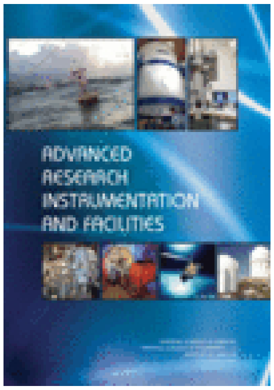

Advanced Research Instrumentation and Facilities

Committee on Advanced Research Instrumentation, National Academy of Sciences, National Academy of Engineering, Institute of Medicine

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THE NATIONAL ACADEMIES
Advisers to the Nation on Science, Engineering, and Medicine

ADVANCED RESEARCH INSTRUMENTATION AND FACILITIES

Committee on Advanced Research Instrumentation

Committee on Science, Engineering, and Public Policy

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NATIONAL ACADEMY OF ENGINEERING, *AND*
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Preface

Forty years ago, Congress asked the National Academies Committee on Science, Engineering, and Public Policy (COSEPUP)—the only joint policy committee of the National Academy of Sciences, National Academy of Engineering, and Institute of Medicine—to look at the relationship between basic research and national goals. That request, from the House Committee on Science and Astronautics in 1964, resulted in the report *Basic Research and National Goals.*[1] One essay in the report pointed out that a side effect of heavy investment in large research facilities is the large cost of operation and maintenance. Another essay addressed the issue of rising cost:

> The costs of scientific research are steadily increasing. It is true that, with the efficient instruments we now have, problems that appeared very formidable many years ago can be solved in a matter of days instead of years, and thus much more cheaply. But we are concerned today with much more difficult problems. These require the full efforts of our investigators aided by the most modern instrumentation. It is the solution of the easy problems and the necessity for facing more difficult ones that makes research more expensive each year.[2]

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[1] Kaysen, C. Allocating federal support for basic research. In *Basic Research and National Goals.* Washington, DC: National Academy of Sciences, 1965, pp. 147-167.

[2] Kistiakowsky, G. B. Allocating support for basic research—and the importance of practical applications. In *Basic Research and National Goals.* Washington, DC: National Academy of Sciences, 1965, pp. 169-188.

Remarkably little has changed since that time, as COSEPUP now responds to a 21st century congressional request for guidance on the issue of instrumentation.

This study is in response to a request from Congress in Section 13(b) of the National Science Foundation (NSF) Authorization Act of 2002, which reads as follows:

> **NATIONAL ACADEMY OF SCIENCES ASSESSMENT ON INTERDISCIPLINARY RESEARCH AND ADVANCED INSTRUMENTATION CENTERS.**
>
> (1) Assessment—Not later than 3 months after the date of enactment of this Act, the Director shall enter into an arrangement with the National Academy of Sciences to assess the need for an interagency program to establish and support fully equipped, state-of-the-art university-based centers for interdisciplinary research and advanced instrumentation development.
>
> (2) Transmittal to Congress.—Not later than 15 months after the date of the enactment of this Act, the Director shall transmit to the Committee on Science of the House of Representatives, the Committee on Commerce, Science, and Transportation of the Senate, and the Committee on Health, Education, Labor, and Pensions of the Senate the assessment conducted by the National Academy of Sciences together with the Foundation's reaction to the assessment authorized under paragraph (1).

A wide array of universities have expressed concerns to Congress in recent years as to the challenge of investing in and finding support for advanced instrumentation used in scientific, engineering, and medical research. The universities highlighted an interest in and a need for the centralization of research equipment on their campuses, but they lacked the resources for that. The desire for concentrating resources has grown as advanced research instrumentation and facilities (ARIF) has grown more powerful, has required additional support, and has been increasingly used by researchers in many fields. Another concern of universities is the potential for direct federal allocation of funds to particular institutions, regions, and fields due to the lack of federal ARIF programs, which can lead to federal support for facilities that are not peer-reviewed and not cost effective.

