R&D consortium is organized as a partnership, but not an R&D limited partnership, then the members of the partnership could use the R&E. Thus, current R&D collaborative efforts may or may not be eligible for the R&E credit, depending on a series of factors including: the specific nature of the agreement that forms the consortium, where the R&E is performed, and the trade or business in which the member firms are engaged before they enter the consortium.

One type of consortium is not eligible for the credit: nonprofit organizations devoted to commercial R&D whose membership is not open to the entire industry, such as SEMATECH. Even in the case of SEMATECH, payments by members might be eligible for the R&E

11. The credit is called the R&E credit because it is limited to expenditures on R&D in the experimental or laboratory sense of the word. Not all development efforts may be eligible.

12. See National Advisory Committee on Semiconductors, "A Strategic Industry at Risk" (November 1989), p. 25. The report does not spell out the rationale for this specific recommendation, but it can be deduced from the context.

13. See Joint Committee on Taxation, *General Explanation of the Tax Reform Act of 1986* (May 4, 1987), pp. 137-140.

credit under the provisions for contract research. SEMATECH might have to pay taxes on such payments as unrelated business or trade income. The problem arises not so much from the regulations surrounding the credit as from the restrictions on tax-exempt activities. Thus, the tension in the central policy is the desire to exempt commercial R&E from corporate taxes using a tax-exempt organization but still to receive the R&E credit. If the federal government creates this opening in the law as a means of sheltering commercial activities, organizations much less worthy of public subsidy may take advantage of the opportunity.

Questions of equity also occur. If the federal government is already contributing to a consortium directly, such as SEMATECH, should the tax system contribute? Alternatively, if the federal government makes this modification to the tax code, will it then wish to contribute directly to new consortia? Furthermore, does the federal government wish to create an entitlement to federal support, which a tax provision implies? If so, does the federal government wish to do so through the tax code or through an administrative agency, such as those (described later in this chapter) that might provide technical assistance to a consortium?

The Congress recently made major modifications to the incremental R&E tax credit and extended it through 1990. These modifications reduce many of the negative incentives of the older credit calculations. Under the revisions, an existing firm calculates its fixed-base percentage as the ratio of total qualified R&E spending to gross receipts during the 1984-1988 period. For any given year, the firm is eligible for a 20 percent credit for qualified R&E spending that is above this fixed-base percentage of its current gross receipts. Thus, if a firm has a fixed-base percentage of 10 percent, any qualified R&E spending above 10 percent of this year's gross receipts would be eligible for the 20 percent credit. Start-up companies are assigned a statutory base percentage of 3 percent. (No firm can get a credit, however, for more than 50 percent of its qualified R&E spending.) In the case of high-technology industries, this percentage would tilt the credit in favor of start-up companies, which often have much higher levels of R&D effort. Such companies often do not have tax liabilities against which to use the credit. The credit is forecast to cost the U.S. Treasury $700 million in lost revenues in fiscal year 1991.[14]

In the electronic industries, many of the most likely members of R&D consortia may be ineligible for the credit. The base period for calculation was 1984 to 1988 in the middle of which a worldwide computer/semiconductor recession occurred. During this period, many firms tried as best they could to maintain R&E effort. Consequently, expected sales, relative to R&E, would be low, especially for many technologically progressive companies. Thus, quite a few firms would be ineligible. To compensate for exceptional circumstances, the legislation set the maximum base level at 16 percent. For most established firms, however, 16 percent is quite high, although small or start-up firms sometimes make this level of research effort.

ENCOURAGING FEDERALLY FUNDED R&D CONSORTIA

The federal government will confront two concerns in its decision on whether to promote commercial innovation through R&D consortia. First, there are general concerns about the appropriate role of the federal government in such an endeavor: what can it achieve, and how should it act? Second, there are specific concerns about what agency the federal government will choose to carry out this mission: what are the trade-offs between using civilian or military agencies?

General Concerns about the Federal Role in R&D Consortia

A systematic program for federal funding of R&D consortia to promote commercial innovation would raise a series of public policy questions. The list could be divided into three general categories: program priorities, program funding, and program operations.

Program Priorities. The federal agencies that now specialize in applied research are all mission agencies that set their research priorities by

14. Joint Committee on Taxation, *Estimates of Federal Tax Expenditures for Fiscal Years 1991-1995* (March 9, 1990), p. 10.

how it affects their mission: Defense Advanced Research Projects Agency by how it affects defense, National Institutes of Health by how it affects health, U.S. Department of Agriculture and Department of Energy, accordingly. Efforts to promote commercial innovation through R&D consortia have no such filter. In lieu, the pipeline model of commercial innovation allows many proposals that would advance generic technology.

