ARPA: A Dual-Use Agency 5

The Advanced Research Projects Agency (ARPA) is the primary agency within the Department of Defense (DoD) for conducting long-range, high-risk research and development (R&D) for advanced technologies that contribute to national security needs.[1] Though receiving only a small percentage of DoD's R&D budget, ARPA has funded many technologies throughout its 35-year history that have both satisfied defense requirements and enjoyed great commercial success. Advanced computer architectures, packet-switched networks, and lightweight composite materials are all examples of technologies that have found widespread use in the private sector after initial development by ARPA.

Since the late 1980s, ARPA has assumed increasing responsibility for dual-use technology. Dual use is now the centerpiece of ARPA's development efforts, accounting for $1.8 billion of the agency's $2.3 billion funding in fiscal year (FY) 1993. Military interest in manufacturing and electronics has driven some of the increase in ARPA's dual-use R&D, but Congress has also played an important role. Since 1987, with the founding of SEMATECH, the government/industry consortium for advancing semiconductor manufacturing, legislative initiatives have assigned several dual-use programs explicitly to ARPA. More recently, Congress gave ARPA a premier role in Federal defense conversion programs enacted in 1992.[2] This legislation raised

[1] The agency's original name was ARPA. Renamed DARPA (.Defense Advanced Research Project Agency) in 1972, its name was changed back to ARPA in February 1993 at the direction of President Bill Clinton and in accordance with the expressed intention of Congress.

[2] The Department of Defense Authorization and Appropriations Acts for Fiscal Year 1993.

331-050 - 93 - 5 : QL 3

ARPA's funding for development of dual-use technologies by about $500 million over the previous year and gave the agency new responsibilities in the diffusion of manufacturing technologies to small and medium-sized fins. Congress has also granted ARPA legal authorities by which it can enter into cooperative partnerships with commercial industry to develop dual-use technologies.

Nevertheless, there are limits to ARPA's role as a supporter of civilian technologies. As a defense agency, ARPA must carefully balance its dual-use activities against other missions relevant to DoD. Several times in the past, ARPA has been called upon to link its objectives more closely to short-term military needs than to long-range, high-risk research with commercial application. Moreover, ARPA cannot demonstrably perform all the activities required to support commercial technology development. Not only are the agency's resources limited, but ARPA's particular expertise is in identifying and supporting path-breaking, new technologies; it has not traditionally focused on issues such as technology diffusion or infrastructure development, which are equally important to commercial competitiveness. Thus, while ARPA will undoubtedly make substantial contributions to commercial industry in the future, the development and diffusion of civilian technologies is not likely to become a central mission of the agency. ARPA is just one component of a larger Federal effort to stimulate U.S. industrial competitiveness.

ARPA AND DUAL-USE TECHNOLOGY

ARPA was founded in 1958 as a defense agency independent of the three services (Army, Navy, Air Force) for supporting long-range, high-risk R&D of interest to the military as a whole. Established largely in response to the Soviet launching of Sputnik, ARPA was initially directed to oversee U.S. space and ballistic missile defense technology programs[3], a mission that would have entailed both research and significant systems development work. However, with the creation of the National Aeronautics and Space Administration (NASA) shortly thereafter, ARPA's responsibility for civilian space applications was rescinded and control of military space programs reverted to the individual services. With its primary development mission gone, ARPA became, and remains, mostly a research agency; though it funds some development of prototypes for new military systems, ARPA directs the bulk of its funding to basic and applied research.

ARPA is a small agency by DoD standards; it received just $1.6 billion of the military's $38 billion in research, development, test, and evaluation (RDT&E) funding in 1992. Yet its charter is broad, allowing it to contribute to many fields with potential military application.[4] As a small player in a relatively undefined field, ARPA has succeeded by carving out its own territory so as not to compete directly with the services or with other technology development agencies, such as NASA or the Department of Energy, that have significantly more resources. From its early days, ARPA has targeted its resources toward specific technologies in which it could gain a large return and has aimed to be an agent for ''order of magnitude' improvements in military weapons and support systems. ARPA has succeeded in nurturing new, emerging technologies such as

[3] See Richard J. Barber Associates, *The Advanced Research Projects Agency, 1958-1974,* report prepared for ARPA under contract MDA-74-C-(X)96, December 1975, chapter III.

[4] ARPA's charter directs the agency to 'Pursue imaginative and innovative research and development projects offering significant military utility . . . [m]anage and direct the conduct of basic research and applied research and development that exploits scientific breakthroughs and demonstrates the feasibility of revolutionary approaches for improved cost and performance of advanced technology for future applications . . . [and s]timulate a greater emphasis onprototyping in defense systems. . . .“ DoD Directive 5105.41, 'Defense Advanced Research Projects Agency," September 30, 1986. See also statement by Dr. Victor H. Reis, Director, DARPA, before the Subcommittee on Research and Development Armed Services Committee, House of Representatives, Apr. 23, 1991.

computing and materials that require much enabling work before their full military (or commercial) impacts become clear and that can contribute to the mission of DoD as a whole. This focus has led to ARPA's support of a number of dual-use technologies.

Early Investments in Dual-Use Technology

As early as 1962, ARPA began funding university research in materials science and computing. ARPA effectively established the field of materials science as an independent discipline by founding a series of 12 Interdisciplinary Laboratories at universities to conduct basic research on new materials.[5] ARPA also established centers of excellence in industry and universities for basic research in computer science that could contribute to improving command, control, communications, and intelligence (C^3I) systems used by the military.[6] These efforts gave rise to significant achievements in timesharing computers (Project MAC and MULTICS), computer networking (ARPANET), artificial intelligence, and parallel computers (ILLIAC IV).[7]

Unlike other ARPA programs of the time, which were driven by specific national defense requirements, the materials and computer science programs were motivated by the need to further basic research. The original mission statement for the materials science labs stated that they should ''conduct research in the science of materials with the objective of furthering the understanding of the factors which influence the properties of the materials and the fundamental relationship which exists between composition and structure and the properties and behavior of materials."[8] Military applications, it was assumed, would arise as byproducts of the effort.

Similarly, in supporting development of computer technology in the 1960s, ARPA acted on the grounds that DoD was a large user of computing technologies and that accelerating the development of new technologies within the commercial U.S. computer industry would have important second-order effects on defense, through military procurement of commercial products.[9] Programs did not focus on particular military applications, but on research with long-term importance to the field, regardless of the potential for immediate military application.[10] As with materials science, many of the innovations that ARPA pursued in computers were fundamental 'enough that they applied to both commercial and military systems.

Political pressures caused a shift in ARPA's focus toward the end of the 1960s. With the escalation of hostilities in Vietnam, the military began demanding greater coherence between its needs and ARPA's research programs. At the same time, unrest at U.S. universities inflamed debates over the propriety of ARPA's sponsorship of university research.[11] In response, Congress passed the Mansfield amendment as part of the Defense Authorization Bill of 1970, requiring that DoD's RDT&E funds be used only to support

5 Richard H. Van Atta et al., *DARPA Technical Accomplishments, Volume III: An Overall Perspective and Assessment the Technical Accomplishments of the Defense Advanced Research Projects Agency: 1958-1990* (Alexandria, VA: Institute for Defense Analysis, July 1991), p. V-17.

6 Funding was concentrated in a limited number of laboratories at universities such as MIT, Stanford, Carnegie-Mellon, and the University of California at Berkeley, and in commercial corporations such as SRI International and Systems Development Corp.

7 Kenneth Flamm, *Government's Role in Computers and Superconductors,* report prepared for OTA under contract H3-6470, March 1988, p. 13.

8 Richard J. Barber Associates, op. cit., footnote 3, pp. V-47-V-48.

9 Ibid, pp. VII-32-VII-33.

10 Flamm, op. cit., footnote 7, p. 14.

11 Some parties believed that ARPA had outlived its usefulness and considered abolishing the agency. Richard H. Van Atta, op. cit., footnote 5, p. II-lo.

projects with a "direct and apparent" relationship to specific military functions or operations.[12] Though softened somewhat in 1971 and later removed from legislation, the amendment had a more lasting influence. It effectively restricted ARPA's funding of basic research, especially in universities, and tended to focus the agency on projects of strict military relevance. The agency's defense mission was further reinforced when DoD officially changed ARPA's name to the Defense Advanced Research Projects Agency (DARPA) in 1972.[13]

Although ARPA continued to fund R&D in some dual-use areas such as computing and communications throughout the 1970s and 1980s, its primary emphasis during much of this time was on defense programs more narrowly defined. In 1976, ARPA initiated a large-scale demonstration program for military systems such as follow-on forces attack, armor/anti-armor systems, space-based surveillance, high-energy lasers, and stealth.[14] These programs accounted for most of the increase in ARPA's budget through the early 1980s. Research programs in areas such as computing and materials were challenged to demonstrate defense-relevant applications.[15] By the early 1980s, the focus of the demonstration program had shifted from military systems to dual-use technologies such as aviation and computing, but programs were still required to demonstrate defense relevance. For example, the Strategic Computing Program, announced in 1983 as a 10-year program to develop computers capable of demonstrating machine intelligence, targeted three specific military applications of interest: an autonomous land vehicle for the Army, a pilot's associate for the Air Force, and an aircraft carrier battle management system for the Navy. Unlike earlier computing research sponsored by ARPA, which was conducted mostly at universities, funding for Strategic Computing was directed toward more traditional defense contractors.[16] The program did contribute to the advancement of massively parallel computing, but its effects were more narrowly focused than ARPA's earlier computing research.