In January 2004, NSF contacted COSEPUP about conducting this study. Staff of the Senate Committee on Commerce, Science, and Transportation and the House Committee on Science were consulted, and they agreed that a committee addressing the issue should respond to the following questions:

1. What are the current programs and policies of the major federal research agencies for advanced research instrumentation?
2. What is the current status of advanced midsized research instrumentation on university campuses? How are such instruments currently designed, built, funded, operated, and maintained?

3. What challenges do federal agencies and universities identify regarding such instruments?
4. Would an interagency program to fund midsized advanced research instruments that are used by researchers funded by many agencies help respond to these challenges? If so, what should be the components of such a program?
5. Are sufficient federal programs available to provide the intellectual and financial resources necessary to develop new midsized instruments that respond to research community needs?
6. What federal policies could be put into place to enhance the design, building, funding, sharing, operations, and maintenance of mid-sized advanced research instruments?

The committee would propose policies, if needed, to make the most effective use of federal resources to fund such instruments. The instruments are and would be in a broad spectrum of academic institutions.

COSEPUP appointed the Committee on Advanced Research Instrumentation to respond to the call from Congress. The charge to the committee defines ARIF as instrumentation and collections of instrumentation that are supported by neither the NSF Major Research Instrumentation (MRI) program nor the NSF Major Research Equipment and Facilities Construction (MREFC) account. By that definition, ARIF is distinguished by capital costs ranging from $2 million to several tens of millions of dollars. A more comprehensive definition of ARIF is put forth by the committee in Chapter 2 of this report. The committee includes all scientific and engineering research fields—including the physical sciences, life sciences, engineering, and social sciences—within the scope of the study.

This study is intended to complement a request in Section 13(a) of the NSF Authorization Act of 2002 for NSF to "conduct a review and assessment" of the MRI program. The MRI program largely excludes support of the instrumentation discussed in this report, although it is capable of partially funding ARIF. NSF is involved in a 5-year effort to design and implement a method for collecting data on science and engineering research instrumentation as part of its study.

The present report also complements two other recent COSEPUP reports that address related issues. *Setting Priorities for Large Research Facility Projects Supported by the National Science Foundation*[3] examined NSF's MREFC account and recommended that the National Science Board (NSB) oversee a process whereby NSF

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[3] National Research Council. *Setting Priorities for Large Research Facility Projects Supported by the National Science Foundation*. Washington, DC: National Academies Press, 2004.

would produce a roadmap for large research facilities that it is considering for construction over the next 20 years; it also provided a set of overlapping criteria that should be used to set priorities among proposals for those projects. *Facilitating Interdisciplinary Research*,[4] part of the Keck Futures Initiative, recommended ways for funding organizations, university administrators, researchers, students and postdoctoral scholars, professional societies, and journal editors to take steps to realize the full potential of interdisciplinary research.

To respond to its charge, the committee sent surveys to university administrators; to scientific, engineering, and medical disciplinary societies; to independent research institutions; to national and federal laboratories; and to researchers. The surveys requested information on current ARIF (obtained in the last 5 years) and ARIF needs (anticipated in the next 5 years). In addition, the surveys gathered information on the opportunities and challenges that institutions, facilities, and researchers face with regard to instrumentation, including suggestions for possible federal policy changes.

The committee met or interviewed agency officials of NSF, NSB, the National Institutes of Health (NIH), the Department of Energy, the National Oceanic and Atmospheric Administration, the Department of Homeland Security, the US Department of Agriculture, the White House Office of Science and Technology Policy, and the National Science and Technology Council (NSTC).

As a result of its deliberations, the committee believes that, owing to the importance of ARIF, it should be elevated by NSTC as a subject of interagency coordination and cooperation; that would enable federal agencies to leverage their resources and thus have the greatest possible impact in responding to the needs of the nation's research communities. The committee does not see a need for "an interagency program to establish and support fully equipped, state-of-the-art university-based centers for interdisciplinary research and advanced instrumentation development."