Some policymakers have interpreted generic technology to mean technology that can be used by many industries as opposed to technology that is used by one or another specific industry. This latter definition would provide a filter; however, it would limit federal actions in many of the areas where policy is important. For instance, the language authorizing the Advanced Technology Program (ATP) dictated a priority on x-ray lithography. Yet, the only industry that uses x-ray lithography directly is the semiconductor industry. As a result, such technology cannot be considered generic in the sense that it is general to many industries.

Most proposals for a technology agency face the problem that federal support for R&D may discriminate among U.S.-owned firms. As noted in a previous chapter, much of SEMATECH R&D supports competitive research to help specific equipment firms. If only truly generic and noncompetitive research were funded, the agency may miss many interesting technological opportunities. Thus, the only filter for an agency concerned with commercial innovation would be generic or applied research, which would exclude industry-specific actions that may be important technologically.

Political favoritism may also distort the process for setting research priorities. Certain technologies may become politically favored and receive a disproportionate share of funding for their contribution to national productivity and competitiveness. The European and Japanese experience is filled with attempts to create "prestige" products or "national champion" firms that have wasted substantial amounts of taxpayers' money.

Although setting priorities constrains policy within the pipeline model of commercial innovation, it is also a problem for the chain-linked model. The chain-linked model allows policy to take actions at any stage, as long as the benefits do not fully accrue to the innovating firm. Thus, policy under this model can take actions to advance national welfare, but which actions to take still has to be determined. Do R&D consortia working in electronics receive more or less support than firms in biotechnology? Unless the federal government is going to make support of R&D consortia an entitlement--that is, any consortium that meets certain qualifications receives specific federal support--it will have to set priorities directly or implicitly through an agency board.

The decision to support an R&D consortium is only one of several the federal government has to make. Joining an R&D consortium might not give the nation the adequate portfolio of R&D projects in a specific technology area. Even if the federal government joins an R&D consortium in a specific area, the government may want to invest in alternative research on the competing approaches to the same technology.

In other cases, the relevant federal agency might decide that the consortium's approach was indeed the best bet and that supporting similar programs for competing technologies was an expensive hedge against risk. For example, as noted in the chapter on x-ray lithography, while private U.S. efforts are concentrating on using synchrotrons with superconducting magnets for production of semiconductors, the synchrotrons might not work as planned. Some physicists have suggested building an additional conventional magnet synchrotron just in case the superconducting magnet synchrotron does not work as needed for x-ray lithography. The federal government will have to weigh the expense and the risks of additional options, independent of its decision on the consortium's approach.

In this sense, supporting R&D consortia is a different decision than supporting commercial innovation in general. A consortium has to agree on a very specific R&D agenda and time frame. That agreement is the reason for its existence. No organization, public or private, can expect that others, even those interested in the same areas, will always agree on a research agenda. Federal objectives may be better served by proceeding alone some times and at other times, when the circumstances are right, by collaborating with others.

Attempting to determine the clients of federal efforts to foster commercial innovation creates some problems, such as the nationality of firms, their output, and their R&D. The issue is whether non-U.S. firms are going to be allowed to participate in R&D contracts and grants sponsored by federal programs to support civilian technology. Currently, SEMATECH does not permit foreign firms to participate in its technology development projects. This issue will arise if the federal government is going to justify civilian technology programs on the grounds of increasing the competitiveness of the U.S. economy.

Most analyses define the nationality of a firm by the nationality of its stockholders. This definition, however, ignores two important criteria: where production occurs and where R&D occurs. Why is a product made in Mexico by a firm owned by U.S. citizens a U.S. product, while a product made in the United States by a firm owned by foreigners a foreign product?

R&D presents an equally vexing problem: while U.S. policymakers might want all firms to perform their R&D in the United States, many U.S.-owned firms find it advantageous to perform their R&D in Japan or Europe. Conversely, many of the high-technology firms owned by foreigners perform a great deal of their R&D in the United States. From a public policy point of view, restrictions on participation by non-U.S. firms apply higher tests for the public good than on U.S.-owned firms. For example, in S. 1978, a proposal now pending for a new civilian technology agency, firms from both the United States and Canada are eligible to participate in programs of the technology agency but make no requirements for U.S. operations.[15] In contrast, the 1991 authorization bill for NIST contains language for the ATP that requires commitments to U.S. manufacturing and R&D.

An additional problem is that some of the criteria for foreign participation are not closely related to the purposes of R&D consortia.

15. This provision appears consistent with the Free Trade Agreement between the United States and Canada. Contrary to usual custom, this act excludes Mexico from its definition of North America.

