Chapter 10

Collaborative Research and Development: A Solution?

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FINDINGS

Since the **early 1980s, numerous collaborative** R&D **programs involving combinations** of government, university, and industry participants have been initiated. These programs have a variety of institutional structures, including university-based consortia, quasi-independent R&D institutes (often funded by State government sources), and Federal laboratories. Such collaborative efforts offer a number of potential contributions to U.S. industrial competitiveness, including an excellent environment for training students, an opportunity for each stakeholder to leverage his R&D investment, and research results that could lead to new commercial products. Collaborations are often seen as a bridge that can facilitate the translation of basic research into commercial products.

The extent to which commercialization is a goal of collaborative R&D programs depends both on each program's organizational structure and the economic incentives perceived by the participating companies. Most current collaborative programs in advanced materials technologies are university-based consortia or are located within Federal laboratories. According to a sampling of collaborative advanced materials, microelectronics, and biotechnology programs undertaken by OTA, neither the programs' staffs nor their industrial participants rank commercialization of research results high on their lists of priorities; furthermore, neither party systematically tracks commercial outcomes. By and large, the industrial participants value their access to skilled research personnel and graduate students more highly than the actual research results generated by the collaboration. This strongly suggests that such collaborative programs should not be viewed as engines of commercialization and jobs, but rather as a form of "infrastructure support," providing industry with access to new ideas and trained personnel.

According to the OTA sampling, the programs' industrial participants often have only a modest amount of involvement in the planning and operation of the collaborative programs. For **the most** part, they approach their relationship with the research performing organizations as being a "window to the future." Furthermore, "collaboration" may be an inaccurate description of the programs studied. In large measure, the programs do not involve intense, bench-level interaction between institutional and industrial scientists; rather, the nature of the collaboration seemed to be mostly symbolic.

In many cases, a desire for commercial outcomes does not seem to drive how collaborative programs are managed or how issues of intellectual property, project selection, etc. are addressed. Many of the university-based programs concentrate on publishable research and graduate training, while those programs based in Federal facilities are only now beginning to move away from their primary agency missions toward a broader concern with U.S. industrial competitiveness.

There are exceptions to these general observations in some of the newer programs in university-based consortia and quasi-independent R&D organizations that conduct both generic and proprietary research in parallel within the same program. Often undertaken in conjunction with State government funding, these organizations incorporate a greater commitment to commercialization and economic development in their mission. This suggests that if commercialization is in fact one of the goals of collaboration, it needs to be a much more organic part of research-performing organizations rather than merely an added-on element.

For the products of collaborative research to be commercialized, there must be a correspond-

ing capacity and willingness on the part of the industrial participants. However, **only about 50 percent of the advanced materials company participants interviewed by OTA reported any** fol**low-on** work stimulated by collaboration.

Overwhelmingly, OTA's industrial respondents did not feel that changes in institutional arrangements with research performing programs would bean important lever in facilitating the commercialization process. Rather, they perceived that the critical issue revolves around an economic problem: how companies, particularly in the advanced materials area, can justify the cost of major investments in R&D and new manufacturing facilities in light of uncertain markets. This highlights the fact that effective commercialization of collaborative R&D requires not only a smooth path for technology transfer from the R&D center to its industrial participants, but also strong economic incentives within the companies to develop the technology.

INTRODUCTION[1]

Conventional wisdom states that one reason for flagging industrial competitiveness in the United States is industry's failure to make full use of a first-class domestic science base. Critics note that many technologies developed in the United States are commercialized abroad, and that the open laboratories **of the best U.S. research universities and Federal laboratories are visited far** more frequently by foreign industry scientists than by U.S. industry scientists. These critics also argue that other countries have a much closer coupling between their research laboratories and industrial production lines. Thus, if the United States does not greatly improve its level of technology utilization, it may continue to produce more new ideas, but may also remain behind its competitors in the commercial exploitation of those ideas.

Collaborative R&D programs involving government, universities, and industry have been touted as the most effective means of bridging this gap.[2] Since the early 1980s, numerous collaborative R&D programs have been initiated in a variety of technologies, including microelectronics, biotechnology, and advanced materials.[3]

This chapter presents the results of an OTA survey of a sample of such programs, to assess the roles and expectations of government, university, and industry stakeholders. The principal question addressed was: What impacts do collaborative research programs have on the translation of basic research into commercial products in these high technology areas?

Collaborations often bring together partners that have very different attitudes and goals.[4] Traditionally, research universities—and to some extent Federal laboratories, as well—have been concerned with the advancement of science and technology for its own sake; in contrast, R&D departments in industry have been oriented toward product development for the markets.[5] One assumption of collaborative R&D programs is that these perspectives will somehow merge, creating a seamless continuum from which innovations can flow.

There are several factors that make collaborative programs an attractive way for industries to supplement their R&D efforts:

1. The high cost of doing research today makes it increasingly difficult for a single company to "go it alone. "

'The discussion in this chapter draws heavily from Louis G. Tornatzky, Trudy S. Solomon, and J.D. Eveland, "Examining Collaborative Agreements in Advanced Materials and Other High Technology Fields, " a contractor report prepared for OTA, February 1987.

²See, for example, Lansing Felker, "Cooperative Industrial R&D: Funding the Innovation Gap, " *Be//At/antic Quarter/y,* vol. 1, No. *2,* winter *1984.*

³For a recent review, see the Govern merit-University-1 ndustry Round Table, *New Alliances and Partnerships in American Science and Engineering* (Washington, DC: National Academy Press, 1986).

4 A review of the barriers to industry/university research relationships may be found in Donald R. Fowler, "University-Industry Research Relationships, " *Research Management,* February 1984.

⁵However, there are wide variations within these generalizations; for instance, there are universities with a strong applied research orientation, and companies that conduct a significant amount of basic research.

2. The collaboration allows each partner or stakeholder to leverage his investment many fold.
3. Many research problems require a multidisciplinary approach; a collaborative program can bring together a "critical mass" of researchers with complementary talents and expertise.
4. Collaborations give a company access to new ideas and also to graduate students whom it may wish to hire.
5. The time horizon of collaborative R&D efforts can be intermediate- to long-term, in contrast to the short time horizons typically imposed on individuals engaged in industrial research.