ARPA Today

In many respects, ARPA today is a dual-use technology agency. Despite its small size, ARPA makes a substantial portion of DoD's contribution to basic and applied research, the two stages of the R&D cycle that DoD refers to as the 'technology base."[17] It is in the technology base-rather than in subsequent development of weapons systems such as tanks, missiles, and fighter aircraft-that

12 Public Law 91-121, Title III, Section 203, 83 Statute 204, Nov. 19, 1969.

13 Department of Defense Directive No. 5105.41, "Defense Advanced Research Projects Agency (DARPA),'' Mar. 23, 1972,

14 These programs were administered under the Experimental Evaluation of Major Innovative Technologies Program (EEMIT), which consumed a large portion of ARPA's budget. The EEMIT program continues to this day, but at a much smaller scale.

15 Van At@ op. cit., footnote 5, p. II-2.

16 Of the 30 prime contractors for Strategic Computing involved in software or AI research in 1987, fewer than 9 were new to defense contracting. Nance Goldstein, "The Defense Advanced Research Projects Agency's Role in Artificial Intelligence," *Defense Analysis*, vol. 8, no. 1, p. 71. See also Kenneth Flamm, op. cit., footnote 7, p. 28.

17 DOD divides its budget into 10 accounting categories. Category 6 contains all RDT&E activities. RDT&E is further subdivided into six more specific areas: 6.1, basic research; 6.2, exploratory development or applied research; 6.3, advanced development; 6.4, engineering development 6.5, management and support; and 6.6, operational systems development. Budget item 6.3 is further subdivided into 6,3a, advanced technology development which includes activities to demonstrate the feasibility of a given type of military system, and 6.3b, in which technology is applied to a specific military program. Categories 6.1 and 6.2 are considered the technology base; categories 6.1 through 6.3a comprise "science and technology" (S&T).

Table 5-l—Defense Department and ARPA Budgets for RDT&E, FY 1992

Budget activity	Defense Department (millions)	ARPA (millions)	ARPA (percent of DoD)
Technology base	$3,920	$ 862	22%
Basic research (6.1)	1,020	116	11
Exploratory development (6.2)	2,890	746	26
Development	$34,420	$ 736	3
Advanced technology development (6.3a)	6,470	701 [a]	11
Advanced development (6.3b)	4,170	0	0
Engineering development (6.4)	10,300	0	0
Management support (6.5)	2,890	35	1
Operational systems development (6.6)	10,590	0	0
Total obligational authority	*$38,340*	*$1,597*	*4%*

a Includes ARPA programs in manufacturing technology.
b Totals may not add due to rounding.

SOURCES: Richard M. Nunno, *Defense l?&D Restructuring,* IB-92090 (Washington, DC: Congressional Research Service, Aug. 20, 1992), p. 3; Advanced Research Projects Agency, Office of the Comptroller, "Project Level Summary Report," Mar. 25, 1993.

dual-use technologies are most likely to be found.[18] While a basic research program might, for example, investigate quantum effects in semiconductor devices, and an applied research program might attempt to create a semiconductor device that exploits quantum effects--both of which are applicable to commercial industry as well-the subsequent development program might be aimed at designing and fabricating a specific chip for a military weapon system that has no commercial corollary.

In FY 1992, DoD spent $38 billion for RDT&E. Only 10 percent went to basic research and exploratory development; 90 percent went to the development of weapons systems. ARPA, on the other hand, invested over half its $1.6 billion budget on basic and applied research; the remainder funded advanced development, some of which may generate dual-use technology (table 5-l). Thus, while ARPA managed only 4 percent of the DoD budget for RDT&E, it made 20 percent of DoD's investment in the technology base.

Virtually all of ARPA's 10 program offices contribute to the technology base, but half are explicitly involved in dual-use technology development. The five "technology offices' '—the Microelectronics, Electronic Systems, Computers Systems, Software and Intelligent Systems, and Defense Sciences offices-develop component technologies for use in military systems (table 5-2). These technologies include optoelectronic components, advanced lithography systems, multichip modules, and parallel computing architectures, many of which are dual-use. The other five ''mission offices' within ARPA—Maritime Systems Technology, Land Systems, Advanced Systems, Nuclear Monitoring, and Special Projects (typically classified)--focus on the development of technologies for military systems such as the advanced tactical fighter, quieter submarines, and smart weapons systems. These systems generally have less potential for commercial application, although some spinoffs do occur.

The technology offices controlled a combined budget of almost $1.8 billion in FY 1993, some

18 This is not always the case. Research and development does not necessarily follow a linear progression from basic research through advanced development to operational systems development. There is considerable feedback or circularity between the generic technology base and subsequent development of specific products or systems. Also, there are instances of civilian use of advanced military systems; for example, night vision goggles developed for the military are beginning to be used by civilian security teams.

Table 5-2—ARPA Program Offices and Major Activities

Program office	Primary activities
Technology offices	
Microelectronics	Microelectronics manufacturing (e.g., modular fabrication facilities, lithography, SEMATECH); gallium arsenide integrated circuits; optoelectronic components; nanoelectronics; infra-red focal plane arrays.
Computing Systems	Parallel processing; computer networking.
Electronic Systems	Microwave and millimeter wave, monolithic integrated circuits (MIMIC); electronic packaging (multi-chip modules); high-definition displays.
Software and Intelligent Systems	Software engineering; reusable software; artificial intelligence (Al).
Defense Sciences	High-temperature superconductors; high-temperature ceramics; composite materials; materials processing.
Mission offices	
Advanced Systems	Sensors (radar, infrared, electro-optic); miniature turbine engines; X-31 advanced technology fighter; smart weapons; space technology; war gaming and simulation.
Land Systems	Armor/anti-armor systems; smart mines; advanced diesel engines; hyper-velocity projectile launcher,
Nuclear Monitoring Research	Surveillance and monitoring systems for nuclear events; treaty verification.
Maritime Systems Technology[a]	Submarine technology; anti-submarine warfare technologies; unmanned undersea vehicles; submarine propulsion systems.
Special Projects	Classified.

[a] The Maritime Systems Technology Office was named the Undersea Warfare Office before 1993.

SOURCE: Office of Technology Assessment, 1993. Based on information contained in *Amended FY 1992/1993 Biennial RDT&E Descriptive Summaries* (Arlington, VA: Defense Advanced Research Projects Agency, January 1992).

three-quarters of ARPA's total R&D budget of $2.2 billion, and an increase of $725 million over their 1992 funding (table 5-3). Half of the technology offices' funding was invested in the technology base in FY 1993, compared with just one-fifth for the mission offices. Development work funded by the technology offices (the remainder of their budgets) also went toward dual-use technologiess-mostly manufacturing processes for electronics and semiconductors plus defense conversion programs.

The composition of ARPA's current research program is not solely an outgrowth of the agency's attempt to fulfill its defense mission. Since the late 1980s, Congress has given ARPA increasing responsibilities for dual-use partnerships with industry. The first of these was SEMATECH, the Semiconductor Manufacturing Technology consortium. Congress directed ARPA to fund SEMATECH for 5 years at $100 million per year starting in 1988 (see box 5-A). Since then Congress has given ARPA additional responsibilities for lithography, high-definition displays, multichip modules, and high-performance computing. In 1993 alone, Congress added over $200 million to ARPA's budget for specific dual-use programs (table 5-4). These programs have made ARPA a leading agency for support of dual-use technology and puts it in good position to insert commercial technologies into military applications to the benefit of DoD. They also put ARPA in position to contribute toward dual-use technologies for commercial applications, especially in the fields of microelectronics, computing, communications, and advanced materials.

ARPA has been given a lead role in the High-Performance Computing and Communications Initiative (HPCCI), a multiagency project designed to accelerate the development and utilization of high-performance computers.