The committee found that there is a critical gap in federal programs for ARIF and that federal agencies should pay more attention to ARIF than they do now. The committee also recommends that all federal research agencies create, maintain, and clearly document programs that allow researchers to submit requests for ARIF. In addition, the committee recommends that NSF and NIH increase or eliminate the capital cost limit of $2 million on proposals now accepted in their agencywide instrumentation programs and permit requests for operation and maintenance costs and that NIH re-evaluate the balance between support for ARIF

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[4] National Research Council. *Facilitating Interdisciplinary Research.* Washington, DC: National Academies Press, 2004.

and for research and increase its investment in instrumentation. Technical research support staff are vital for ARIF, and the committee recommends increased recognition and support at both the academic level and the federal level.

By taking those steps, the nation will be able to optimize its investments in instrumentation for research. Instrumentation is the key to the advancement of scientific, engineering, and medical research and to the development of new and improved technologies. The continued competitiveness of our nation's research depends critically on the tools we have available.

Martha Krebs
Chair
Committee on Advanced Research Instrumentation

Acknowledgments

This report is the product of many people. First, we thank all those who spoke at our committee meetings (in alphabetical order):

ARDEN BEMENT, Director, National Science Foundation
NORMAN BRADBURN, Tiffany and Margaret Blake Distinguished Service Professor Emeritus, University of Chicago
NORKO RUIS BRAVO, Deputy Director for Extramural Research, National Institutes of Health
JERRY BRIDGES, Chair, Costing Policies Subcommittee, Council on Government Relations, Controller, Johns Hopkins University
DAN BYERS, Staff Director, House Committee on Science, Subcommittee on Research
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JEAN TOAL EISEN, Senior Professional Staff Member, Senate Committee on Commerce, Science, and Technology
ANITA JONES, Lawrence R. Quarles Professor of Engineering and Applied Science, University of Virginia; and Former Chair, Committee on Programs and Plans, National Science Board

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NATHANIEL PITTS, Director, Office of Integrative Activities, National Science Foundation
DONALD TENNANT, Distinguished Member of the Technical Staff, New Jersey Nanotechnology Consortium and Lucent Technologies

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Thanks go to institutions that responded to the survey (in alphabetical order):

Arkansas, Little Rock, University of
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Auburn University
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Brandeis University
Brown University
California, Berkeley, University of
California, Irvine, University of
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Carnegie Institution of Washington
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North Carolina, Greensboro, University of
Northern Illinois University
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Pennsylvania State University
Princeton University
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Rice University
Rutgers University
San Diego State University
Syracuse University
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Texas A&M-Health Science Center
Texas, Austin, University of
Washington State University
Washington University, St. Louis
Wayne State University
Wisconsin-Madison, University of

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Laboratory of Membrane Biochemistry and Biophysics, National Institute on Alcohol and Alcoholism, National Institutes of Health
National Marine Fisheries Service, National Oceanic and Atmospheric Administration
Oak Ridge National Laboratory
Princeton Plasma Physics Laboratory
Science Directorate, National Aeronautics and Space Administration
Southwest Fisheries Science Center, National Oceanic and Atmospheric Administration

In addition, we thank the disciplinary societies that responded to our survey. Note that staff from some of the disciplinary societies responded to the survey as individuals with a broad view of the status and needs of their field and not as representatives of their society. The disciplinary societies are (in alphabetical order):

American Astronomical Society
American Chemical Society
American Physical Society
    Division of Condensed Matter Physics
    Division of Particles and Fields
American Political Science Association
American Society for Mass Spectrometry
American Society of Plant Biologists
Federation of Materials Societies

The committee also thanks the individual researchers who responded to our survey. Without their input in addition to the input from institutions, this report would not have been possible.

Next, we would like to thank the reviewers of this report. This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Academies' Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the process.

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Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Pierre Hohenberg, New York University, and R. James Cook (Retired), Washington State University. Appointed by the National

Academies, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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Summary

Research instruments have revolutionized how we look at the world, refining and extending the range of our senses. From the beginnings of the enlightenment, development of the modern scientific method, with its emphasis on testable hypotheses, required the ability to make ever more accurate measurements. Instruments for research continue to grow more and more sophisticated. The Committee on Advanced Research Instrumentation was created to determine what federal policies could be put into place to enhance the design, building, funding, sharing, operation, and maintenance of advanced research instruments.