Although commercialization of research and job creation are often touted as major benefits of collaboration, it would not be appropriate to evaluate all collaborative programs by these two criteria. Federal laboratories, which represent a significant subset of the programs in the forefront of advanced materials research, historically have been discouraged from involving themselves with commercial development, although industry has sometimes been able to use Federal facilities on a full cost reimbursement basis. In recent years, there has been a growing recognition of the contribution that Federal laboratories could make to U.S. industry's ability to compete in international markets.[6 7 8] With the passage of the Stevenson-Wydler Act of 1980 (Public Law 96-480) and the Technology Transfer Act of 1986 (Public Law 99-502), the culture of the Federal laboratories appears to be shifting toward incorporating U.S. industrial competitiveness as a goal along with their traditional missions.

Although collaborative R&D arrangements involving government, academia, and industry have received a great deal of attention recently, they are not a new phenomenon. The original model for much collaborative government/university/industry R&D work is the National Agricultural Extension Service program, which can be traced back in various forms to the 1880s. It was not until World War II, though, that major Federal research efforts were initiated. These included collaborations between government and academia, as well as the creation of the large Federal laboratory system, including Oak Ridge, Sandia, Los Alamos, and Lawrence Livermore, tied to the Defense establishment.

In the postwar years, the steady growth of Federal research spending through the National Science Foundation (NSF) and the Department of Defense encouraged the proliferation of university research facilities. During the same period, industrial laboratories grew substantially, but beyond specific contracts and consulting arrangements, they had few institutional connections,

Major trade and industry associations emerged during this postwar period to concentrate talent and resources in particular areas, but active collaboration among industrial firms continued to be inhibited by antitrust considerations. The emergence of the industry associations as neutral research brokers was a response to these concerns.

In the mid-1970s, NSF's Research Applied to National Needs (RANN) program began to experiment with various cooperative ventures. The RANN program represented an attempt by NSF to expand its traditional base in academic basic research to a range of other research approaches. However, this initiative coincided with a period of budget stringency, and RANN programs began to be perceived as competitors to traditional basic research programs–the primary thrust of NSF's mission—rather than as new opportunities. Thus, only a few RANN programs were sustained, among them the University/Industry collaborative programs, largely because they were able to point to successful leveraging of industry funds for research in universities.[9]

NSF's current Engineering Research Center (ERC) initiative adopts something from the earlier University/Industry collaborative model, particularly the idea of industrial liaison.[10] However, in

[6] Joseph Morone and Richard Ivins, "Problems and Opportunities in Technology Transfer from the National Laboratories to Industry," *Research Management,* May 1982.

[7] Herb Brody, "National Labs, At Your Service," *High Technology,* July 1985.

[8] Paul A. Blanchard and Frank B. McDonald, "Reviving the Spirit of Enterprise: Role of the Federal Labs, " *Physics Today,* January 1986.

[9] For a recent review, see Robert M. Colton, "University y/Industry Cooperative Research Centers Are Proving Them selves," *Research Management,* March-April 1987.

[10] Lewis G. Mayfield and Elias Schutzman, "Status Report on the NSF Engineering Research Centers Program, " *Research Management,* January-February 1987,

its provision of indefinite Federal funding (as opposed to phasing out Federal support after 5 years), and the lack of industrial leverage over research agendas, the ERC program resembles traditional university-oriented NSF programs more than do the University/Industry Cooperative Research programs.

Relative newcomers to the collaborative R&D effort are a variety of State programs, such as Ohio's Edison Centers and Pennsylvania's Ben Franklin Partnerships. Along with more focused initiatives such as the Microelectronics Center of North Carolina, these new State programs represent some of the more innovative develop-merits.[11] They support a mixture of basic and applied research, and are focused particularly on job creation and economic development, usually in the high technology sector.

Although gross Federal R&D has been increasing, the share of Federal support going to universities has declined one percentage point per year for the past several years.[12] This has stimulated university interest in securing industrial funding through collaborative programs. At the same time, legislative changes have reduced antitrust concerns inherent in industrial collaboration in R&D and have improved the patent incentives for commercialization of the research.[13] These changes have produced a climate favoring various collaborative models, and the visibility of several of these efforts, such as the Microelectronics and Computer Corp. (MCC) and NSF's ERC program, have become quite high.

Many different models for collaborative R&D are currently being explored .14 These include "one-on-one" joint projects involving a company and a university, small business incubator programs associated with research universities, quasi-independent research institutes associated with universities, private sector consortia, and multidisciplinary centers based at universities and national laboratories. These models differ widely in their goals, procedures, and sources of funding.

Table 10-1 outlines some salient characteristics of four common models of collaborative R&D:

[11] Walter H. Plosila, "State Technical Development Programs, " *Forum for Applied Research and Public Policy,* summer 1987.

ı2 Erich Bloch, "New Strategies for Competitiveness: Partnerships for Research and Education, " an address to the New York Science Policy Association, New York Academy of Sciences, Jan. 20, 1987.

[13] The National Cooperative Research Act of 1984 (Public Law 98-462) permitted companies to form joint ventures for R&D. In 1980, Public Law 96-517 amended the U.S. Code to permit small businesses and non-profit organizations to hold title to patents resulting from Federal grants and contracts; in 1983, this policy was extended to all Federal R&D contractors.

[14] For an overview, see Herbert 1. Fusfeld and Carmela S. Haklisch, "Cooperative R&D for Competitors," *Harvard Business Review,* November-December 1985.

Table 10-1.-Characteristics of Four Prominent Models of Collaborative R&D

	Trade/industry associations	University-based consortia	Quasi-independent institutes	Federal laboratories
Start	1960s	1970s	1980s	1940s
Scale of program	$5 million plus	$1-$5 million	$3-$10 million	$10-$100 million
Site of research	usually universities	universities	universities or special facilities	own facilities or contracts
Focus of research	applied to development	basic to applied	applied	basic to development
Performers	usually academics	academics/students	academics/full-time staff/ students	full-time staff/contractors
Patent rights	association	university/members	research performers	government/industry
Major accountability	industry through board	university, indirect to industry sponsors	sponsors (often State government)	Federal Government/agency missions
Commercialization interest	high	generally low	generally high	low except where needed for mission
Major products	products/processes	research reports/students	research reports	products/processes
Planning horizon	2-3 years	1-2 years	1-4 years	2-10 years
Proprietary work	yes, mostly	not usually	sometimes	not usually, but often classified
Funding sources	industry members	mostly Federal Government, some industry	State government, industry	Federal appropriation
Dissemination mechanisms	industry visits, personnel exchanges	seminars, publications	visits, some exchanges, publications	limited exchanges, seminars, some publications