Often participation is restricted if the home country is guilty of unfair trade practices, despite meeting other criteria. Thus, if Thompson Consumer Electronics sells in the French television market, which some consider is protected, then it might not be allowed to join a U.S. consortium on HDTV, even though its subsidiary, RCA, accounts for 20 percent of televisions produced in the United States as well as a substantial portion of the U.S. industry's R&D. Similarly, Japanese firms are in a unique position to contribute semiconductor manufacturing expertise to joint ventures with U.S.-owned firms.[16] In many cases, their domestic markets are allegedly closed to U.S.-owned firms.

As noted in the evaluation of SEMATECH in Chapter II, the clearest benefits of R&D consortia come from the increased communications between suppliers and their customers. Increased communication along the manufacturing chain without vertical integration through ownership decreases risk and uncertainty for all concerned. This communication also improves each firm's ability to allocate its scarce resources effectively because the need to hedge against unforeseen conditions is less.

This experience suggests that federal agencies responsible for R&D consortia for commercial innovation should make every effort to encourage membership from the supplier industries. Thus, a flat-panel consortium might include not only producers of flat panels but also suppliers of glass, chemical, and manufacturing equipment as well as major consumers of flat panels, such as producers of personal computers. In assisting communication among these diverse groups, federal agencies may perform their most important role.

Program Funding. DARPA can often take the initiative for technological innovation because it is well funded. DARPA has roughly $500 million to spend on dual-use technologies, although not all of this amount is for R&D consortia.[17] Unless other federal agencies have enough funds and flexibility to take advantage of opportunities for

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16. This point is made in Dorothy Chistelow, "U.S.-Japan Ventures: Who Gains?" *Challenge* (November-December 1989), pp. 29-38.

17. Jeffrey Rayport, "DARPA" case study N9-390-142 prepared for the Harvard Business School (Boston, Mass.: January 18, 1990), p. 13.

commercial innovation, they will have a hard time overcoming the passive federal role as delegated in private consortia.

SEMATECH has created a precedent for 50/50 cost sharing for federal involvement with industry in R&D consortia. This ratio, of course, may not always be optimal. In the case of SEMATECH, the ratio seemed appropriate to establish the industry's serious interest. Other industrywide consortia may also be able to draw on substantial private contributions.

In other cases, a 50/50 ratio may be difficult for the industry to match. For example, with point source x-ray lithography or other advanced non-x-ray lithography, the firms involved may be small start-up companies that simply cannot afford to match a federal commitment. In this case, the federal government might be better off funding such research directly without agreeing on an agenda with numerous firms.

The cost-sharing approach creates good incentives. Industry is not likely to create an irrelevant research agenda if its own money is at stake. In the case of SEMATECH, the initial 50/50 ratio was further leveraged. SEMATECH only pays for one-third of the R&D in its equipment improvement and development programs; the recipient firm provides the rest. In this case, the recipient firm has every incentive to create commercially viable technology, rather than technically interesting but commercially irrelevant knowledge, which often results when federal agencies fund the development of technology. Furthermore, because of the various cost-sharing arrangements, the SEMATECH R&D contracts for equipment result in $5 of private funds for every federal dollar spent.

As an incentive system, cost sharing is important in consortia devoted to commercial innovation, as opposed to those devoted to basic research. Discriminating among interesting technologies requires detailed knowledge, which is usually located in private industry. While the federal government does not lack advice on how best to spend its money, the expertise and motivation behind such advice are always open to question. If the private sector has its own funds and own experts involved, the research will more likely be relevant to the needs of industry. Cost sharing helps avoid situations where the federal government backs R&D for innovations that the marketplace has bypassed.

Program Operations. Regardless of their specific mandate, federal research agencies have to rely on private sector partners for making R&D consortia successful. While the federal government provided SEMATECH with moral and financial support and DARPA specifically provided some organizational help, SEMATECH was organized largely at private initiative. Private parties agreed on its mission, both the overarching framework and the technical details. Without federal assistance, this R&D consortia might not have come together; nevertheless, SEMATECH was largely a private endeavor. While a federal agency can provide technical assistance, organizational wherewithal, and funds, federal agencies suffer from limited technical abilities, industry standing, and market information. Hence, the federal role in the formation of R&D consortia for commercial innovation cannot substitute for private initiative.

Even after the R&D consortium is formed, the initiative may stay in private hands. While a government agency may be able to offer some organizational advice and encouragement, the greater technical expertise of the private sector often requires the government to play a relatively passive role. In SEMATECH, for example, no federal agency has the expertise in semiconductor manufacturing technology that semiconductor producers have. Thus, by supporting a consortium, the federal government will often be implicitly delegating its authority to decide on the R&D agenda. In other areas, such as x-ray lithography, where the disparity between private and federal technical expertise is not so great, the federal government may play a larger role in determining the R&D agenda.