KEY RECOMMENDATIONS

On the basis of its deliberations and the fundamental importance of instrumentation to research, **the committee recommends that each federal research agency**[1] **establish centralized, transparent, and peer-reviewed programs for advanced research instrumentation and facilities** (ARIF) **that publicly solicit proposals.**[2] In particular, **the National Science Foundation** (NSF) **should expand**

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[1] The committee designates the following as federal research agencies: the National Science Foundation, the National Institutes of Health, the Department of Energy, the US Department of Agriculture, the National Oceanic and Atmospheric Administration, the National Aeronautics and Space Administration, the Department of Defense, and the Department of Homeland Security.

[2] See R4-3 of this report.

its Major Research Instrumentation program so that it includes ARIF whose capital costs are greater than $2 million but that are not appropriate for NSF's Major Research Equipment and Facilities Construction account, which handles facilities that cost hundreds of millions of dollars.[3] In addition, **the National Institutes of Health should eliminate the $2 million proposal cap in its High End Instrumentation program, re-examine the balance between support of ARIF and support of research grants, and substantially increase its instrumentation investment.**[4]

Each federal research agency ARIF program should require that proposals contain a business and management plan that includes information on space, technical staffing, and the long-term source of funding for operation and maintenance.[5] **These programs should support operation and maintenance costs when requested by institutions** and use proposal evaluation criteria that enhance the geographic distribution, sharing, and efficient use of instrumentation. When it is appropriate, agencies should encourage researchers to present proposals to multiple agencies simultaneously. To capitalize on federal investments in instrumentation and to ensure that ARIF are effective and productive, **each federal research agency should establish career development and support programs for the PhD-level technical research support staff vital to ARIF.**[6]

INTRODUCTION TO INSTRUMENTATION

In recent years, the instrumentation needs of the nation's research communities have changed and expanded.[7] The need for particular instruments has become broader, crossing scientific and engineering disciplines. The growth of interdisciplinary research that focuses on problems defined outside the boundaries of individual disciplines demands more instrumentation. Instruments that were once of interest only to specialists are now required by a wide array of scientists to solve critical research problems. The need for entirely new types of instruments—such as distributed networks, cybertools, and sensor arrays—is increasing. Researchers are increasingly dependent on advanced instruments that require highly specialized knowledge and training for their proper operation and use.

This study is in response to a request from Congress in Section 13(b) of the 3-year National Science Foundation Authorization Act of 2002 to assess the need

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[3] See R4-6 of this report.

[4] See R4-7 of this report.

[5] See R4-3 of this report.

[6] See R4-5 of this report.

[7] See F1-1 of this report.

for an interagency program to establish and support fully equipped, state-of-the-art university-based centers for interdisciplinary research and advanced instrumentation development.

The National Academies Committee on Science, Engineering, and Public Policy Committee on Advanced Research Instrumentation was asked to describe the current programs and policies of the major federal research agencies for advanced research instrumentation, the current status of advanced mid-sized research instrumentation on university campuses, and the challenges faced by each. The committee was then asked to evaluate the utility of existing federal programs and to determine the need for and, if applicable, the potential components of an interagency program for advanced research instrumentation.

The committee first developed a term, advanced research instrumentation and facilities, to describe the aforementioned set of activities. ARIF is defined as instrumentation and facilities housing closely related or interacting instruments and includes networks of sensors, databases, and cyberinfrastructure.[8] ARIF is distinguished from other types of instrumentation by its expense, and in that it is commonly acquired by large-scale centers or research programs rather than individual investigators. The acquisition of ARIF by an academic institution often requires a substantial institutional commitment and depends on high-level decision-making at both the institution and federal agencies. ARIF at academic institutions are often managed by institution administration. Furthermore, the advanced nature of ARIF often requires expert technical staff for its operation and maintenance.

METHOD

In responding to its charge, the committee spoke with federal government officials and members of the science and technology policy community, and it surveyed academic institutions, researchers, disciplinary societies, and federal laboratories.

KEY FINDINGS

On the basis of the information gathered, the committee found that there is a critical gap in federal programs for ARIF. Although federal agencies do have instrumentation programs, few allow proposals for instrumentation when the capital cost is greater than $2 million. No federal research agency has an agencywide ARIF program.