SOURCE: Louis G. Tornatzky, Trudy S Solomon, and J D Eveland, "Examining Collaborative Agreements in Advanced Materials and Other High Technology Fields, " contractor report for OTA, February 1987

trade/industry associations, university-based consortia, quasi-independent institutes, and Federal laboratories. Some models are more prominent in particular technologies. For example, collaborative advanced materials R&D is often carried out in multidisciplinary centers based at universities and Federal laboratories, while collaborative microelectronics and biotechnology R&D are more often associated with private sec**tor consortia, quasi-independent institutes, and** one-on-one university/company relationships. **The suitability of a given model depends on several technology-specific variables, such as the maturity of the technology, the costs of R&D and production scale-up, and private sector expecnations regarding the size and timing of potential markets.**

Since the early 1980s, there has been an explosion of collaborative **R&D efforts in advanced materials fields.** For instance, table 10-2 lists some advanced materials programs that have been ini-

Table 10.2.—Examples of Recent Advanced Materials Programs[a]

State	Program	Location	Year founded	Program emphasis
California	Center for Advanced Materials, Lawrence Berkeley Laboratory	U. of California, Berkeley	1983	Electronic materials, structural materials, and catalysts
Colorado	Advanced Materials Institute	Colorado School of Mines	1984	Interdisciplinary materials research
	University-Industry Cooperative Steel Research Center	Colorado School of Mines	1985	Thermomechanical processing and alloying effects on properties and deformation behavior
Delaware	ERC for Composites Manufacturing Science and Engineering	U. of Delaware/Rutgers U.	1985	Processing, fabrication, and testing of polymeric and composite materials
Florida	Bio-Glass Research Center	U. of Florida, Gainesville	1983	Biocompatible ceramic materials
Illinois	Basic Industry Research Institute	Northwestern U.	1984	Technology for basic auto, metal, and construction industries
	ERC for Compound Semiconductor Microelectronics	U. of Illinois	1986	Advanced electronic materials
Massachusetts	Polymer Processing Program	Massachusetts Institute of Technology	1976	Synthesis of new processes, interdisciplinary research
	Materials Processing Center	Massachusetts Institute of Technology	1980	Generic materials processing in metals, ceramics, polymers, electronic materials, and composites
	Polymers Program	U. of Massachusetts	1980	Synthesis of new functional polymers, polymer composites
New Jersey	Center for Ceramics Research	Rutgers U.	1984	Automotive engine parts, computer components, optical fibers
New York	Center for Composite Materials	Rensselaer Polytechnic Institute	1986	High-temperature structural composites
	Center for Advanced Technology in Ceramic Materials	Alfred U.	1987	Advanced ceramics research
Ohio	Polymer Innovation Corp.	U. of Akron/Case-Western Reserve U.	1984	Macromolecules, polymer blends, composites
	Welding Center	Ohio State U.	1984	Welding, joining of advanced materials
	ERC for Near-Net Shape Manufacturing	Ohio State U.	1986	Manufacturing sciences
Pennsylvania	Center for Advanced Materials	Penn State U.	1986	High-temperature engineering materials
	Materials Research Laboratory	Penn State U.	1964	Dielectrics, structural ceramics, advanced materials
	Consortium on Chemically Bonded Ceramics	Penn State U.	1986	High-strength cementitious materials

[a]Supported by Federal, State, and industry sources.

ERC: Engineering Research Center (sponsored by the National Science Foundation).

SOURCE: Adapted from R.M. Latanision, "Developments in Advanced Materials in the Industrialized Count ries," a paper presented at the Federation of Materials Societies' 9th Biennial Conference on National Materials Policy, Fredericksburg, VA, Aug. 4-7, 1966.

tiated in recent years. Most of these are associated with universities and involve combinations of Federal, State, and industrial support. There has been little attempt to coordinate these efforts, and consequently there has been some overlapping in research agendas as well as in sources of industrial funding. **This has given rise to concern that such a fragmented approach is wasteful, will dilute resources, and will fail to generate the results necessary to make a competitive difference** for the United States in the international marketplace.[15] This issue is discussed further in chapter 12.

The Federal laboratories within the Departments of Energy, Commerce, Defense, and the National Aeronautics and Space Administration also conduct extensive advanced materials research programs in support of their various missions. They are important resources of facilities and expertise, especially in advanced ceramics and composites technologies. Federal laboratories are especially important in advanced ceramics research: in 1985, for instance, Federal laboratories accounted for 30 percent of the total Federal budget of $51 million for structural ceramics R&D.[16] Of the Federal laboratories conducting research, only the National Bureau of Standards within the Department of Commerce has a mission explicitly directed toward industry.

Three industrial consortia focusing on advanced ceramics R&D are being planned at this writing. These are the Ceramic Advanced Manufacturing Development and Engineering Center **(CAMDEC), which intends to focus on processing and manufacturing technology and will be located at Oak Ridge National Laboratory;** the Advanced Ceramic and Composite Partnership (ACCP), part of the Midwest Technology Development Institute, a consortium funded by nine Midwestern States and based in St. Paul, MN; and the National Applied Ceramic Research Association (NACRA), based in southern California. Discussions are currently underway among the three consortium organizers, officers of the United States Advanced Ceramics Association, and the U.S. Department of Commerce as to how the agendas of these consortia can be coordinated. Because these efforts are in an early stage, the consortia membership rosters are still incomplete. Many of the prospective member companies are already participating in various other collaborative programs, and they are uncertain about which arrangements would offer them the best return on investment.

15 R.M. Latanision, "Developments in Advanced Materials in the Industrialized Countries," a paper presented at the Federation of Materials Societies' Ninth Biennial Conference on National Materials Policy, Fredericksburg, VA, Aug. 4-7, 1986.

16 According to unpublished data compiled by S.J. Dapkunas, National Bureau of Standards.

COLLABORATIVE RESEARCH AND DEVELOPMENT: SURVEY RESULTS

To provide a current basis for examining collaborative R&D efforts as a factor in enhancing the competitiveness of U.S. advanced materials industries, OTA undertook independent surveys of individuals representing the three principal stakeholders in the process: research-performing organizations, industry participants, and government policy makers with long experience in collaborative research programs. In all, OTA examined a total of 19 research-performing organizations engaged in collaborative R&D, consisting of 11 in advanced materials, and, for purposes of comparison, 4 each in information technology and biotechnology. These are identified in table 10-3, and they represent three of the model types discussed earlier: the university-based consortia, quasi-independent institutes, and Federal laboratories. In addition, OTA interviewed-in separate surveys-representatives of **19** industrial collaborators of these research-performing organizations, plus 9 government policy makers, as shown in table 10-4.