Table 5-3—ARPA's FY 1993 Program Budget

Office/Program element	Budget category	Appropriations (millions) 1992	1993
Technology offices		$1,032	$1,756
Defense Research Sciences	6.1	116	110
Computer Systems and Communications	6.2	289	347
Particle Beam Technology	6.2	2	0
integrated Commandant Control Technology	6.2	109	152
Materials/Electronics Technology	6,2	198	255
Small Business innovative Research	6,2	—	16
Defense Reinvestment (Partnerships)	6.3	60	562[b]
Electronics Manufacturing Technology	6.3	206	219
Microelectronics Manufacturing (SEMATECH)[a]	6.3	—	95
Consolidated DoD Software Initiative	6.3	52	—
Mission offices		$528	$466
Tactical Technology	6.2	128	98
Treaty Verification	6.2	19	0
EEMIT[c]	6.3	249	287
Relocatable Targets	6.3	28	0
Advanced Submarine Technology	6.3	71	52
Advanced Simulation (National Guard)	6.3	0	29
DoD Intelligence Support	3.5	33	—
Comptroller/Director's office	6.5	35	27
Total		$1,597	$2,248

a Funding for SEMATECH was included in the Electronics Manufacturing Technology program element before 1993. The FY 1992 appropriation was $100 million,

bThe 1993 figure includes $95 million for Dual-Use Critical Technology Partnerships, $28 million for advanced materials partnerships, andan additional $439 million for other partnerships to support defense conversion activities in industry. Funding in 1992 was for Dual-Use Critical Technology Partnerships only.

c A *large advanced technology demonstration* program for new technological systems.

SOURCE: Advanced Research Projects Agency, "Project Level Summary Report," Mar. 25, 1993.

Planned by the President's Office of Science and Technology Policy and coordinated by the Federal Coordinating Council on Science, Engineering, and Technology, HPCCI was given major impetus by the passage of the High Performance Computing Act of 1991 (Public Law 102-194), which provided multiple-year authorizations to eight Federal agencies, including DoD. Funding for HPCCI totaled $805 million in 1993, with ARPA receiving the largest portion at $275 million. ARPA's efforts in HPCCI will cut across all four portions of the program: High-Performance Computing Systems, Advanced Software Technology and Applications, National Research and Education Network, and Basic Research and Human Resources. In recognition of the fact that ARPA's particular strengths lie in the development of advanced technology, ARPA has the lead role in developing high-performance computer systems, their associated operating system software, and high-speed data network technology; responsibility for evaluating advanced computers, coordinating work in applications software, and for organizing the National Research and Education Network has been given to other agencies, including NASA, the Department of Energy, the National Institute for Standards and Technology, and the National Science Foundation.

Congress also added funds to ARPA's 1993 budget to support defense conversion programs. The technology offices' budget for FY 1993 includes $439 million in new programs mandated by Congress to assist industry in the transition

Box 5-A–ARPA's Cooperation With SEMATECH

The Semiconductor Manufacturing Technology consortium (SEMATECH) was founded by 14 member companies in 1987 to help U.S. manufacturers recapture world leadership in the semiconductor industry, a position that had been eroded by intense Japanese competition throughout the early 1980s. The group, which has its own facilities and staff at its headquarters in Austin, Texas, proposed to meet this goal by developing within 5 **years** a process for manufacturing chips with 0.35-micron feature size on 8-inch wafers. In December 1987, Congress authorized DoD to provide SEMATECH with 5 years of funding at a level equal to industry's contribution, expected to be $100 million per year. DoD assigned ARPA responsibility for working with SEMATECH in April 1988.

SEMATECH originally planned to develop new production processes in-house for manufacturing next-generation semiconductors, but later decided that its primary goal should be to develop a strong base of semiconductor manufacturing equipment suppliers. Without strong suppliers, U.S. semiconductor manufacturers could not expect to keep up with their Asian competitors, who have closer contacts with Japanese equipment makers and thus have earlier access to the most advanced Japanese semiconductor manufacturing equipment. **At** SEMATECH's inception, U.S. semiconductor equipment suppliers were losing market share at the rate of 3.1 percent per year.[1] Semiconductor manufacturers expected to purchase less than 40 percent of their submicron equipment from U.S. suppliers.[2]

SEMATECH established a number of partnerships with U.S. equipment manufacturers to help them develop next-generation production tools. It also helped the semiconductor industry achieve consensus as to its future needs, especially in regard to requirements for new semiconductor manufacturing equipment. As a result, equipment manufacturers have been able to produce equipment to one set of industry specifications rather than to diverse company specifications. In addition, SEMATECH has developed standard methodologies for evaluating candidate manufacturing technologies both analytically and experimentally. Perhaps most important, the Partnership for Total Quality program established by SEMATECH has improved communication links between semiconductor manufacturers and their suppliers. While some suppliers had previously maintained close relationships with preferred customers, SEMATECH replaced and repaired those that had been severed and created a much broader set of ties, in this way, information that is not easily quantified can be exchanged directly between users and suppliers of manufacturing equipment.

While critics claim that SEMATECH has benefited only its member companies, **others credit the consortium with contributing to the recent improvement** in the health of the semiconductor equipment industry as a whole. Since 1990, equipment manufacturers have reversed their declining market share **and currently command** 53 percent of the world market versus 38 percent for Japan? U.S. semiconductor manufacturers now purchase over 70 percent of their equipment domestically. Motorola's new wafer fabrication facility in Austin, Texas, which was originally planned to include 75 percent foreign tools, now has an 80 percent U.S. tool set.[4] Production yields of U.S. semiconductor manufacturers, which were 60 percent versus Japan's 79 percent in 1987, have improved to 84 percent versus 93 percent in Japan.[5]

ARPA managers consider their relationship with SEMATECH highly successful. Many of ARPA's objectives for SEMATECH are now reflected in SEMATECH's new mission statement, which commits the consortium to focus on developing methods for more rapidly converting manufacturing technology to practice and to develop technology for more flexible, highly automated semiconductor production (in coordination with other ARPA programs).

1 Peter Burrows, "Bill Spencer Struggles to Reform SEMATECH," *Electronic Business,* May 18,1992, p. 58.

2 SEMATECH, *1991 Annual Report,* p. 2.

3 *The Washington Post,* Nov. 18, 1992, p. A7, from data provided by VLSI Research, Inc.

4 SEMATECH, op. cit., p. 18

5 U.S. General Accounting Office, "Federal Research: SEMATECH's Technological Progress and Proposed R&D Program," GAO/RCED-92-223BR, July 1992, p. 10.

Table 5-4-Congressional Add-ens for Dual-Use Technology in FY 1993

Technology	Program funding (millions) Request	Add-on	Appropriation[a]
SEMATECH	$80	$20	$100
Advanced lithography	0	75	75
High-resolution displays	10	90	100
Multi-chip modules	44	31	75
Total	$134	$216	$350

a FY 1993 figures do not reflect a 3-percent, congressionally mandated, general reduction from original appropriations to be apportioned to individual programs.

SOURCE: U.S. Congress, *Making Appropriations for the Department of Defense for the Fiscal Year Ending September 30, 1993 and For Other Purposes,* conference report 102-1015, October 5, 1992.

from defense to civilian activities (table 5-5). The programs fall into three categories: technology deployment programs to help defense companies convert to commercial markets and better their commercial performance; technology development partnerships to enable the military to maintain its technological superiority over potential adversaries while increasing its reliance on a commercial technology base; and investments in the future of the industrial technology base. These programs aim both at near-term defense conversion and longer-term investment in the Nation's military prowess and economic well-being.

These programs depart from ARPA's traditional mode of supporting the development of new, pathbreaking technologies through contracts with universities and industry. Several require ARPA to enter cooperative partnerships in which industry supplies half or more of the funding and ARPA contributes the rest; others require the agency to manage programs for technology diffusion and extension—tasks outside ARPA's traditional realm of expertise. ARPA has only recently begun conducting cooperative research and has not previously supported extension activities.

To carry out these unaccustomed tasks, ARPA has formed the Defense Technology Conversion Council (DTCC). With participation from the Department of Energy (Defense Programs), the Department of Commerce (through the National Institute of Standards and Technology), NASA, and the National Science Foundation, the Council will solicit, evaluate, and select proposals for participation in the program. ARPA plans to use its capabilities in information technology to satisfy some of the new missions. Other programs that depend less on ARPA's unique capabilities will benefit from the contributions of the other participating agencies.[19]

Congressional add-ens for dual-use programs reflect a tension that existed during the late 1980s and early 1990s between the legislative and executive branches with regard to ARPA's mission. Congress favored greater Federal involvement in supporting precompetitive R&D and, seeing ARPA as an effective agency for technology development, sought to increase its sponsorship of advanced technologies with both commercial and military application. The Reagan and Bush Administrations often viewed such support as involving the Federal government too closely in commercial technology development, and sometimes in support of individual companies.