Most new technology endeavors fail. Venture capitalists estimate that 5 out of 10 new ventures that they fund are commercial failures.[18] Similarly, many existing firms that try to develop new technologies also fail. The International Business Machines Corporation tried to

18. See Congressional Budget Office, *Federal Financial Support for High-Technology Industries* (June 1985), p. 72.

develop its own flat-panel display before deciding instead to develop new technology jointly with Toshiba.

The unpredictable nature of R&D together with the incremental nature of most commercial innovation makes it difficult to ever pronounce a research effort a complete failure. DARPA itself spent a great deal of funds in the late 1960s and early 1970s on a project to develop parallel supercomputers.[19] Although the resulting Illiac V computer eventually worked and some of the techniques developed were subsequently used elsewhere, the project itself was a failure. Yet, during this time, DARPA was making substantial contributions to the general development of computers by supporting advanced research at leading universities. In addition, failure in one R&D effort may generate insights that spur technology developments in subsequent R&D.

This productive value of failure will make oversight of R&D consortia for commercial innovation exceptionally difficult. Consensus on policy to support commercial innovation would be quite different than that to support technological innovation for defense. Efforts to promote commercial innovation are more likely to come under attack for supporting failed research and for "second guessing the market." Yet, failure is the dominant mode of development toward new technology. Project managers, especially in the early years, find it hard to maintain the "right" level of failure--that is, the federal government's need to push the technological frontier balanced against the industry's need to perform research that is commercially relevant. The right level of failure is also hard for policymakers to determine.

One way of ensuring the right level of failure is to diversify project investments. By supporting many smaller developments in technology, the federal government could ensure that some of these technologies have commercial potential. By having a broad portfolio of smaller projects rather than a few large ones, one or another project could fail without jeopardizing additional funding. In contrast, however, the first computer network, ARPANET, was successful because DARPA committed more funds and time than originally projected,

19. Defense Advanced Research Projects Agency, "The Advanced Research Projects Agency, 1958-1975" (produced under contract by Richard J. Barber Associates, Washington, D.C., December 1975), pp. vii-33 and vii-34. Referred to hereafter as the *Barber Report*.

retaining a major role through 1975 instead of ending its funding in the 1970-1971 period as intended.[20]

Any new efforts to promote commercial innovation should not be held to a higher standard than DARPA currently is. Over its 30-year history, DARPA has made some major contributions to commercial innovation, such as its early funding of computer R&D. Advances now are more often in general technology. Over the last decade, DARPA's work has evolved from producing specific systems for further development by the armed services to strengthening general civilian technology.[21] Although important, this R&D does not put DARPA in the headlines. Because of DARPA's history of previous successes, these activities are assumed to pay off handsomely one day. A new agency would not have a backlog of successes from which to draw political support. Hence, because years may pass before a technological breakthrough of "headline quality" occurs, a political consensus in favor of a civilian technology agency will be difficult to sustain.

The incremental and cumulative nature of technical change is likely to exacerbate this problem. Even in an industry as technologically dynamic as the semiconductor industry, most products and processes are improvements of older products and processes. For example, today's 32-bit microprocessors were preceded by 16-bit microprocessors, which were in turn preceded by 8- and 4-bit microprocessors.

Technical progress is like a ladder where skipping the rungs is difficult and risky. Consequently, many if not most changes are likely to seem unexciting and trivial to outsiders and policymakers. Taken together, however, these small changes are often more important than the single "breakthrough" that makes the headlines. SEMATECH's work on the current generation of semiconductor manufacturing equipment is founded on the view that change is cumulative and incre-

20. *Barber Report*, pp. vii-32 through vii-34 and ix-57 though ix-59. See also David Bushnell and Victoria Elder, "Computers in the Public Interest: The Promise and Reality of ARPANET," Presentation to the Computer Professionals for Social Responsibility Conference (Fairfax, Va.: George Mason University, Center for the Productive Use of Technology, July 12, 1987).

21. Burton Edelson and Robert Stern, "The Operations of DARPA and its Utility as a Model for a Civilian ARPA" (Washington, D.C.: Johns Hopkins Foreign Policy Institute, November 1989), pp. 20-25.

mental. Therefore, producing the current generation of equipment is the foundation for the next generation.

Organizational Alternatives

DARPA is a main source of federal funds for all the projects described in the previous chapters: SEMATECH, high-resolution systems, and x-ray lithography. While DARPA is by no means the only federal source of support for semiconductor or other technology R&D--for example, the armed services each have technically oriented laboratories, and other agencies also support R&D--many observers have questioned the appropriateness and advisability of having a defense agency lead many of the federal government's efforts to promote civilian commercial innovation.[22] If the federal government wants to encourage the creation of federally funded R&D consortia, several options exist:

- DARPA can continue with its present assignment;
- DARPA can expand its mission to include civilian technology;
- ATP within NIST can serve this need; and/or
- A new agency can emerge.