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[8] See R2-1 of this report.

Instrumentation programs are inadequately supported. Few provide funds for continuing technical support and maintenance.[9] The programs tend to support instrumentation for specific research fields and rarely consider broader scientific needs.[10]

The shortfalls in funding for instrumentation have built up cumulatively and are met by temporary programs that address short-term issues but rarely long-term problems. The instrumentation programs are poorly integrated across (or even within) agencies. The ad hoc ARIF programs are neither well organized nor visible to most investigators, and they do not adequately match the research community's increasing need for ARIF.

RECOMMENDED FEDERAL AGENCY ACTIONS

The committee believes that each major federal research agency should enhance its ARIF policy. Some specific measures have been mentioned above. The committee's proposed federal policy enhancements are in three categories:

- Program establishment and centralization.
- Proposal processing and transparent opportunities.
- PhD-level technical research support staff career development and support programs.

In the case of program establishment and centralization, the committee believes that *each federal research agency* should create more clear opportunities for researchers to propose ARIF for federal funding by establishing centralized, transparent ARIF programs. The agencies should determine the appropriate balance between instrumentation and research grants and, in all instrumentation programs, determine the appropriate balance between small-, mid-, and large-scale instrumentation and facilities; sustain support for ARIF programs even when agency funding levels are stagnant or declining; and coordinate with ARIF programs at other agencies.

RECOMMENDED MULTIAGENCY ACTIONS

The committee recommends that the White House Office of Science and Technology Policy (OSTP), as part of its National Science and Technology Council

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[9] See F4-2 and F4-6 of this report.

[10] See F4-4 of this report.

(NSTC) activities, enhance federal research agency coordination and cooperation with respect to ARIF.[11] The NSTC can serve as a mechanism for federal agencies to work together to develop joint solicitations, invite researchers from diverse disciplines to present opportunities for ARIF that would be useful to many fields to multiple agencies simultaneously, seek out and identify best practices, and discuss the appropriate balance of funding among people, tools, and ideas, which could become part of the regular White House Office of Management and Budget-OSTP budget memorandum. The committee does not believe that there is a need for an interagency program to establish and support fully equipped, state-of-the-art, university-based centers for interdisciplinary research and development of advanced instrumentation.

RECOMMENDED ACADEMIC INSTITUTION ACTIONS

The committee believes that academic institutions' policies regarding ARIF can be enhanced.[12] Academic institutions should review their internal financial support and their planning and budgeting processes for ARIF to ensure that funds are identified to support the instrumentation properly, including operation and maintenance costs, technical staff support, and space. The funding and management of ARIF should be structured so that they are institutionwide, inasmuch as most ARIF are used by more than one research field in multidisciplinary and interdisciplinary research. Academic institutions should work to enhance the career paths of ARIF technical research support staff by placing such staff in long-term, regular positions. Finally, academic institutions should continue to discuss the issue of federal agency support for operation and maintenance costs of instruments with the NSTC's Research Business Models Subcommittee.

CONCLUSION

The health and progress of the science and technology research enterprise depend on many types of instrumentation, including the advanced instrumentation and facilities discussed in this report. By taking the actions recommended in this report, the nation will optimize its investment in research and thus the benefits that research provides to society.

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[11] See R4-8 of this report.

[12] See Recommendations in Chapter 3 of this report.

1

Introduction

Instruments are the key to the advancement of scientific, engineering, and medical research and the development of new and improved technologies. Progress in research impacts every aspect of our modern lives—from agriculture and health to national and homeland security. Instrumentation is a critical component of the research enterprise and thus is in part responsible for the benefits that research brings to society. The National Academies Committee on Advanced Research Instrumentation was charged with examining the nation's investment in instrumentation and determining whether an interagency program to promote the development of new instruments is warranted.