Congressional add-ens provide government support, that would have otherwise be lacking, for

19 With the expiration in FY 1994 of the Budget Enforcement Act of 1991, which man&ted that through 1993 reductions in the defense portion of the budget not be redirected to nondefense programs, some of the funding given to ARPA for defense conversion could be redirected to these other federal agencies.

Table 5-5-New ARPA Conversion-Assistance Programs for FY 1993 (millions)

Program	Funding	Purpose
Partnerships for Technological Superiority		
Commercial-Military Integration Partnerships	$47.7	Establish cost-sharing partnerships for the development of commercial technologies with defense applications.
Defense Advanced Manufacturing Technology Partnerships	23.9	Encourage cost-shared efforts with industry to develop manufacturing technologies, especially those that reduce health, safety, and environmental hazards,
Industrial Base Transition and Integration		
Regional Technology Alliances	$95.4	Fund regional efforts to apply and commercialize dual-use technologies. ARPA may match funds contributed by State and local government or by industry.
Defense Dual Use Extension Assistance	95.4	Enable ARPA to work with the Departments of Energy and Commerce to support Federal, State, and local programs that assist defense companies in obtaining dual-use capabilities.
Defense Manufacturing Extension	95.4	Support on a cost-shared basis existing State and regional manufacturing extension programs to assist small and medium-sized manufacturers in improving their commercial performance,
Investments in the Future Industrial and Technology Base		
Agile Manufacturing	$28.6	Develop agile manufacturing technologies in partnership with industry.
Manufacturing Engineering Education	28.6	Support manufacturing education, in coordination with the National Science Foundation, through rest-sharing with universities.
Miscellaneous Manufacturing Technology Initiatives	23.8	Support programs such as U.S.-Japan management training and the Instrumented Factory for Gears.
Total	$438.8	

SOURCE: Dee D. Dawson, Assistant Director, Financial Management, Defense Advanced Research Projects Agency, personal communication, Dec. 9, 1992; "Summary of Conference Actions: FY93 Defense Authorization and Appropriations Bills," attachment to Statement by Senator Jeff Bingaman, Chairman, Subcommittee on Defense Industry and Technology, Senate Committee on Armed Services, Oct. 8, 1992.

critical technologies. However, in some cases Congressional intervention has resulted in micro-management. For example, Congress added funding to ARPA's 1991 and 1992 budgets for x-ray lithography. ARPA officials and many industry representatives favored a broader approach to lithography that would examine both optical and x-ray systems, but were unable to sway this decision by Congress until the 1993 appropriations cycle.

Legislation enacted in 1993 contains an unprecedented level of funding earmarked for particular technologies or institutions. The conference report for 1993 defense authorizations lists 14 suggested technologies for ARPA to support through industry partnerships.[20] The appropriations committee conference report identifies 24 technologies for ARPA to support through its defense conversion programs, earmarking over $120 million in funds.[21] The Defense Appropriations Act of 1993 itself also contains over $100 million in earmarked funds for defense agencies (including ARPA) to spend at particular institutions.[22] With greater collaboration between Con-

20 *National Defense Authorization Act for Fiscal Year 1993*, conference report 102-966, Oct. 1, 1992, p. 374.

21 *Making Appropriations for the Department of Defense for the Fiscal year Ending September 30, 1993, and for Other Purposes*, conference report 102-1015, Oct. 5, 1992, pp. 162-163. ARPA is not legally bound to satisfy these earmarks, as they are spelled out not in legislation but only in the conference report. Moreover, ARPA is required bylaw to use a competitive process to select among proposals solicited from industry for its dual-use partnership programs.

22 Public Law 102-396, Title IV, 106 Statute 1893-1894.

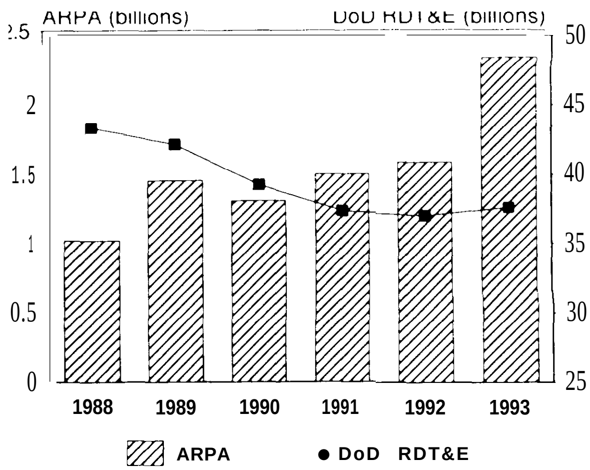
gress and the Administration, the level of Congressional add-ens for specific dual-use technologies and earmarking of funds for particular institutions could decline. The Clinton Administration has expressed support for greater involvement by the Federal Government in precompetitive commercial technology development, suggesting that such cooperation may replace or augment congressional initiative in this area.

THE FUTURE OF ARPA

ARPA will continue to be an important part of the defense R&D infrastructure despite recent changes in the national security environment. Former Secretary of Defense Richard Cheney announced a new, post-Cold War DoD strategy of spending less on procurement of new military systems, while maintaining funding for R&D to develop new technologies for building future systems and for upgrading existing systems.[23] The FY 1994 budget request reflects similar priorities, suggesting that the Clinton Administration may continue to pursue this strategy. Early stages of R&D, in which ARPA is most heavily involved (basic research through technology demonstration), will probably be least affected by reductions in defense spending. This strategy reinforces trends in ARPA funding that have been evident since the end of the Cold War. While defense spending has declined since the late 1980s, ARPA's funding has grown markedly. Defense RDT&E funding dropped 13 percent in real terms between 1988 and 1993; but ARPA's budget more than doubled from $1 billion to $2.3 billion in real terms (figure 5-l). ARPA's 1993 budget appropriation included some $960 million above the Administration's request.

ARPA's mission will therefore continue to be of central importance to DoD. Furthermore, based on military interests alone, ARPA will probably

Figure 5-l—ARPA Budget Compared Wit h DoD RDT&E, FY 1988-93



SOURCE: Budget of the United States Government: Fiscal Year 1993, Supplement.

become more involved in the development of dual-use technologies. Despite the apparent divergence of military and commercial systems, many component technologies from which these systems are constructed continue to converge. The most recent science and technology strategy promulgated by the director of Defense Research and Engineering identifies 11 key areas in which defense research (much of it supported by ARPA) will be concentrated. These areas include: computers, software, communications and networking, electronic devices, materials and processes, and design automation.[24] All are areas in which commercial industries have a strong interest.

In strengthening its ties to commercial industry, DoD can benefit from improved access to the most advanced technologies. As commercial markets for computers and other electronic devices have expanded, the commercial electronics industry has surpassed the defense electronics

23 OTA has analyzed options that follow a similar strategy. See U.S S. Congress, Office of Technology Assessment, *Building Future Security*, OTA-ISC-530 (Washington, DC: U.S. Government Printing Office, June 1992).

24 Director of Defense Research and Engineering, *Defense Science and Technology Strategy* (Washington, DC: U.S. Department of Defense, July 1992), p. I-23.

industry as the primary source of technological innovation. In fact, by the time the military initiated its VHSIC (Very High Speed Integrated Circuit) program in 1980, the microelectronics technology being incorporated into military systems were already 8 to 10 years old.[25] This lag reflects, in part, the impediments erected by defense procurement practices. DoD is no longer the principal driver of technology advance in many portions of the electronics industry. Its purchases make up less than 10 percent of the semiconductor market and are expected to comprise only a small percentage of the demand for high-definition displays and multichip modules once they become commercially available. Although DoD cannot expect to drive these industries, it can, by becoming allied with them, lower its costs both in development and procurement while taking better advantage of new technologies.

Commercial industries may also benefit from the alliance. Although private companies will invest in many of the technologies that are key for defense, ARPA can help by assuming some of the technological and financial risks. For example, ARPA is developing processes for manufacturing multichip modules (MCMs). MCM technology allows manufacturers to interconnect bare (unpackaged) integrated circuit (IC) chips on a single substrate rather than packaging the chips individually and connecting them on a printed circuit board. MCM offers many benefits to both military and commercial manufacturers of electronic systems, including higher chip densities, higher operating speeds, reduced power consumption, improved reliability, and reduced manufacturing costs. Many commercial firms and consortia such as the Microelectronics and Computer Technology Corporation (MCC) are funding research on MCMs, mostly for "chips-last" systems, in which the bare ICs are attached to the substrate after the interconnects are etched. ARPA is supporting ''chips-last systems, but is also developing "chips-first" processes in which the interconnects are etched after the chips are affixed to the substrate. Commercial manufacturers have found this technology too risky to pursue themselves, but ARPA believes it can achieve higher densities than with chips-last technology.