Given the range of collaborative models and technologies, as well as the small sample of research-performing organizations and industry

Table 10-3.–Collaborative Research-Performing Organizations Surveyed by OTA

Organization	Model type	Location
Advanced materials:		
Center for Ceramics Research, Rutgers University	University-based consortium	Piscataway, NJ
Center for Composites Manufacturing Sciences and Engineering, University of Delaware	University-based consortium	Newark, DE
Center for Composite Materials and Structures, Virginia Polytechnic Institute	University-based consortium	Blacksburg, VA
Center for Applied Polymer Research, Case-Western Reserve University	University-based consortium	Cleveland, OH
Center for Dielectrics, Pennsylvania State University	University-based consortium	University Park, PA
Materials Science Department, Massachusetts Institute of Technology	University-based consortium	Cambridge, MA
Materials Laboratory, Wright-Patterson Air Force Base	Federal laboratory	Wright-Patterson AFB, OH
High Temperature Materials Laboratory, Oak Ridge National Laboratory	Federal laboratory	Oak Ridge, TN
Center for Materials Science, National Bureau of Standards	Federal laboratory	Gaithersburg, MD
Materials Processing Division, Sandia National Laboratory	Federal laboratory	Albuquerque, NM
Materials Research Program, NASA-Lewis	Federal laboratory	Cleveland, OH
Biotechnology:		
Biomedical Technologies Consortium, University of Utah	University-based consortium	Salt Lake City, UT
Center for Biotechnology Research/Engenics	Quasi-independent institute	Menlo Park, CA
Center for Advanced Research in Biotechnology	Quasi-independent institute	Rockville, MD
Michigan Biotechnology Institute	Quasi-independent institute	Lansing, Ml
Information technology:		
Center for Integrated Systems, Stanford University	University-based consortium	Palo Alto, CA
Magnetics Technology Laboratory, Massachusetts Institute of Technology	University-based consortium	Cambridge, MA
National Research and Resource Facility for Submicron Structures, Cornell University	University-based consortium	Ithaca, NY
Microelectronics Center of North Carolina	Quasi-independent institute	Research Triangle Park, NC

SOURCE: Louis G. Tornatzky, Trudy S. Solomon, and J.D. Eveland, "Examining Collaborative Agreements in Advanced Materials and Other High Technology Fields," contractor report for OTA, February 1987.

participants surveyed, the results described in this chapter should be considered suggestive rather than definitive. However, it should also be recognized that data from the three surveys are consistent with one another, and the conclusions drawn therefrom are supported by independent studies. The following is a summary of the survey results.

Program Scope and Organization

As **a** survey group, the Federal laboratory programs, which are particularly important in advanced materials R&D, are considerably larger and better established than the other research-performing organizations in the sample. The Federal laboratory programs are staffed by large complements of full-time employees, while the university-based consortium programs generally consist of small groups of full-time staff and large numbers of part-time faculty and student affiliates.

These various organizational types also depend on different sources of funding. The Federal laboratories depend almost exclusively on Federal appropriations. The university-based consortia depend primarily on Federal grants, but also have some industry and State government support. The quasi-independent institutes tend to receive their funding from State governments and industry.

The consensus of government policy makers interviewed was that the States now have assumed an equal, if not leading role in the development of collaborative research programs.[17] Several of the respondents noted the relative advantages that States have in this area, including special knowledge about regional economies, the ability to tie R&D initiatives more closely to State-level economic planning, and the ability to control incentives such as taxation and regulation in a much more targeted manner. As one policy maker

[17] A review of State and local programs aimed at promoting regional economic development may be found in another OTA report entitled *Technology, Innovation, and Regional Economic Development, OTA-STI-238* (Washington, DC: U.S. Government Printing Office, July 1984).

Table 10-4.—Industry Participants and Government Poiicymakers Surveyed by OTA

Industry participants:

1. Allegheny-Ludlum Corp.
2. Aluminum Co. of America
3. Arco Chemical Co.
4. Bell-Northern Research Ltd.
5. Boeing Commercial Airplane Co.
6. Corning Glass Works
7. E.I. du Pont de Nemours & Co.
8. General Motors Corp. Technology Center
9. Goodyear Tire & Rubber Co.
10. Hewlett-Packard Co.
11. Honeywell, Inc.
12. Johnson & Johnson
13. Martin Marietta Corp.
14. McDonnell Douglas Corp.
15. MIPS Computer Systems
16. Noranda, Inc.
17. Shipley Co., Inc.
18. TRW, Inc.
19. Upjohn Co.

Government policymakers:

State-level administrators of collaborative programs (2)
Federal policy researchers (2)
Federal administrators of collaborative R&D programs (2)
Congressional policy analysts (2)
Member of White House science policy staff

SOURCE: Louis G. Tornatzky, Trudy S. Solomon, and J.D. Eveland, "Examining Collaborative Agreements in Advanced Materials and Other High Technology Fields," contractor report for OTA, February 1987.

noted, it is a "finite universe at the State level," and the limited number of stakeholders permits a "type of flexibility impossible for the Federal Govern merit."

On the other hand, the government policymakers saw a continued and important role for the Federal Government in developing and supporting collaborative programs in which the major emphasis is on fundamental science. Some felt that because the Federal Government is not hampered by provincial (and perhaps competitive) State economic interests, it is capable of developing and siting such programs in a more objective way. However, there were strong opinions expressed about the need for State/Federal collaborative planning in future initiatives. Respondents felt that there was a strong possibility—and some existing cases—in which Federal programs and State programs were duplicative. At the least, they felt that the Federal Government has an obligation to consult with State-level technology planners before siting a major facility in a State.