HISTORICAL ROOTS

This study followed a tradition of instrumentation assessments.[1] Many of the issues identified in the past still resonate. The first National Science Foundation (NSF) study on federal funding of scientific instruments and facilities occurred in 1954 and resulted in a discussion of the need for facilities and equipment in NSF's 1955 and 1956 annual reports. The following, from the 1956 annual report is of particular note:

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[1] Much of this section is based on Stine, J. K., and G. A. Good. Government funding of scientific instrumentation: A review of U.S. policy debates since World War II. *Science, Technology and Human Values* 11(3):34-46, 1986.

> To the increased need for basic research and the training of scientists, we must add the urgent need for general research equipment to supplement and replace the obsolete equipment now in use. For that matter, there is a great need to renovate research facilities of all kinds at colleges and universities.[2]

The National Academies first examined the issues surrounding instrumentation in 1964 at the request of the House Committee on Science and Astronautics. The National Academy of Sciences Committee on Science and Public Policy (today's Committee on Science, Engineering, and Public Policy) was tasked to address the subject of instrumentation. The resulting report, *Basic Research and National Goals*, included two essays that discussed the rising cost of instrumentation[3] and how heavy investment in large research facilities was accompanied by rising operation and maintenance costs.[4] In 1970, the National Science Board (NSB) stated in its recommendations to Congress that

> The acquisition and construction of new instrumentation is the pacing item for research in much of the physical science. . . . Expensive research facilities, including instrumentation, should be established as national or regional resources. . . . Federal agencies should be prepared to bear part of the added cost of utilization of such facilities as a trade-off against duplicating facilities and expensive instrumentation at additional locations.[5]

In 1971, NSF and the National Academies conducted a joint study that examined instrumentation needs in 10 fields of science. Throughout the 1970s and 1980s, a number of reports, largely from the Association of American Universities, highlighted an increased need for capital investment in instruments.

NSF conducted four comprehensive national surveys of academic research instrumentation in the period 1982-1993. Information on the status and funding of instruments and the operations, maintenance, and repair costs were collected. Results highlighted the differing requirements of various research fields and enabled NSF to assess the needs of the nation's research communities.

The most recent NSF assessment, the 1993 Survey of Academic Research Instruments and Instrumentation Needs, surveyed instruments with capital costs

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[2] Waterman, A. T. The director's statement. In *Sixth Annual Report for the Fiscal Year Ended June 30, 1956.* Arlington, Va.: National Science Foundation, 1956.

[3] Kistiakowsky, G. B. Allocating support for basic research—and the importance of practical applications. In *Basic Research and National Goals.* Washington, DC: National Academy of Sciences, 1965, pp. 169-188.

[4] Kaysen, C. Allocating federal support for basic research. In *Basic Research and National Goals.* Washington, DC: National Academy of Sciences, 1965, pp. 147-167.

[5] National Science Board and National Science Foundation. *The Physical Sciences: Report of the National Science Board Submitted to the Congress, 1970.* Washington, DC: US Government Printing Office, 1970.

TABLE 1-1 NSF Future Infrastructure Needs, FY 2003-2012

Range of Project Cost, millions of dollars	Total, millions of dollars	Percent
1-10	3,950	20
11-50	5,400	29
51-250	6,800	37
251-500	1,700	9
>500	1,000	5
All projects	18,850	100

Source: National Science Board (2003).

of $20,000 or more (1993 dollars) in agriculture, biology, computer science, environmental sciences, chemistry, physics and astronomy, and engineering at medical and nonmedical university laboratories and laboratories managed by universities. The survey assessed the condition and age of the instruments, their capital cost, and annual expenditures on their maintenance and repair. The survey[6] found that 22% of the instrument expenditures was for instruments that cost $1 million or more. The federal government supported about half the total cost of the instruments reported in the survey, and academic institutions about 30%.