Manufacturing Technology

DoD is increasing its emphasis on new manufacturing technologies, a direction that is also likely to generate dual-use technologies. As defense procurement budgets fall, the military is looking for ways to reduce manufacturing costs for new systems. DoD's new science and technology strategy identifies ''Technology for Affordability" as one of its seven thrusts for future research.[26] Primary goals are to support integrated product and process design tools (referred to as concurrent engineering), develop flexible manufacturing systems for low-cost production of a wide variety of goods, promote enterprise-wide information systems for improved program control and reduced overhead costs, and develop integrated software engineering environments to increase software productivity.

If successful, ARPA's work on manufacturing technology could benefit commercial manufacturers. Many manufacturing technologies are inherently dual-use. While commercial and military products themselves may vary, the processes for manufacturing them are often very similar. For example, some commercial and military semiconductors and jet engines are made side-by-side in the same facilities, using much of the same equipment. Even when military and commercial production is separated, many of the underlying processes are the same. DoD was a strong, early

---

Paul S. Killingsworth and Jeanne M. Jarvaise, *VHSIC Electronics and the Cost of Air Force Avionics in the 1990s*, Project Air Force report prepared for the U.S. Air Force (Santa Monica, CA: RAND Corporation November 1990), p. 1.

26 Director of Defense Research and Engineering, *Defense Science and Technology Strategy* (Washington, DC: U.S. Department of Defense, July 1992), pp. II-65 to II-73.

supporter of numerically controlled machine tools that have since found application in many commercial companies. Today, military and commercial manufacturers often use the same machine tools and semiconductor fabrication equipment in their plants.

Moreover, manufacturing technology is a field in which U.S. commercial industry, universities, and the Federal Government have traditionally underinvested. The large expenditures for product development have not been matched for process development. U.S. companies typically spend two-thirds of their R&D budgets on product development and only one-third on process design; Japanese companies reverse these proportions.[27] For Federal R&D spending, the disproportion is even greater. DoD's expenditures for manufacturing R&D together with the defense-related share of the Department of Energy's manufacturing expenditures totaled about $1.2 billion in 1992. These expenditures represented some 80 percent of all Federal funding for manufacturing R&D, but equaled only 2 percent of total defense-related R&D.[28] Much of the concern over flagging U.S. competitiveness in manufacturing stems from the lack of investment in process development.[29]

ARPA is taking a new approach. ARPA's office managers estimate that about one-third of ARPA's total budget is spent on manufacturing. In FY 1992, ARPA allocated $206 million, or 14 percent of its budget, to a program designated "Manufacturing Technology;" FY 1993 allocations will grow to $313 million (table 5-6). This program contains funding for five programs: SEMATECH, to improve semiconductor manufacturing equipment and processes;[30] MIMIC,[31] to accelerate development, manufacturing and demonstration of affordable microwave and millimeter-wave monolithic integrated circuits; Infrared Focal Plane Array (IRFPA), to establish a manufacturing base for producing infrared sensors for military weapons systems; Electronic Module Technology, to rapidly develop state-of-the-art, application-specific electronic modules for quick insertion into electronic systems; and High-Definition Systems, to focus on the manufacture of high definition displays for military systems. While the MIMIC and IRFPA programs are targeted primarily toward military goals, the other three programs are directed toward technologies in which defense markets may be much smaller than commercial markets. Other ARPA programs not contained under the Manufacturing Technologies programs are also geared toward manufacturing and could be of value to commercial industry. These programs address software productivity, manufacturing automation, and concurrent engineering (table 5-7).

Microelectronics Manufacturing Science and Technology

The Microelectronics Manufacturing Science and Technology (MMST) program is one of ARPA's manufacturing efforts that could potentially benefit commercial industry. This 5-year, $86-million program, funded jointly by ARPA, the Air Force's Wright Laboratory, and Texas Instruments (TI), is intended to develop fast, flexible, cost-effective techniques for manufac-

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

John Alic *et al.*, *Beyond Spinoff: Military and Commercial Technologies in a Changing World* (Boston, MA: Harvard Business School Press, 1992), pp. 341-343.

29 U.S. Congress, Office of Technology Assessment, *Making Things Better: Competing in Manufacturing*, OTA-ITE-443 (Washington, DC: U.S. Government Printing Office, February 1990).

30 In FY 1993, funding for SEMATECH will be listed as a separate line item at the request Of Congress.

31 The Microwave and Millimeter-Wave Monolithic Integrated Circuit program.

Table 5-6—ARPA's Budget for Manufacturing Technologies, FY 1992-93 (millions)

Project title	Budget authority (millions)	
	FY 1992	FY 1993
Semiconductor Manufacturing Technology	$98	$94
Microwave and Millimeter-wave Monolithic Integrated Circuit	86	80
infrared Focal Plane Array	17	34
Electronic Module Technology	5	67
High Definition Systems[b]	—	38
Total[c]	$206	$313

a Funding for Semiconductor Manufacturing Technology (SEMATECH) is included under a separate program element in FY 1993.
b In FY 1992, $75 million was provided for High Definition Systems under a separate program element, some of which was manufacturing-oriented. In 1983, $38 million was provided for High Definition manufacturing programs, and another $152 million was provided under another program element, some of which may also have manufacturing implications.
c Totals may not add due to rounding.

SOURCE: DARPA, *Amended FY 1992/1993 Biennial RDT&E Descriptive Summaries,* (Arlington, VA: DARPA, January 1992).

Table 5-7-Other ARPA Initiatives in Manufacturing

Program title	Lead office	Annual funding (millions)	Purpose
Software Technology for Adaptable, Reliable Systems (STARS)	SSTO	$20	Improve productivity in software generation; develop reusable code, software engineering environments,
Manufacturing Automation for Design Engineering (MADE)	SSTO	9	Apply information technology to manufacturing; develop product data models.
ARPA Initiative on Concurrent Engineering	DSO	20	Develop tools for concurrent engineering; establish pilot projects,

KEY: SSTO - Software and Intelligent Systems Technology Office.
DSO = Defense Sciences Office.

SOURCE: Defense Advanced Research Projects Agency, *Amended W 199271593 Biennial RDT&E Descriptive Summaries* (Washington, DC: January 1992); and OTA staff interviews.

turing microelectronic devices.[32] The primary goal of MMST is to overcome limitations in current semiconductor manufacturing processes that prevent the military from procuring small volumes of specialized integrated circuits at affordable prices.

Current semiconductor manufacturing practices are characterized by large economies of scale that result from high capital costs and inflexible production processes. Due to rising equipment costs and the increasing number of processes required for each new generation of semiconductor chip, the cost of a state-of-the-art wafer fabrication facility ("fab") has risen to over $500 million and is expected to exceed $1 billion by 1995.[33] Equipment costs comprise about 75 percent of this cost and double with each new generation of semiconductor technology as equipment prices climb and additional equipment is needed to maintain throughput effectively doubles equipment costs. Processing a typical wafer now requires over 3(K) steps, conducted on

32 ARPA and the Air Force's Wright Laboratory are contributing a total of $58.5 million to the program; TI, the prime contractor, is contributing the balance. ARPA's contribution will total $28.3 million over 5 years, having peaked at $9.5 million in 1992.

33 "Wafers" are disks of silicon on which hundreds of semiconductor chips are simultaneously produced.

Table 5-8--Initial Goals of ARPA's MMST Program for Flexible Intelligent Microelectronics Manufacturing

Characteristic	Current State-of-the-art fab	MMST scalable fab
Minimum efficient throughput (wafers/month)	30,000	1,000
Minimum efficient plant cost (millions of dollars)	$750	$50
Cycle time (days)	75	5
Equipment utilization time (percent)	35%	90%
Test Wafers (percent)	>10%	0%
Processing steps	300	>200
Clean Environment	clean rooms	"micro-environments"
Clean room requirement (class)	1-1oo	1,000-10,000

SOURCE: Arati Prabhakar, Director, ARPA Microelectronics Technology Office, "Flexible Intelligent Microelectronics Manufacturing," briefing to the OTA,June 16,1992.

hundreds of pieces of semiconductor manufacturing equipment, each of which can cost between $200,000 and $3 million, and each of which must be maintained in a clean environment that allows fewer than one 0.15 -micron particle per cubic foot.

Because existing semiconductor manufacturing equipment cannot be easily reconfigured to produce ICs of different designs,[34] manufacturers tend to produce large quantities of a limited number of circuit designs in order to spread their capital investments over abroad production base. This strategy is effective for volume production of standardized devices such as memory chips and microprocessors, but it does not allow for cost-effective production of specialized chips of interest to both military and commercial customers.[35] Firms that produce custom chips tend to be small and operate only in niche markets. Often it is not economical for them to invest in state-of-the-art capital equipment.