Industry Involvement

In general, the R&D programs covered by the OTA surveys do not involve intense, bench-level interaction between research staff and industry collaborators. In many programs, the nature of the collaboration is more symbolic, and written reports or special seminars are the most common methods for disseminating research results. Thus, use of the word "collaboration" may be misleading in describing these programs.[18]

Industry respondents were asked about their companies' involvement in strategic planning, project selection, and project monitoring. Their responses showed only a moderate degree of involvement, with no significant differences across technology areas.[19]

Virtually all of the government policy makers interviewed saw industry's limited involvement in collaborative programs as a continuing problem for which there is no quick or easy solution. They felt that while a number of specific mechanisms and approaches could be used, the level of industry involvement would depend on good person-to-person contact at the technical level. Suggestions included sabbaticals for industry personnel to spend time at research organizations, and vice versa. Also mentioned was involving people other than scientists (e.g., managers or production personnel) from the participating companies. However, some respondents cautioned that extensive involvement of industrial personnel or university personnel in sabbatical exchanges might be hampered by the career disincentives arising from being absent from one's regular position for an extended period of time.

[18] The extent of industry participation appears to be greater in the context of one-on-one, project-specific cooperation between a company and a university, as compared with multicompany, multiproject centers. See, for example, Denis Gray, Elmima Johnson, and Teresa Gidley, "Industry-University Projects in Centers: An Empirical Comparison of Two Federally Funded Models of Cooperative Science," *Evacuation Review,* December 1987.

[19] A graphic example of the isolation of industry participants from the communication network of industry/university collaborative centers may be found in J.D. Eveland, "Communication Networks in University/Industry Cooperative Research Centers, " (Washington, DC: Division of Industrial Science and Technological innovation, National Science Foundation, 1985).

Intellectual Property

Both university-based consortia and Federal laboratories tend to have similar policies on patent ownership. The most common pattern is for research-performing organizations to retain intellectual property rights to the work and to grant nonexclusive licenses to industry participants. In a minority of cases, the organizations are able to grant exclusive intellectual property rights to industry participants.

However, there were some subtle differences in how patent policies were administered and implemented. Overall, access to intellectual property by industry partners seems easier in university programs. One industry respondent noted:

> The Department of Energy's procedures are incredibly slow and ineffective, They almost never give exclusive licenses to technology–so it's hard for firms to pick up patents.

And as one Federal laboratory director put it:

> The time and hassle involved for a firm in working with us is a major impediment to doing industrial research . . . and because industry wants clear titles granted or exclusive licenses from any resulting technology, they figure, "Why collaborate?"

There is some survey evidence of informal skirting of the bureaucratic procedures at Federal laboratories. As one respondent noted:

> Most exchange of information is based on "technical intelligence, " not patents, Most commercialization takes place through informal, old-boy networks. People hear about things . . . come for visits, talk to staff, very little [happens] through formal channels, such as patent transfer.

The Federal Technology Transfer Act of 1986 (Public Law 99-502) has made it possible for government laboratories to grant exclusive licenses to industry for technologies resulting from joint R&D. Industry and government sources contacted by OTA were in agreement that the legislation now in place clears the way for effective collaboration, The questions remaining are how the legislation will be implemented at the laboratory level, and how quickly the culture of the laboratories will change to address industry needs.

Proprietary Research

Among the survey respondents, there is a mixture of practices relating to how proprietary work is handled by the research staff. In some programs, no proprietary work is done by members of the staff. However, roughly 40 percent of the programs permit staff to conduct proprietary work using the same equipment and facilities, but that work is done "outside" the program—typically through a one-on-one consulting contract. In three programs, proprietary work is not only done by the program personnel but it is a legitimate and visible part of the organization's formal efforts.

One interesting development, seen particularly in the biotechnology area, and to a lesser extent in the advanced materials area, is what may be termed a hybrid program; i.e., one portion of the overall program agenda is dedicated to basic or applied research of a nonproprietary nature, while parallel, proprietary work is also done on a project-specific basis, but still within the overall program scope.

For instance, one respondent described a two-tiered research program in the advanced materials area. The research-performing organization engages in generic research but also takes on contracts with individual companies. There tends to be a great deal of interaction between university researchers and industry scientists in both tiers. In the contract projects, the company retains exclusive patent rights, but the research-performing organization retains the right to publish the results stemming from the projects, often after a built-in period of delay. For the most part, the hybrids exist as new State government/university initiatives, often closely tied to economic development planning.

The one clear area of difference between university- and Federal laboratory-based collaborative programs lies in the ability of staff to do proprietary work for or with industry partners, Virtually all of the university respondents in the advanced materials area indicated that proprietary work is undertaken. In a few cases, this is done as part of an official program, most often through one-on-one contracts and consulting agreements.

The situation in the Federal laboratories is quite different. All of the Federal laboratory respondents indicated that proprietary work is rare at best. The inability, prior to the Federal Technology Transfer Act, of firms to get nondisclosure agreements regarding collaborative research results was seen as the primary barrier to collaboration.

A majority of the policy makers interviewed felt that the legitimation of proprietary work in the collaborative programs is essential for accelerating the commercialization of research results. One respondent noted that it is "impossible to pursue commercialization without doing proprietary work." Unless researchers and research teams can continue the thrust of basic work into **more dedicated applications for individual companies, observed the policy makers, promising findings would** not be followed through. Nonetheless, **they also felt that proprietary** work should not be the primary or exclusive mission of publicly supported research-performing organizations.

The policy maker respondents offered a variety of specific solutions as to how proprietary work could be conducted in the context of collaborative programs. The common element in these solutions was the notion of establishing a parallel structure: the basic or generic research program would constitute the core thrust of the research-performing organization, with other dedicated projects being conducted simultaneously for individual companies.

The policy makers suggested various organizational solutions for achieving parallel structures. One was to setup for-profit subsidiaries. Another was to set up a campus-based but legally independent institution which could pursue product development as a follow-on to research from the core program. The overall feeling among the respondents was that it is not difficult to figure out a way to perform proprietary work. In the words of one policy maker, "People seem to be able to juggle these things. "

Although the policy makers presented a generally positive attitude toward proprietary research, some noted that there are several university administrators and scientists who are concerned that doing such work will harm the traditional culture of the university.[20] They also suggested that there are significant differences across research-performing organizations (particularly universities) in the cultural values or sense of mission supporting proprietary work. One implication for policy makers would be to locate collaborative programs in institutions that perceive industry-oriented research to be part of their overall mission, rather than in institutions that have little or no interest in such research.

Participation by Foreign Companies

Because of concerns about losing the competitive edge in key technologies, the participation of foreign companies in U.S. collaborative R&D programs remains a thorny issue. In the advanced materials area, university-based consortia generally have foreign companies as members, whereas Federal laboratories work only with U.S. companies. This issue becomes even more complicated as advanced materials companies become more multinational.