More recently, an NSB report[7] recommended that a larger portion of the NSF budget be devoted to infrastructure, including instrumentation. The board highlighted an outstanding need for the support of midsize infrastructure, including, in the present committee's terminology, advanced research instrumentation and facilities (ARIF). Table 1-1 excerpts a 10-year projection of future science and engineering (S&E) infrastructure needs. From data provided by each of the NSF directorates and the Office of Polar Programs, the board estimated a funding need of $18.9 billion over the next 10 years.[8] For FY 2003-2012, the NSB estimated a need for $3.95 billion for infrastructure projects that each cost between $1 million and $10 million; assuming an even distribution, that translates to 646 infrastructure projects of over $2 million each over 10 years—about 65 per year. In the range of $11 million to $50 million, the NSB reports a need of $5.4 billion over 10 years and thus roughly 177 projects total—18 per year—assuming the projects cost $30.5 million on average. The number of estimated projects is in line with the results of the present committee's survey of academic institutions.

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[6] National Science Foundation. *Characteristics of Science and Engineering Instrumentation in Academic Settings: 1993.* NSF 98-311. Arlington, Va.: National Science Foundation, 1998.

[7] National Science Board. *Science and Engineering Infrastructure for the 21st Century: The Role of the National Science Foundation.* Arlington, Va.: National Science Foundation, 2003.

[8] The NSB did not assess or formally endorse this estimate.

According to the NSB report, many NSF directorates identified a midsize infrastructure (capital cost, millions to tens of millions) funding gap. The NSB identified several high-priority but unfunded instruments and projects that fall into that gap, including incoherent scatter radar, replacement of an Arctic regional research vessel, replacement or upgrade of submersibles, beamline instrumentation for neutron science, and major upgrades of computational capability. According to the NSB, in many cases midsize instruments and projects do not fall under NSF's Major Research Equipment and Facilities Construction (MREFC) account because they combine research and instrumentation construction. The board noted that these projects are essential to the nation's research enterprise, citing the magnetic resonance imager and laser eye surgery, which had their start in research on advanced instrumentation.

The NSB directed NSF to increase its infrastructure investment from 22% to the high end of the historical range (22-27%). That resulted in changes in the NSF tools budget as shown below:

- FY 2002 tools: $1.1 billion (22%)
- FY 2005 tools: $1.4 billion (25.7%)
- PB[9] 2006 tools: $1.5 billion (27.4%)

The board requested that NSF use the funds in part to advance instrument technology, address the increased need for midsize infrastructure, increase support for large facility projects (otherwise known as MREFC), and deploy advanced cyberinfrastructure. The infrastructure report also recommended that NSF expand education and training opportunities at new and existing research facilities for K-12 students and teachers, undergraduates, graduate students, and mature researchers to educate people in how S&E instruments and facilities work.

Figure 1-1 shows the funding provided in the general NSF "tools" category, which includes all types of equipment, instrumentation, and facilities, and in the MREFC and Major Research Instrumentation (MRI) categories.

Anita Jones, a former member of the NSB who helped develop the NSB infrastructure report, offered the following personal observations in her presentation to the committee:[10]

- Midsize infrastructure rarely stands alone. Both midsize and large infrastructure typically require staff for effective use.

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[9] PB = President's budget as submitted to Congress.

[10] Jones, A. Mid-sized infrastructure for science and engineering as viewed by the National Science Board. Presentation to the Committee on Advanced Research Instrumentation, February 22, 2005.