The aim of MMST is to develop technologies for flexible, "modular' fabs that can quickly and easily switch between product designs. R&D is centered around three primary enabling technologies: single-wafer processes, cluster tools, and real-time process control and routing (see box 5-B). The new semiconductor manufacturing equipment and computer-integrated manufacturing (CIM) software developed under MMST are intended to allow not only increased flexibility, but a reduction in the minimum scale for an efficient-sized plant, reduced capital costs for minimum capacity, and reduced manufacturing cycle time as well (table 5-8). Modular fabs constructed using MMST technologies could then operate efficiently at low levels of production; higher levels of output could be achieved by combining several modules into one production facility. These technologies could have significant benefits for producers of both commercial and military ICs.

Numerous technical and financial obstacles could prevent MMST from achieving commercial success; but if these hurdles can be overcome, MMST could benefit some commercial U.S. semiconductor manufacturers by allowing shorter product development times, shorter manufacturing times, smaller inventories, smaller efficient-sized plants, reduced retooling requirements,

34 Reconfiguring existing semiconductor manufacturing equipment to produce ICs with different designs is a difficult process: ne" sequences of processing steps must be developed and tested for each new chip design, and individual pieces of equipment must be configured to deposit the correct thickness of insulator between layers of conductor on the wafer or implant the desired concentration of dopant into the substrate to give the material its semiconducting characteristics.

35 Military products are more likely than commercial products to use a wide variety of custom integrated circuits based on proprietary designs. Many are procured only in limited numbers.

Box 5-B-Microelectronics Manufacturing Science and Technology (MMST) and Single-Wafer Processing

The Microelectronics Manufacturing Science and Technology program is an attempt to meet DoD's requirements for fast, flexible, affordable production of microelectronic devices by replacing traditional batch processing techniques with single-wafer processes, cluster tools, and real-time process control. Texas Instruments, the industry partner in the program funded jointly with ARPA and the Air Force, is developing an operational pilot production line that will demonstrate the technical feasibility of these new manufacturing techniques. The line is being designed to provide less than 3-day turnaround on more than 1,000 integrated circuit (IC) designs per year with a throughput of 800 wafers per month and with line widths as small as 0.35 microns.[1] As of April 1993, final demonstration and test were scheduled for completion within the month.

Key to MMST's success is the development of single-wafer processing tools, which process wafers rapidly one at a time rather than slowly in large batches, as is done with much existing equipment. Single-wafer tools can help eliminate bottlenecks in manufacturing lines caused by mismatches in the processing speeds of different pieces of equipment. Such bottlenecks, which are often found in batch processing lines, reduce equipment utilization time and lengthen manufacturing cycle times.[2] With single-wafer processes, production lines can also be balanced at lower levels of throughput, effectively reducing the economies of scale in production.

Single-wafer processes also allow the use of real-time monitoring and control systems to help maintain process uniformity across the wafer and achieve high yields. Uniformity and yield are becoming increasingly

1 A 0.35 micron line width is required to produce device sizes on the scale of those required for 64-megabit DRAMs (Dynamic Random Access Memories). Testing of the production system was on schedule in April 1993 and was expected to be completed within the month.

2 With batch processes there can be substantial variation in the processing speed of different pieces of equipment. Certain pieces of equipment may have to remain idle while wafting for a downstream operation to be completed. In order to overcome these inefficiencies, manufacturers can use multiple pieces of equipment In parallel to speed up siow processes, but doing so increases the capital investment required for an efficient plant. Krishna C. Saraswat and Samuel C. Wood, "Adaptable Manufacturing Systems for Microelectronics Manufacturing: Economic and Performance issues," paper presented at *Strategies for Innovation and Changes in the U.S. and Japan*, an IBEAR Research Conference, University of California, Los Angeles, May 10-12, 1992.

greater product variety, and a shift toward competition based on functionality instead of price. Since 1975, the number of new chip designs produced each year has increased from 2,000 to over 100,000.[36] LSI Logic Corp., the world leader in the production of application specific integrated circuits (ASICs), has itself designed over 11,000 integrated circuits for specific applications.[37] The ability to produce multiple products cost-effectively in a single facility may therefore provide many firms with a competitive advantage.[38] Economic models suggests that factories producing less than 1 million chips per month using MMST could have costs about half those of

36 C. Coot (Philips), Data Quest, October 1988. Cited in Krishna C. SaraSwat and Samuel C. Wood, "Adaptable Manufacturing Systems for Microelectronics Manufacturing: Economic and Performance Issues,' paper presented at ''Strategies for Innovation and Changes in the U.S. and Japan,' an IBEAR Research Conference, University of Southern California, Los Angeles, May 10-12, 1992.

37 LSI Logic Corporation, ''An ASIC Company as a Process Leader: Oxymoron or Competitive Model," Spring 1992.

38 For a more complete discussion of the economic benefits of flexible manufacturing to semiconductor manufacturers, systems integrators, and the semiconductor manufacturing equipment industry, see W. Edward Steinmueller, "The Economics of Flexible Integrated Circuit Manufacturing Technology," *Review of Industrial Organization, vol. 7,* pp. 327-349, 1992.

difficult to maintain with batch processes as minimum feature sizes on ICs decline and wafer sizes continue to expand. With single-wafer processing it is possible to design small process chambers in which uniform conditions can more easily be monitored and maintained. Before each wafer is processed, a computer determines the required equipment settings and sends appropriate instructions to properly configure the machinery. Sensors measure the conditions within the chamber (temperature, optical emission from plasmas, etc.) and on t he wafer during processing. Feedback from the sensors is used to automatically adjust equipment settings and correct conditions within the chamber, ensuring proper processing.[3] TI completed a prototype of this computer-integrated manufacturing (CIM) system in 1990 and expected to test a beta version in a 1993 demonstration.

TI has combined single-wafer process modules into "cluster tools" that perform multiple steps, sequentially, on individual wafers. A cluster tool consists of several process modules centered around a single-wafer handler and computer system. Each module maintains a clean "microenvironment" around the wafer while it is being processed; the wafer can then be transferred *in vacuo* to the next processing chamber so it is not exposed to the external environment. In this way duster tools might replace large clean rooms. Cluster tools could also help reduce capital costs if modules can be designed with common mechanical and electrical interfaces. In that case, only portions of the equipment might have to be replaced to accommodate new generations of semiconductor technology, and it might be possible to produce common modules of equipment such as the wafer handler and vacuum chambers in large quantities.[4]

The manufacturing equipment and software developed under MMST are demonstration models only, and are far from being commercial products. Additional development is required before such tools can be manufactured cost- effectively and made to operate reliably overlong production runs at high levels of throughput. SEMATECH and TI are working together to commercialize the CIM system developed under MMST Portions of the lithography and rapid thermal processing technologies developed under MMST have been licensed to commercial companies, but additional efforts may be needed to ensure commercialization. Few equipment companies can assume the risk associated with further development. Though reportedly pleased with the program to date, ARPA has not committed itself to funding additional work to bring MMST to commercialization.

3 Robert R. Doering, Texas Instruments, Inc., Semiconductor Process and Design Center, "Microelectronics Manufacturing in the 1990s—MMST," p. 1.

4 TI is currently working with the Modular Equipment Standards Committee of SEMISEMATECH to develop standards for modular interfaces.

a conventional fab at similar capacity .39 Flexible producers should find that MMST can lower wafer production cost regardless of production volume, though the cost advantages of modular fabs may become more apparent at low production volumes where high yields are harder to achieve with traditional manufacturing techniques.

In addition, as product life-cycles have shortened, time-to-market has become a more significant competitive factor in the electronics industry. Many traditional fabs take up to 75 days to produce a wafer; TI has achieved 3-day cycle times on the MMST line, even for chips with complicated designs.[40] Markets for both commodity and custom chips are becoming increas-

39 Samuel C. Wood, "The Microelectronics Manufacturing Science and Technology Program (MMST): Overview and Implications, ' Feb. 15, 1992, p. 1.

40 Computer models demonstrate that at production levels of 5,000 wafers per month, cluster fabs based on single-wafer processing tools can theoretically produce wafers with cycle times half those of conventional fabs and at comparable cost. For higher levels of throuput, additional modules of production equipment may need to be added to the plant. Depending on the chip technology, the degree of loading, and product variety, models indicate that MMST can reduce production time by a factor of 3 to 10 over traditional manufacturing methods. See Krishna C. Saraswat and Samuel C. Wood, op. cit., footnote 32, pp. 1, 11-13.

ingly time-sensitive.[41] Flexible tools may also help reduce time-to-market by allowing semiconductor manufacturers to rapidly expand a pilot facility to production capacity, adding additional modules as demand increases. This would enable manufacturers to avoid large up-front commitments to new production facilities. Companies interested more in speed than in flexibility will probably find, however, that flexible MMST technologies result in higher manufacturing costs per wafer than traditional methods. They will have to consider the tradeoff between cycle time and cost.