All of the policy maker respondents viewed foreign participation as a highly sensitive and important issue. However, none argued for a more restrictive approach to foreign access to U.S. research. The general feeling was that the Nation would lose more than it would gain through more restrictive policies, and that such a policy would not address the true underlying problem: U.S. companies are not effectively using the research results coming out of collaborative R&D programs, particularly those based in the Federal laboratories.

The respondents noted that U.S. companies have not adopted the aggressive pursuit of external information practiced by foreign companies, and have not been willing to assign their best scientific personnel to participate in collaborative research programs. As one respondent declared: "The challenge is not to restrict access, but to run faster. "

[20]The effects of industrial support on academic researchers in biotechnology are reviewed in David Blumenthal, et al., "University-Industry Research Relationships in Biotechnology: Implications for the University, " *Science,* Jjune 13, 1986.

The respondents also discussed the need for "parity" or "equity" in scientific exchanges, which would enable U.S. **institutions to obtain as much quality scientific information as they give out. The respondents felt this principle should also guide personnel exchanges and site visit access.**[21]

A few respondents suggested providing a preferential approach to the dissemination of research results to U.S. companies, to give them an advantage over foreign competitors. For instance, one respondent suggested that U.S. companies, or member companies in collaborative program consortia, be given early versions of unpublished results. Another suggested that foreign clients or companies should pay a premium to obtain research results or reports from such programs.

Collaborative Program Goals

Goals of Research-Performing Organizations and Their Industry Partners

In surveying research-performing organizations, OTA asked managers to assess the relative importance of various program goals on a scale of 1 to **4. A summary of their answers is given in table 10-5, organized by technical area.**

There was a consensus across the technical areas in the priority and ranking given to the various goals. Generally speaking, high marks were given to such goals as expanding the knowledge base, transferring knowledge, enhancing training, and fostering different types of industry research. Goals such as patents or commercialized products were not ranked highly, although there was considerable variance.

Similarly, OTA asked the industry participants to rank their goals and motives for affiliating with the collaborative centers, The answers are also given in table IO-5 so they can be compared with those of the research managers. As can be seen, the results closely parallel one another, indicating convergence between the two groups on program goals and expectations. Most highly ranked by both were the general expansion of knowledge as well as the transfer of basic scientific information between collaborative partners. Although the industry participants ranked goals such as patents and commercial products somewhat higher than R&D managers in the research-performing organizations, these goals do not appear to be the principal motivating force behind the collaboration.[22]

Responses to related survey questions provided further insight into the collaborative relationship. The industry participants were asked how affiliation with research programs complemented their own companies' activities, The most frequent comments centered around the idea that affiliation is a way for the company to acquire knowledge. As one respondent noted,

> **When we started we had no experience in this area. The program provided a window on potential areas of advanced materials in the future.**

It is important to note that in large measure the industry participants did not gain such knowledge through reading reports. Rather, they valued in particular the access to knowledgeable people–both faculty and graduate students. The respondents also were asked about their primary motivation for corporate affiliation with collaborative R&D programs. Comments received most often included "technical expertise, " the organization being a "leader in a specific technology process," and the desire to "maintain and facilitate a window on developments . . . especially work being done at the best U.S. universities. "

Access to graduate students was a significant motivator for some companies, particularly in the

[21] The principle that the United States and Japan should have "symmetrical access" to each other's science and technology institutions was advanced at the Second U.S.-Japan Conference on High Technology and the International Environment, a meeting jointly sponsored by the U.S. National Academies of Sciences and Engineering and the Japan Society for the Promotion of Science, held in Kyoto, Japan, Nov. 9-11, 1986.

[22] These results for organizations based on the university consortium model are consistent with those of previous studies: see Den is Gray and Teresa Gidley, "Evaluation of the NSF University/Industry Cooperative Research Centers: Descriptive and Correlative Findings from the 1983 Structure/Outcome Survey s," unpublished paper, Department of Psychology and Center for Communications and Signal Processing, North Carolina State University, Raleigh, NC, June 1986; Gray, Johnson, and Gidley, op. cit., see footnote 18, 1987; Mike Devine, Tom James, and Tim Adams, "Government Supported University/Industry Research Centers: Issues for Successful Technology Transfer, " paper presented at the Twelfth Annual Meeting and International Symposium of the Technology Transfer Society, Washington, DC, June 23-25, 1987.

Table 10-5.– Relative Importance of Collaborative Program Goals Identified by Industry Participants (1P) and Research Managers (RM) by Technical Area[a]

Goal	Advanced materials		Information technology		Biotechnology	
	IP	RM	IP	RM	IP	RM
General expansion of knowledge	3.4	3.7	4.0	4.0	2.8	3.8
Transferring knowledge between collaborative partners	3.2	3.6	3.0	4.0	3.2	3.8
Enhancement of training for research personnel	2.8	3.0	3.7	3.8	2.8	3.0
Enhancement of industrial research	3.1	2.8	2.0	3.0	3.0	2.5
Redirection of university research	2.5	2.6	2.0	2.0	2.8	1.0
Development of new research projects with collaborating firms	2.9	2.1	2.0	2.5	3.0	2.3
Development of patentable products	2.4	2.5	1.0	1.5	3.0	3.0
Development of commercialized products	3.1	2.2	2.0	1.5	3.0	2.8

[a]Scores could range from 1 to 4 with 4 being the highest in importance. Entries are mean scores.

SOURCE: Louis G. Tornatzky. Trudy S. Solomon, and J.D. Eveland, "Examining Collaborative Agreements In Advanced Materials and Other High Technology Fields," contractor report for OTA, February 1987.

information technology area. Research-performing organizations are seen by some industry participants as being akin to "intellectual feed lots" for the nurturing of future personnel. Some respondents mentioned that access to particular facilities, unavailable in their own companies, was another motivating force for affiliation.

overall, the industry participants' reasons for corporate affiliation with research-performing organizations are best summed up by one respondent:

> **The specific projects are not as important. People in charge are too far removed from the realities of product and market development. It's not their bag, and we don't expect them to do it. They rejuvenate our bag of tricks; we take it to the marketplace.**

Commercialization as Mission

Typically, the research managers interviewed by OTA cited three reasons for establishing collaborative R&D programs: 1) response to a funding opportunity or an opportunity to establish stability of funding, 2) response to industry needs or to a larger economic agenda, or 3) response to the fulfillment of a government agency mission.