DARPA and R&D Consortia. DARPA has a long history of assembling and supporting teams to perform mission-oriented research. DARPA has not had a substantial history of funding projects where the initiative was outside of federal hands. SEMATECH is the exception. If R&D consortia become the preferred way to promote commercial innovation, DARPA may have to change its habits.

The Congress recently expanded DARPA's flexibility in dealing with industry. DARPA can now enter collaborative research agree-

22. For a tabulation and analysis of federal semiconductor R&D spending, see the Congressional Budget Office, *Benefits and Risks of Federal Funding for Sematech* (September 1987), pp. 59-72.

ments and joint ventures with small R&D firms. The "New Agreements Authority" allows DARPA to allocate $25 million a year over two years to a revolving fund from which joint ventures with industry could be financed. The only requirement is that DARPA issue a prospectus on each project to the Congress within 30 days. These joint agreements would be free of the usual requirements for federal auditing and intellectual property. Other limitations are that DARPA cannot provide more than 50 percent of the funds for the joint venture and, if the venture is profitable, the private partner will return DARPA's capital. In essence, this program allows DARPA to provide risk-less, interest-free loans to private interests for developing technology. DARPA recently made its first investment using this authority, investing $4 million in Gazelle Microcircuits, Inc., an integrated circuit producer specializing in high-speed gallium arsenide devices.

An Expanded DARPA and R&D Consortia. Advocates of expanding DARPA's mission to include explicitly civilian technology development argue that, in many instances, national security is just a fig leaf for DARPA's real purpose in many areas of technology--that is, improving competitiveness.[23] These advocates state that DARPA is already considering civilian uses of the technology it is developing and, therefore, expanding DARPA's mission will only acknowledge current practice. Taking DARPA out of DoD could also accomplish this goal.

The trade-off here is the extent to which the federal government wants to weigh the development of civilian technology against the development of military technology. Officially expanding DARPA's mandate would come at some cost to its military mission. Removing it from DoD and expanding its mission would further tilt the priorities in the direction of developing civilian technology. Despite the tension between the military and civilian missions, an expanded DARPA might be in a better position to aid in forming R&D consortia than it is currently. Removing the military requirement should increase the technology projects from which it could draw.

23. This analysis is largely taken from Burton Edelson and Robert Stern, "The Operations of DARPA and its Utility as a Model for a Civilian ARPA" (Washington, D.C.: Johns Hopkins Foreign Policy Institute, November 1989), pp. 30-33.

In actual practice, however, DARPA and the federal government have been very casual in defining the areas in which DARPA could provide support. For instance, although SEMATECH may have national security implications, the competitiveness of the U.S. semiconductor industry was a more central concern throughout the debate. Any increased effectiveness in the civilian arena would probably come at a cost of reduced effectiveness in DARPA's core function--that is, military technology--especially if DARPA were removed from DoD.

At one level, this option might seem the best of all possible worlds: a continuation of DARPA's history and organizational expertise but released from any military justification for pursuing technology. Such a change would parallel DARPA's move away from product development and into technology development. Such a change, however, would most likely subordinate the efforts on civilian technology development to the military efforts, as long as DARPA was located within DoD. Another question is whether efforts directed at cost reduction, as opposed to performance enhancement, would ever receive their due within DoD.

Advanced Technology Program and R&D Consortia. The 1988 Omnibus Trade Bill reorganized the National Bureau of Standards and renamed it the National Institute of Standards and Technology. This bill also authorized the ATP as a new section within NIST. The intent of the ATP was to accelerate commercialization of new technology by encouraging U.S.-owned firms to form joint R&D ventures, such as consortia. The ATP would do this by providing support services, technical assistance, and, under limited conditions, minority funding for up to five years. The ATP is authorized to provide technology development assistance directly to individual businesses, especially small businesses. While the Congress has authorized $100 million for the ATP, the Congress only appropriated $10 million for fiscal 1990, giving the agency a chance to organize itself and use its funds more efficiently. The Administration has requested that the same level of funding be maintained for fiscal year 1991.

Also included in the bill was the requirement that NIST set up Regional Centers for the Transfer of Manufacturing Technology. These centers would help small and medium-sized businesses make better use of the latest innovations in manufacturing technology. In a separate bill passed in 1988, the Department of Commerce was reorganized making NIST part of its larger Technology Administration.

NIST is in the process of formulating final regulations; therefore, final analysis of their procedures and selections is not possible. Analysis of its preliminary regulations is.[24] NIST will be concentrating on generic technology as defined previously, meaning a broad range of applications for many industries. NIST has selected no specific area of technology; rather, it will allow the quality of proposals submitted to determine those areas.