Other portions of the MMST program might benefit traditional as well as flexible semiconductor manufacturers. Enhanced simulation capabilities developed for real-time control systems might be adapted for developing new processes on a computer. More than 10 percent of all wafers processed in today's fabs are test wafers used to troubleshoot new manufacturing processes. Computer simulation can bypass much of this trial and error troubleshooting. In addition, CIM software used for routing wafers between cluster tools could help batch manufacturers use their equipment more efficiently. Semiconductor manufacturing equipment is used productively only 35 percent of the time in most fabs. While equipment failures and required set-up times account for part of the downtime, much of it occurs while machines are operable but lags in the production system prevent wafers from being delivered.

Single-wafer processing techniques developed under MMST may also help semiconductor manufacturers maintain uniform distributions of reactants and energies across wafers as they become larger and feature sizes become smaller. Sensors to measure processing conditions such as temperature and pressure across the surface of each wafer are not as easily deployed in batch processing chambers as in single wafer processing chambers. With batch thermal processes, which comprise about one-third of the processing steps in a typical fab, hundreds of wafers are loaded just millimeters apart into a hot-wall furnace. Only the edges of the wafers may be visible to sensing devices, and conditions cannot be varied over localized areas. Some manufacturers have expressed concern that an approach based on real-time sensing and control will not prove robust enough for high-volume commercial production and that instabilities could be generated in systems relying on real-time process control. These companies wish to improve their understanding of variables affecting individual processing steps so they can continue to use existing processing techniques, but with a greater probability of success and higher yields. Nevertheless, participants in a recent workshop indicated that single wafer rapid thermal processing would probably reach the break-even point when device sizes reach 0.25 to 0.18 microns.[42]

Even if technical obstacles can be overcome, commercialization of MMST results may be difficult. Despite the benefits of flexible production, manufacturers in many segments of the semiconductor market, such as DRAMs (Dynamic Random Access Memories) and microprocessors, will continue to produce large quantities of a limited number of device types. These manufacturers will likely find traditional manufacturing techniques more cost-effective than MMST processes. While some effort is being made to commercialize technologies developed under MMST, there is still considerable uncertainty about the size of future markets for MMST technologies, enough to make equipment manufacturers hesitant to commit resources to their development. Many semiconductor equipment manufacturers are small and are therefore unable

41 First-mover advantages are strong in commodity chips. With only 3 y&US or so between product generations and large capital costs, manufacturers must try to get to market first in order to move rapidly down the learning curve and expand output.

42 Given current scaling trends, this point would be reached between 1995 and 1998. See Semiconductor Industry Association, *Semiconductor Technology: Workshop Working Group Reports*, Preliminary Copy, 1993, p. 69.

to take on the risk of commercializing risky, new technologies. Few can independently support the development of MMST-like tools while continuing to pursue development of traditional tools. As of early 1993, ARPA did not plan to fund continued commercialization of MMST technologies.

TECHNOLOGY TRANSFER FROM ARPA

As the MMST program demonstrates, commercialization and dissemination of technologies developed by ARPA cannot be taken for granted. If technologies are to be put into commercial practice they must match industry's needs, and linkages to industry must be established. While some ARPA programs fall short of providing commercial prototypes for new technologies, the agency as a whole has become more interested in bringing research results to the point at which they can be incorporated into products or manufacturing processes. This is one of the primary factors behind a shift in ARPA's funding priorities from universities to industry in recent years.

Linkages to Industry

ARPA has neither research facilities nor research staff. Instead, ARPA charnels funding to researchers in industry, universities, and nonprofit research centers, with its staff of approximately 109 program managers and 76 staff personne1[43] providing management oversight and technical direction. This structure tends to forge links between ARPA and industry and keep the agency in contact with members of the technical community outside government.

ARPA often links together research groups with complementary capabilities to work on a common project. Some companies share proprietary information with ARPA managers, giving ARPA a better understanding of the strengths and weaknesses of individual companies within an industry than companies themselves may have. ARPA can use this information to form loose teams of collaborators, in which several companies are given individual contracts to work on different pieces of a single problem; or subcontracting arrangements may be used to link university researchers with commercial product developers. In some cases, ARPA has formed explicit teaming arrangements with a consortium of companies.

ARPA has also had some success in transferring research out of university labs and into corporate development centers. For example, the Defense Sciences Office is funding research in high-temperature superconductors (HTSC) by the University of California at Santa Barbara via a contract with a small manufacturer of superconducting products that has little in-house R&D capability, but a strong knowledge of practical problems that can be solved with superconductivity. Under its contract the company must subcontract the full value of the contract to the university without deducting costs for overhead and management. In effect, this arrangement requires the company to manage the university's research free of charge, giving the company a stake in the project and helping to assure the potential practical value of the research. In return, the company gains access to research results that it can then incorporate into new products. ARPA benefits through the purchase of products from the company.

Industry Partnerships

Several programs initiated by Congress have established legal mechanisms and provided funding to more explicitly support cooperative partnerships between ARPA and commercial industry. The goal of these programs is to improve ARPA's (and hence DoD's) access to commercial technology and to link ARPA's R&D programs more closely to commercial needs. The programs

[43] These figures reflect authorized totals of 145 civilians, 24 military personnel, and 16 scientific personnel assigned to ARPA under the Inter-Departmental Personnel Act (IPA) for FY 1993.

include cost-sharing and other financial arrangements that are not allowed under traditional contracting regulations.

As with other Federal agencies, ARPA's funding of R&D has historically been governed by the Federal Acquisition Regulations (FAR). With the purpose of assuring fair procurement practices and avoiding fraud, the FAR requires Federal agencies to work only with companies that establish approved accounting and auditing procedures. Many high-tech companies-especially small startup fins-do not adhere to the FAR's accounting and auditing requirements because of the costs involved or simply because they are unwilling to open their books to government auditors.[44] The FAR also precludes ARPA and other government agencies from entering into collaborative relationships with industry in which both project costs and management control are shared, and it prevents them from entering into agreements with unincorporated groups of companies (in consortia).

Starting in 1990, Congress began lifting some of these prohibitions for ARPA, granting the agency authority to enter into 'cooperative agreements and other transactions' with research partners.[45] Under cooperative agreements, ARPA can support research programs in which it maintains an active role but shares management and direction with participating partners. Also, ARPA can share project costs with industry, up to 50 percent of the total, and work with groups of companies in informal consortia. ''Other transactions" are to be used in cases in which other mechanisms are inappropriate; they may take on any legal form consistent with the completion of the desired mission, but as with cooperative agreements, must be approved by the Office of the Secretary of Defense. The new authority also established an account in the Federal Treasury where ARPA can bank returns on the earnings commercial companies make from ARPA-sponsored research. ARPA may use these funds to support additional R&D programs.[46]

Congress also included provisions in the National Defense Authorization Act of 1991 and in subsequent legislation directing ARPA to use its cooperative agreements authority to fund precompetitive R&D projects with industry consortia. The law requires that these ''Dual-Use Critical Technology Partnerships' '[47] be with two or more eligible companies or a nonprofit research corporation established by two or more eligible firms.[48] Funding for dual-use partnerships totaled $50 million in 1991, $60 million in 1992, and $95.4 million in 1993, and through the frost 2 years has been used to support 13 projects (table 5-9). Although these partnerships were designed so that ARPA could use its cooperative agreements authority, most have been funded through traditional contracts because of resistance within the Bush Administration to use of the new authority.

44 ARPA has been able to work with commercial companies only by subcontracting through a university or defense contractor or by waiving FAR regulations. FAR requirements can be waived in the best interest of the government.

45 The National Defense Authorization Act for Fiscal Years 1990 and 1991 granted DARPA the authority, for a 2-year trial period ending September 30, 1991, to enter into cooperative agreements or other transactions with commercial firms. The authority was made permanent in the National Defense Authorization Act for Fiscal Years 1992 and 1993 and codified in Section 2371 of Title 10, U.S. Code.

46 Payments may be based on royalties from commercial products that result from ARPA's investment, increases in the value of the company's stock, or other measures of the company's performance. While the government can receive payments under R&D contracts governed by the FAR, money is returned to the U.S. Treasury rather than ARPA, and practical problems have precluded full use of this mechanism.

47 Original provisions for precompetitive partnerships are provided in U.S. House of Representatives, *National Defense Authorization Act for Fiscal Year 1991*, conference report 101-923, Oct. 23, 1990, p. 562. Legislation to incorporate these provisions into Title 10 of the U.S. Code are contained in U.S. House of Representatives, *National Defense Authorization Act for Fiscal Year 1993*, conference report 102-%6, Oct. 1, 1992, pp. 372-374.