programs that were founded to address industry needs or economic development concerns were able to identify more in the way of commercial results. This observation, of course, merely reflects that an organization that plans from the beginning for a certain outcome is more likely to achieve it. However, it also reflects distinct differences in the way these organizations engaged in collaborative programs approach their missions. For instance, one academic respondent whose organization reported few commercial outcomes stated that it would be "repugnant" to consider commercialization as a factor in how research reports are disseminated. By contrast, a peer in the same technical area, when questioned about project monitoring, noted that "one of the things we look at when we review projects . . . is whether something is patentable. "

Another respondent at a Federal laboratory noted that strategic planning was approached with the idea that commercialization was a "real gold star." In the biotechnology area, when asked about the strategic planning function, one respondent stated,

> **We don't want to overlook the science, but the thrust of our activities is the enhancement of economic development through information and technology transfer . . . Essentially everything being done in the program has some commercial potential.**

These comments capture the more pervasive sense of commercialization as mission in some research-performing organizations. This mission would seem to be established early and is probably woven into the very fabric of the organization. There appear to be some differences in com-

mercialization perspective across technical areas, though. The **newer biotechnology centers appeared to be significantly more oriented toward commercialization as "embedded mission" than is the case with the more established centers in the other technologies.**

There was considerable disagreement among the policy makers on the extent to which research-performing organizations should adopt a full-blown commercialization perspective in their operations. Two of the respondents argued that some collaborative research organizations, particularly universities, will always be oriented primarily toward fundamental science. Moreover, they argued, this is appropriate and desirable, given the historical mission of university research. on the other hand, the other respondents suggested that a commercialization perspective ought to be built into research organizations, but they differed as to how to accomplish this objective.

Several of the policy makers suggested that the hybrid programs represent a desirable option. Virtually all the policy makers suggested that the adoption of a more aggressive commercialization perspective would be enhanced by facilitating a greater mingling across the stakeholder groups; i.e., through greater use of joint staff/industry committees to set the research agendas, increased emphasis on personnel exchanges, and informal interactions among the different stakeholder groups.

Industry Capacity and Incentives for Commercialization

Only about half of the surveyed industry participants who are affiliated with advanced materials research-performing organizations reported any internal follow-on work initiated as a result of collaboration. Given that the organizations had identified the surveyed industry participants as their most active collaborators, this proportion is likely to be an overestimate of follow-on activities on a nationwide basis.

Obstacles to Commercialization

To further explore the industry respondents' views on the commercialization process, OTA asked them to rate several potential obstacles to this process. These included such issues as the management of the collaborative program, skill levels of company technical personnel, interdisciplinary content of the new technologies, manufacturing scale-up costs, market uncertainties, cost justification, government policies, the planning process, and the lack of integration between the design and manufacturing functions. Each factor was rated on a 4-point scale, with 1 representing no obstacle at all and 4 representing a significant obstacle to commercialization.

In addition, the respondents were given the opportunity to identify other obstacles, as well as to elaborate on why they felt some factors were more important than others. They were also asked whether the institutional arrangements between their companies and the collaborative research-performing organizations constituted a significant obstacle,

Table 10-6 presents the summary data on obstacles to commercialization, as ranked in importance by industry participants and organized by technical area. Over the three technologies, the cost to scale-up manufacturing processes was the most significant obstacle, closely followed by market uncertainties and difficulties in the cost justification of new technologies. In the opinion of the respondents, advanced materials technologies are particularly beset by a cluster of problems centering on economics. There are major market uncertainties in the advanced materials area, which, coupled with high scale-up costs, create significant cost justification problems.

The issues of market uncertainty, planning, and cost justification tended to be intertwined **in the perceptions of** the **respondents.** The following three comments are illustrative:

> **If we develop something that looks real good, but has never been commercialized and it takes a big chunk of capital . . . it's a very tough decision.**
>
> **This contrasts to the costing of products and their justification, where the product and market are known, and payback comes in a few years. The entire management chain is conditioned to this, and R&D programs tend to be funded through product line management.**

Table 10-6.—Relative Importance of Obstacles to Commercialization Identified by Industrial Participants by Technical Area[a]

Obstacle	Advanced materials	Information technology	Biotechnology	Overall
Management of collaborative program	1.4	1.7	1.0	1.4
Level of technical training in company	1.9	2.0	1.6	1.8
Cost to scale-up manufacturing	3.2	3.3	2.4	3.0
Market uncertainties	3.3	2.0	2.2	2.8
Interdisciplinary nature of R&D	1.9	2.0	1.4	1.8
Cost justification	3.2	2.7	2.0	2.8
Government policies	2.3	1.7	3.0	2.4
Short-term planning	2.6	3.0	2.2	2.6
Lack of integration between design and manufacturing	3,0	2.3	2.4	2.7

[a]Scores could range from 1 to 4 with 4 being the highest In importance. Entries are mean sources.

SOURCE: Louis G. Tornatzky, Trudy S. Solomon, and J.D. Eveland, “Examining Collaborative Agreements in Advanced Materials and Other High Technology Fields.” contractor report for OTA, February 1987.

To the extent that you are directly replacing a product with a new one, this is not a problem . . . New products or applications are the problem.

Only in the biotechnology area were government policies seen as the greatest obstacle to commercialization. Concerns expressed by respondents focused on the intensity of environmental and safety pressures and the overlap between Federal and State regulations.

The industry respondents offered several partial solutions to these obstacles to commercialization. In the advanced materials area, some suggested approaches centered on temporarily suspending a market-pull philosophy and moving toward a more aggressive technology-push approach. One respondent suggested that industry should: “. . . invest money, make product, and create a market. We do it backwards. ”

Some suggested that the present market in advanced materials is insufficient to warrant major investments in commercialization, given the traditional approaches to cost justification. Some suggested a more systemic long-term approach to product planning and development. Some suggested that the government should play a role, perhaps with some tax incentives to “encourage risk capital to go after new processes. ” Some pointed out that such countries as Japan are developing ceramics without an obvious current market need. (These comments echo the themes presented in chs. 8 and 9.)

In assessing the industry participants’ views on commercialization obstacles, all survey respondents were asked whether changes in the institutional arrangements between their companies and research-performing organizations would help. By a large majority (82 percent), they indicated that this was not the case. Rather, they perceived the obstacles as emanating from their own companies.