This policy choice may easily leave the ATP without a central focus and, hence, unable to make an impact. Deciding that a small program, such as NIST, can productively concentrate on only a few areas is not inconsistent with the policy objective that R&D programs be "industry led" and that the central focus be determined outside the government. If retained, this policy may prevent NIST's work from being cumulative in one area of technology.

The general arguments against using NIST to promote R&D consortia for commercial innovation are similar to those against using DARPA: it is a distraction from its main mission. As the former National Bureau of Standards, NIST has a long and distinguished history of developing standards and their related infrastructure. Indeed, NIST became the recipient of the ATP largely because of the high regard in which its work on standards is held. Developing standards is a central economic exercise; consequently, NIST has developed many ties to industry in the course of its work. These ties could be easily compromised or damaged as NIST's efforts on commercial innovation become a larger part of its total R&D. Firms that did not participate in a NIST-sponsored consortium might view NIST's standards work in their area with suspicion.

Like DARPA, however, NIST has a cadre of trained technical people who have a long history of working collaboratively with industry. While there would be some cost, perhaps even substantial, in

24. *Federal Register*, vol. 55, no. 65, April 4, 1990, pp. 12504-12509.

transferring their duties, the trained personnel is at least available and might make a new program easier to start up. Using NIST resources as an initial endowment might also be useful if the ATP were spun off from NIST's core activities as the ATP matures.

The Advanced Civilian Technology Agency. One proposal receiving substantial attention is pending in Senate bill S. 1978, the Trade and Technology Promotion Act of 1989. This bill addresses the reorganization of the Department of Commerce to promote U.S. exports, the expansion of the National Security Council, and the elevation of the President's Science Advisor. In addition, the bill proposes the creation of the Advanced Civilian Technology Agency (ACTA) within the Department of Commerce. In this proposal, both NIST and ACTA would be within the Department's Technology Administration.

ACTA would provide grants and sign contracts or cooperative agreements to support development projects. These projects might develop new commercial technology of potentially significant value to the U.S. economy, generic R&D to speed the commercialization of new technology, or R&D for high-risk applications of such technology.[25] ACTA could contract with institutions that have some history of R&D expertise or consortia composed of such institutions. The general terms of such agreements are: a U.S. or Canadian company or entity must lead the recipient organization; the federal funding cannot exceed 50 percent of the total; and any proposals considered by ACTA must meet certain administrative and auditing requirements, including plans for disposing of intellectual property rights.

Companies not owned or controlled by U.S. or Canadian citizens can generally participate but must meet certain conditions. They must contribute materially. They must also commit to procuring parts and materials from U.S. suppliers. Finally, they must be from a country with a domestic government that gives symmetrical treatment to U.S.-owned firms in terms of access to their domestic markets, protection of intellectual property rights, and membership in R&D consortia.

25. See S. 1978, Part B, Sec. 212.

The intent of the legislation is for the ACTA to set up a revolving fund. Projects funded by ACTA that prove successful will pay back all or part of their costs into the revolving fund, which will use those funds for future projects. ACTA would be allowed to determine its share of a project's total costs (up to the 50 percent maximum specified above). The legislation calls for ACTA funding of $100 million in fiscal year 1991, $160 million for fiscal year 1992, and $240 million in fiscal year 1993.

ACTA may take several years to fulfill its mission. DARPA has a community of alumni and colleagues who know its staff, its policies, and its procedures. When DARPA moves into a new area of technology, its reputation of technological competence precedes it. Without a backlog of respect and goodwill on which to draw, a new agency will need time to reproduce such reputation.

This delay in a new agency maturing might not be costly. Over the years, DARPA contractors have produced many major advances but not so many that some discontinuity would be critical to continued U.S. technological progress. While timing may be crucial to some of DARPA's individual projects (such as panel displays), other research (such as advanced neural networks) are much longer-term programs. In addition, the R&D consortia, not the agency, will conduct the research.

CONCLUSION

R&D consortia are often touted as one solution to improving the competitiveness of U.S. industry. Consortia represent only one of many forms of collaborative R&D, ranging from cross licensing to joint development ventures. R&D consortia can be useful in a variety of circumstances, but they complement more than substitute for the effort of individual companies and government research programs.

The main concern of economists regarding joint R&D among large numbers of firms within an industry is the possibility for collusion to restrain competition. So far, this is not the case with either publicly or privately funded collaborative efforts. While consortia by their nature agree on a research agenda, little evidence exists of more centralization than this. Such consortia have the potential, however, to influence public policy in ways that may protect the domestic industry and restrain competition through government intervention.

The federal experience with consortia so far is inconclusive. SEMATECH has only recently begun the R&D into semiconductor manufacturing for which it was founded, so its outcome is unknown. While DARPA has often assembled teams of companies to perform its R&D, how easily this experience can be translated into policies regarding larger R&D consortia is not clear.