48 Other government facilities are also allowed to participate in the partnerships with approval of the Secretary of Defense.

Table 5-9-ARPA Dual-Use Critical Technology Partnerships

Year	Technology	Funding (millions)
1991	Ceramic fibers	$ 3
	Opto-electronics	20
	Superconducting electronics	2
	Linguistic data processing	5
	Scalable computer systems	10
	Advanced Static Random Access Memory chips	10
	Total	$50
1992	Magnetic and optical storage	$12
	Algorithms for Maxwell's Equations	9
	Microelectronics technology Computer-Aided Design	8
	Micromagnetic components	10
	Precision investment casting for propulsion	6
	Ultra-dense capacitor materials	5
	Ultra-fast, all-optical communications systems	10
	Total	$60
1993	[Projects yet to be determined]	
	Total	$100

SOURCE: U.S. Congress, National Defense Authorization Act for Fiscal Year 1993, Conference Report 102-966, Oct. 1, 1992; DARPA, memorandum from Gary L. Denman, Director, to House and Senate Armed Services and Appropriations Committees, Apr. 20, 1992; and Senator Jeff Bingaman, "Why We Need an ARPA in the Defense Department," address to the American Enterprise Institute, July 28, 1992.

ARPA's cost-shared partnerships are somewhat different from research projects it funds under traditional contracting arrangements. Under its contracts, ARPA maintains full management control of programs. It selects their objectives, costs, and time frames. With partnerships, ARPA must share management and costs with industry; all participants must reach consensus on the programs' goals and costs. As a result, partnerships tend to pursue projects that are less revolutionary and in which the technological risks are smaller than in many traditional ARPA projects.

ARPA's work with SEMATECH demonstrates this difference. Compared with MMST, which is attempting to develop an entirely new framework for manufacturing semiconductors, SEMATECH's goals, though ambitious, are in the mainstream. Technologies developed under SEMATECH are geared toward moving existing semiconductor manufacturing processes ahead to make next-generation chips, not toward creating a new model for factory organization. Nevertheless, such goals are within ARPA's interest and play a significant role in the portfolio of programs ARPA conducts. ARPA would like to ensure a domestic supply of semiconductor chips and of requisite production equipment to meet DoD's demand.

While effective in linking ARPA's programs with industry needs, partnerships do not necessarily resolve all issues of commercialization. In interviews conducted by OTA staff, industry representatives reported that, in order to avoid antitrust problems, they often involve only their research personnel-not their product development personnel-in cooperative R&D programs. While this precaution may ensure that developed technologies are truly ''precompetitive," such rigid barriers run counter to the idea of concurrent engineering and may also retard attempts at later commercialization. Further, industry partners in ARPA's consortia are not always interested in commercializing new technologies themselves. For example, the Optoelectronic Interconnect Consortium, founded in July 1992, has four industrial partners: General Electric, Honeywell, IBM, and AT&T. Of the four, AT&T is the only company that may decide to develop a commercial product.[49] The other companies hope that once the technology is developed, a supplier industry will develop (possibly from spinoffs) to commercialize the new technology. The current partners would prefer to act as systems integrators, not component manufacturers.

ARPA views its cost-shared partnerships with industry in a positive light. Reportedly, program managers compete vigorously for the funding, trying to piece together partnerships that build on

49 David Lewis, General Electric Corp, Administrator, Optoelectronics Consortium, personal communication, Nov. 4, 1992.

partners' strengths and that complement other ARPA R&D projects. ARPA managers regard the partnerships as a effective way of diffusing new technologies to industry and developing sources for new defense and commercial products.

EXTENDING THE ARPA MODEL

ARPA's reputation for successfully identifying and supporting risky technologies with significant long-term benefits has led some people to suggest that the agency be given broader purview over technology development. While some proposals have called for removing ARPA from DoD and giving it a civilian mission, most have pushed for a more explicit broadening of ARPA's dual-use responsibilities while keeping it within DoD. The Carnegie Commission on Science, Technology, and Government, for example, recommended that ARPA (then DARPA) be renamed the National Advanced Research Projects Agency (NARPA) and be given a charter within DoD to support dual-use technologies and long-range, high-risk technologies with potentially high payoff.[50] The 1993 Defense Authorization Act also expressed a Sense of the Congress that DARPA be renamed ARPA, with responsibility for researching imaginative and innovative technologies applicable to both dual-use and military missions, and for supporting development of a national technology base.[51] President Clinton implemented the frost portion of this recommendation, renaming the agency ARPA in March 1993.

ARPA is, in many ways, already a dual-use agency. Even without legislation to specifically mandate such work, ARPA will continue to pursue technologies of interest to commercial industry. In its projects to develop manufacturing technologies, ARPA is trying to work primarily with commercial companies, not dedicated defense companies or defense divisions of larger companies. To ensure access to state-of-the-art technology and procure advanced technologies affordably, DoD will have to become more closely allied with commercial industry. Reform of DoD's procurement regulations will be a central part of such integration. At the same time, AREA's focus on enabling technologies such as materials, computers, and electronics, combined with DoD's growing interest in manufacturing technology, will allow ARPA programs to contribute to commercial as well as military missions. ARPA has experience working with industry and the legal authority to enter into cooperative, cost-shared partnerships with commercial industry. With the recent decline in corporate R&D spending, additional government funding through ARPA may prove especially helpful.

There are limits to ARPA's ability to support commercial competitiveness, however. As a defense agency, ARPA is unable to fund strictly commercial technologies with no military application. The agency has channeled little support to fields, such as biotechnology, that have demonstrated significant potential for contributing to commercial competitiveness but little potential to support national security .52 Even with dual-use technologies, ARPA's support is influenced by the political and national security environment. Both the Mansfield amendment in the early 1970s and more recent concerns about the role of Federal Government in funding commercial R&D, have required ARPA to link its research programs more closely to established defense needs. The current national security environment may be more receptive to dual use as a large part of

50 Carnegie Coremission on Science, Technology, and Government, *Technology and Economic Performance: Organizing the Executive Branch for a Stronger National Technology Base* (Washington, DC: Carnegie Commission on Science, Technology, and Government, September 1991), pp. 39-41.

51 U.S. Congress, *National Defense Authorization Act for Fiscal Year 1993*, conference report 102-966, Oct. 1, 1992, PP. 390-391.

52 ARPA has, however, considered applying its expertise in information technology to health care on the grounds that DoD is the largest single health care provider in the Nation.

ARPA's responsibilities and funding, but future changes might refocus ARPA's projects more narrowly on technologies that are unique to defense. While giving ARPA specific authority to pursue dual-use technology may help legitimize the dual-use mission, such programs will continue to be balanced against other military objectives.

There may also be a limit to the additional duties ARPA can effectively undertake. Too many new responsibilities could diminish the very qualities that have made ARPA a success. ARPA has been successful, in part, because it is a small, non-bureaucratic agency. Its managers can respond rapidly to new opportunities and cut off programs that are not producing results. ARPA officials have stated that the agency could perhaps double in size without losing its efficiency, but beyond that, its character and mission could suffer. ARPA's budget more than doubled in real terms between 1988 and 1993, but its staff grew minimally. ARPA officials admit that understaffing is impeding effectiveness. Many of ARPA's FY 1992 research contracts were slow in receiving approval, and some were not yet signed by the start of the new fiscal year.[53]

In addition, ARPA's strength is in the intelligent placement of its bets on high-risk, high-payoff technologies. Development of commercial technology requires much more than that. Commercial success also requires attention to incremental product and process improvements, to the development of infrastructure, and to the diffusion of best practices throughout industry. While ARPA has gained some experience with industry's concerns through partnering, that is not its principal area of expertise. Nor is ARPA experienced in technology diffusion. As a project-oriented agency, ARPA funds projects only to the point of demonstrating technological feasibility and perhaps through the construction of prototypes. Its portfolio of projects changes rapidly with time. Technology diffusion, in contrast, is a continual process that has no identifiable end point and cannot be terminated upon reaching a specific objective.

Thus, ARPA is best viewed not as the single or the foremost Federal agency for supporting commercial technologies, but as one component of a broader government effort. Programs like the High Performance Computing and Communications Initiative (HPCCI) and the Defense Technology Conversion Council demonstrate ways in which ARPA's capabilities can best be used to complement those of other Federal agencies such as the National Institute of Standards and Technology, NASA, the Department of Energy, and the Department of Commerce in support of objectives other than national security. By linking ARPA's capabilities with those of other Federal agencies as these programs do, the benefits of its dual-use research may best serve commercial competitiveness.

53 Michael E. Davey, *The Defense Advanced Research Projects Agency: DARPA*, 93-27 SPR (Washington, DC: Congressional Research Service, Jan. 15, 1993), p. 11.