Several policy makers pointed out the lack of a technology infrastructure to enable promising research results to move across the boundaries between research-performing organizations and their industry clients. They suggested that the level of industry involvement in these organizations be increased, and especially that it be expanded to include individuals who represent different levels and functions within the industry organization, including those from manufacturing and product development, as well as R&D. As one respondent noted:

People in industry in a position to commercialize results, whose job it is to do it, are not in communication with those with the data in these programs.

CONCLUSION

The capability of collaborative R&D arrangements to enhance the competitiveness of U.S. industry depends on several interrelated factors: the institutional structure of the collaborative program, the type of technology involved, and the economic incentives for commercializing that tech no logy.

In assessing the effectiveness of collaborations in bridging the gap between basic research and commercial products, a distinction must be made between the technology transfer process and the driving force behind the transfer. When the economic driving force is present, the institutional arrangements can have a significant impact on the pace of commercialization. For instance, experience suggests that hybrid programs featuring opportunities for proprietary, project-specific research as well as nonproprietary, generic research lead to greater commercialization than do those featuring generic research alone.

However, if the economic driving force is not present, specific institutional arrangements are not likely to make much difference. In the case of advanced materials, a significant gap still remains between the point at which collaborative work leaves off and that at which industry commitment begins. This is largely due to economic factors, especially the high cost of manufacturing scale-up in an uncertain business climate. Thus, while collaborative programs of the type surveyed by OTA do provide valuable products in the form of trained students and new research results, these surveys suggest that the programs should not be viewed as solutions to the problem of relatively slow commercialization of advanced materials in the United States. options for addressing this problem are discussed further in chapter 12.

APPENDIX 10-1: METHODOLOGY

The purpose of the OTA surveys was to provide a basis for an analytical description of collaborative R&D activities in advanced materials, and to draw lessons where appropriate from similar activities in biotechnology and information technology. The particular focus was on research-performing organizations that have significant government support, either from Federal or State funding programs, and that have collaborative arrangements with industrial firms operating in the same technology area. The primary analytic question was, "What impacts do collaborative research programs have on the translation of basic research into commercial products in these technical areas?"

OTA used a methodology intended to "triangulate" a set of results. Primary data and other information were collected from three sources: research-performing organizations, companies that are the clients and collaborators of the research-performing organizations, and former and current government policy makers at the Federal and State level who are familiar with the context in which the collaborative arrangements have been established and managed.

Data collection and analysis were driven by a set of 10 major issues, formulated as follows:

1. What is the evolutionary history of collaborative R&D in terms of stakeholder involvement, initial premises and mission, funding support, and growth? Are these founding issues related to involvement in and success with the commercialization experiences of industry partners?
2. To what extent are industry participants involved at both a policy and management level in the ongoing operations of research-performing organizations? Is this involvement related to an increased level of interaction or commercialization by industry partners, and what are the ways in which programs can become more collaborative?
3. To what extent do commercialization issues influence the policies and practices of research-performing organizations, and how can collaborative R&D programs be made more responsive to the goal of commercialization?
4. What has been the experience and success of industry partners' commercialization of results emanating from collaborative R&D programs, and how does this differ across different types of research-performing organizations and the three technical areas under study?
5. What is the nature of work being done collaboratively with the research-performing or-

ganizations, and to what extent has this work contributed to follow-on R&D by the industry participants or to commercial products and processes?

6. What are the primary obstacles to commercialization in the three technical areas from the perspective of industry participants?
7. How should publicly supported collaborative R&D programs resolve the issue of doing proprietary work for industry participants?
8. Are any programmatic changes needed in the area of intellectual property and patents?
9. What can be done to improve the industry participants' utilization of research results stemming from these collaborative programs?
10. What are the appropriate roles of Federal and State governments in the future design, funding, and operation of collaborative R&D programs?

Selection of Survey Participants

Survey of Research-Performing Organizations

Several key criteria were used by OTA in selecting organizations to participate in the survey of research-performing organizations. The survey was confined to distinct organizational entities, such as institutes or centers, that were engaged in several discrete projects. Organizations were selected that had significant fiscal, intellectual, or contractual involvement with one or more industrial firms, that were judged to be technologically in the upper tier of their field, and that had an experience record of at least 2 to 3 years of operation.

Initially, 22 candidate organizations were identified and contacted. Of these, 3 declined to participate. The final sample of 19 research-performing organizations consisted of 11 in the advanced materials area (including 5 Federal laboratories), 4 in biotechnology, and 4 in information technology. The typical survey respondent in each of the organizations was a program administrator and/or senior scientist. A list of participating organizations is given in table 10-3.

Industrial Participants Survey

As part of the survey of research-performing organizations, respondents at each of the 19 organizations that participated were asked to identify at least two individuals from industry who had a significant ongoing relationship with his or her program. Of these 19 respondents, 2 declined to identify industry personnel, and 2 identified only a single contact each, yielding a potential sample of 32 industry participants. Of these, 10 could not be contacted during the time period for data collection and 3 declined to participate, leaving a final sample of 19 individuals.

The job categories of the industry participants were relatively homogeneous. Of the 19 respondents, 12 functioned as research managers and 7 performed in a business management capacity. A list of the companies represented in the survey is given in table 10-4.

Survey of Government Policy makers

Information was gathered through telephone interviews with nine respondents. Respondents were chosen to reflect a variety of sectors and viewpoints: two State-level administrators of collaborative R&D programs; two policy researchers; two current or former administrators of collaborative R&D programs; two congressional policy analysts; and one current member of the White House science policy staff. The sample was constructed so as to provide a broad-based evaluation of—and expansion on—findings from the other two surveys.

Survey Data and Analysis

For each of the three surveys, an interview protocol was developed consisting of both short-answer and open-ended questions grouped according to the 10 major issue areas described above. The interviews, which lasted from 30 to 90 minutes, yielded a mixture of qualitative and quantitative information, supplemented by written background material supplied by the interviewees. For the qualitative information, a master coding protocol was used to convert the data to nominal (yes/no) form suitable for descriptive statistics. In the survey of policy makers, no formal content analysis procedures were employed; the intent was to capture recurrent themes contained in the interviews rather than to generate quantitative or quasi-quantitative data.

Statistical treatment of the data was primarily descriptive in nature. Some comparative analyses were also performed. The small sizes of the samples precluded more sophisticated analysis. Data presented in the tables in the body of this chapter should be considered as useful abstractions of an essentially qualitative analysis rather than as quantitative or rigorous.