The usefulness of R&D consortia depends largely on the research agenda and the specific situation of the relevant industry. In the areas discussed in this study, high-resolution and advanced imaging systems and x-ray lithography present very different circumstances. In x-ray lithography, a high level of institutional and informal collaboration is already occurring, plus a high division of labor among the relevant organizations. In this area, what a federally sponsored R&D consortium would add is not clear, other than committing the federal government to stable funding. In advanced imaging, the terrain is so diverse that an agreement on a single R&D agenda is unlikely; different segments of technology users, however, might be able to agree on different agenda. Already a collaborative research effort for flat panels is reportedly forming.

No agreement exists on any one change in federal policy that would encourage R&D consortia. The evidence on antitrust legislation is weak and more asserted than proven. SEMATECH's role and funding could be increased; but, since SEMATECH is unique, this assistance would not advance the cause of consortia in general. Finally, despite growing agreement on the usefulness of an agency to oversee developing civilian technology, widespread disagreement remains over the specifics of such an agency, its mandate, and its structure. Moreover, encouraging private sector R&D consortia would be only one task of such an agency, and, because the federal government may often be a silent partner in such consortia, it might be one where the agency's likelihood of success may be slim.

GLOSSARY

The following definitions of terms are largely based on Daniel Okimoto, Takuo Sugano, and Franklin Weinstein, eds., *Competitive Edge: The Semiconductor Industry in the U.S. and Japan* (Stanford, Calif.: Stanford University Press, 1984); the Department of Commerce, Industry, and Trade Administration, *A Report on the U.S. Semiconductor Industry* (September 1979); and David J. Elliott, *Integrated Circuit Fabrication Technology*, 2nd ed. (New York: McGraw-Hill, 1989).

Advanced Imaging Technology. The use of computers and other electronic equipment to create, reproduce, manipulate, store, and display documents, drawings, and other images.

Application-Specific Integrated Circuit (ASIC). An integrated circuit designed for a single narrow use, such as substituting one large integrated circuit for many small ones. These circuits are often custom or semi-custom.

Bit. A binary digit of zero (0) or one (1) in the language of computers.

Byte. Eight (8) bits.

Cathode Ray Tube. A type of vacuum tube commonly used for television and other electronic displays. At one end of this tube, a cathode emits electrons that are accelerated and focused through high voltage until they hit a fluorescent screen at the opposite end of the tube.

Custom Circuit. An integrated circuit designed and manufactured for a particular customer. Contrasts with semi-custom, which has only the last few manufacturing steps tailored to customer specifications. Also contrasts with integrated circuits of standard design, which are produced in volume for many users.

Die. The small piece of the wafer on which an individual semiconductor device has been formed.

Diffusion. A semiconductor manufacturing process in which desired impurities are introduced into the silicon by baking the silicon wafers at high temperatures and pressures in chemically altered atmospheres. A less precise alternative to ion implantation.

Diode. A semiconductor device that allows electricity to flow only in one direction.

Dynamic Random Access Memory (DRAM). A type of integrated circuit that requires some external support circuitry to maintain storage of information. (See RAM.) Contrasts with static random access memory. Categorized by packaging, speed, and memory capacity.

Epitaxy. A semiconductor manufacturing process in which a layer of semiconductor material (usually silicon) is grown on the surface of a silicon wafer. This new layer is grown because it possesses, or will be altered to possess, a unique crystalline structure or other desirable feature not found on the wafer itself.

Erasable Programmable Read Only Memory (EPROM). A memory device that can be read but not written to. Unlike other programmable memories, it can be erased (by exposing it to ultraviolet light) and reprogrammed.

Etching. A semiconductor manufacturing process in which acid is used to remove previously defined portions of the silicon oxide layer covering the wafer to expose the silicon underneath. Removing the oxide layer permits introducing desired impurities into the exposed silicon through diffusion or ion implantation or the deposition of aluminum paths for electrical interconnection of circuit elements.

Flat-Panel Display. A type of video display that is relatively thin (usually less than 3 inches), unlike the cathode ray tube found in most home television receivers and computer desktop monitors. Most commonly used in portable personal computers and portable television sets.

Gallium Arsenide (GaAs). A compound semiconductor material that allows transistors and integrated circuits to operate much more rapidly than similar devices made of silicon. Much more difficult and hence more expensive to manufacture than silicon.

Gate Array. A kind of semi-custom integrated circuit composed of a matrix of logic gates (switches) substituting for collections of gates on separate integrated circuits or other logic circuits.

High-Resolution System. An electronic video system capable of displaying roughly 1,000 lines along its vertical axis.

Integrated Circuit (IC). A complete electronic circuit composed of interconnected diodes and transistors and fabricated on a single semiconductor substrate, usually silicon. Also called a computer chip.

Ion Implantation. A semiconductor manufacturing process in which the silicon is bombarded with high-voltage ions in order to implant them in specific locations and provide the appropriate electronic characteristics. Ion implantation is more precise alternative to diffusion.

Liquid Crystal Display. A type of flat-panel video display.

Lithography. A semiconductor manufacturing process in which the desired circuit pattern is projected onto a resist coating that covers the silicon wafer. When the resist is developed, somewhat like an ordinary photograph, portions of the resist can be selectively removed by use of a solvent, thus exposing parts of the wafer for etching and diffusion.

Logic Circuit. A type of integrated circuit that performs certain logical or mathematical functions and often provides connections between other major parts of electronic equipment.

Magnetic Storage. Magnetic materials used as electronic memory devices, including magnetic tapes (commonly used in audio and video cassette recorders and computers) and magnetic disks (commonly used in computers).

Mask. The master pattern (usually made of quartz or glass) containing the circuit image that is used in lithography like a photographic negative to define the areas for etching in the resist.

Megabit. One million bits of zeros (0s) or ones (1s) in the binary language of computers.

Memory Device. An electronic component that stores binary data. Categorized according to accessibility (random or serially), size, speed, and whether it is a device that can be written to or read only. Also categorized by storage media--that is tape, disk, or semiconductor.

Metallization. A semiconductor manufacturing process in which a layer of metal, such as aluminum, is placed on the wafer to connect the transistors and diodes within an integrated circuit.

Metal-Oxide Semiconductor. One of the two families of silicon transistors and integrated circuits; the other is bipolar. Simpler to fabricate and hence is often used in manufacturing large, dense integrated circuits. It is also slower than bipolar and sensitive to radiation, which limits its military applications.

Metrology. The science of measurement.

Micron. A micrometer or one-millionth of a meter.

Microprocessor. An electronic integrated circuit that performs the function of a central processing unit in a computer.

Optical Lithography. Lithography that uses ordinary or ultraviolet light to expose the circuit pattern. Currently, the most commonly used technology. Contrasts with x-ray lithography.

Optical Scanner. A piece of electronic equipment that reads (or scans) paper documents and converts the texts and images into a format readable by a computer.

Optoelectronic Components. An electronic device that converts light signals into electronic or electronic signals into light. Optoelectronic components include laser diodes and photodiodes.

Photovoltaic Cell. A specialized diode that turns light into electricity. Used in space and other remote applications, and becoming common in some consumer uses.

Planarization. A semiconductor manufacturing process in which a flat layer of glassy material is deposited over the lower layers of an integrated circuit. This step simultaneously creates a flat surface for further processing and isolates the lower layers.

Plasma. An ionized gaseous system composed of an electrically equivalent number of positive ions and free electrons.

Plasma Display. A type of flat-panel video display.

Random Access Memory (RAM). A type of integrated circuit whose individual memory cells can be read from or written to at random (that is, not serially).

Read Only Memory (ROM). A memory device whose contents can be read from but not written to. Refers to both optical disks and integrated circuits.

Resist. A light-sensitive emulsion used to coat silicon wafers during lithography. The resist makes the wafer like photographic paper. The integrated circuit pattern is projected onto the coated wafer, and then the wafer is developed. See lithography.

Semiconductor. A material that is neither a good insulator nor a good conductor. A material (usually silicon, germanium, or gallium arsenide) crafted to take advantage of the unusual properties of charge carriers or field effects derived from knowledge of solid state physics. The term has come to refer to all devices made of semiconducting material, including integrated circuits, transistors, and diodes.

Semi-Custom Circuit. An integrated circuit that has the initial phases of its fabrication standardized but allows the later stages to be tailored to suit the individual customer.

Silicon. A semiconducting material commonly used in semiconductor devices because it is so easy to work with.

Static Random Access Memory (SRAM). A type of integrated circuit that has self-contained memory circuitry. (See RAM). Contrasts with dynamic random access memory. Categorized by speed and memory capacity.

Synchrotron. A type of oval or circular particle accelerator that may be a potential source of x-rays for use in x-ray lithography.

Transistor. A three-terminal semiconductor device used mainly to amplify or switch. Its invention at Bell Laboratories in 1948 started the semiconductor revolution.

Video Graphics Array (VGA). A video display standard for IBM-compatible personal computers.

Wafer. When most semiconducting material is purified, it comes out in sausage-like lengths between one and eight inches in diameter that are a single crystal, which are then sliced into wafers, roughly one millimeter thick. The wafer is then used as the substrate for forming semiconductor devices.

Wafer Stepper. A type of lithography equipment that exposes the wafer a few circuits at a time, instead of the whole wafer at once.

X-ray Lithography. An emerging type of lithography that uses x-rays instead of light to expose the circuit patterns on the wafer.