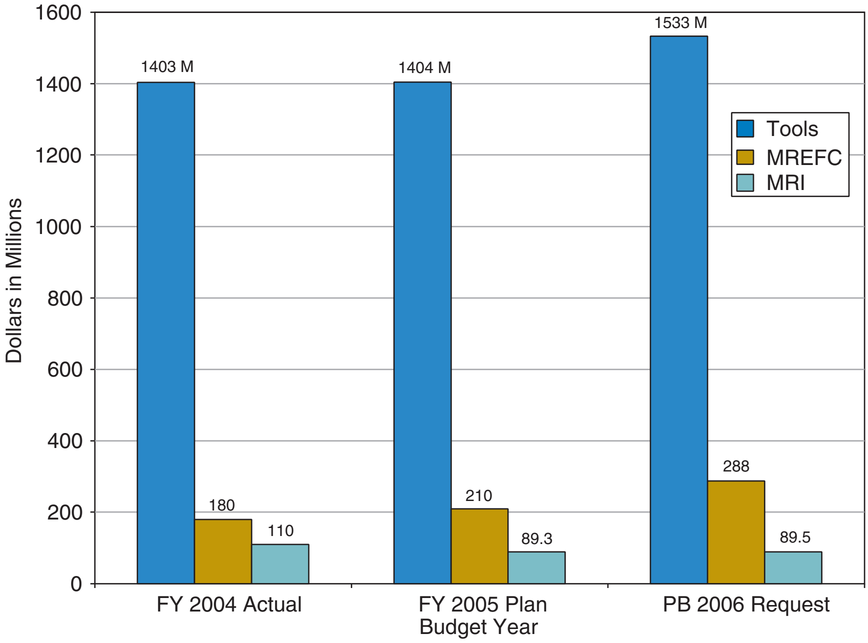

FIGURE 1-1 National Science Foundation Tools, Major Research Equipment and Facilities Construction (MREFC), and Major Research Instrumentation (MRI) budgets, FY 2004-2006.
Source: Analysis by committee of data from National Science Foundation (2005).

- The lag between proposal and funding of both midsize and large facilities debilitates research progress.
- Cyberinfrastructure is a major issue for academic researchers because NSF invests more in the "high middle end" of computation than in software tools or high-performance cyberfacilities. Furthermore, security restrictions and processes present obstacles for academics who wish to use Department of Energy (DOE) and Department of Defense (DOD) high-performance computing facilities.
- The organization of distributed resources is lagging.
- The cost of infrastructure per principal investigator is increasing in all categories, and there is competition between the need for funding for infrastructure and for students.
- It is unknown whether instrument research is sufficiently vigorous.

- For NSF, new kinds of midsize infrastructure include long-lived (digital) data collections, which have a propensity to become permanent rather than retiring and therefore involve large continuing investments.

Other recent federal government reports include a 1995 National Science and Technology Council study, which stated that academic research infrastructure needs substantial renewal and provided a conservative cost estimate of $8.7 billion for facilities and instrumentation,[11] a 1998 NSF survey of academic research facilities, which estimated the cost of deferred capital projects to be $7 billion for the construction of new facilities and $4.4 billion for the repair or renovation of existing facilities,[12] and a 2001 report to the director of the National Institutes of Health (NIH), which found that $5.6 billion was needed for biomedical research equipment.[13]

According to the 2004 NSB S&E indicators report, about $1.5 billion was spent for academic research equipment in 2001. The federal government share in research equipment expenditures declined from about 62% to 55% from 1983 to 2001. The funds spent for academic research equipment on the average over the past 5 documented years (1997-2001) were concentrated in three fields: life sciences (41%), engineering (23%), and physical sciences (18%).

HOW IS INSTRUMENTATION DIFFERENT TODAY IN ITS USE?

Since the last survey of instruments was conducted over a decade ago, the instrumentation needs of the nation's research communities have changed. A need for entirely new types of instruments—such as networks, computational tools, surveys, and distributed sensor systems—has emerged. And the need for particular types of instruments and facilities has broadened, crossing scientific, engineering, and medical disciplines; instruments that were once of interest only to specialists are now required by scientists in a wide array of disciplines to solve critical research problems.

As instrumentation has grown more and more complex, research has become increasingly dependent on instruments that require highly specialized knowledge

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[11] National Science and Technology Council. *Final Report on Academic Research Infrastructure: A Federal Plan for Renewal*. Washington, DC: National Science and Technology Council, March 17, 1995.

[12] Division of Science Resources Statistics. *Science and Engineering Research Facilities at Colleges and Universities, 1998*. NSF-01-301. Arlington, Va.: National Science Foundation, October 2000.

[13] Working Group on Construction of Research Facilities. *A Report to the Advisory Committee of the Director*. Washington, DC: National Institutes of Health, July 6, 2001.

and training for their proper use. The problem-oriented approach to research often demands bringing many different techniques to bear on a research question. As a consequence, demand for a number of particular advanced instruments has increased. The advanced instruments are often required by a number of users who are not well versed in their effective use.

Many different types of technical staff are vital to instrumentation. Specialists in electronics and machining, for example, are often highly involved in instrument development and in the modification and enhancement of existing instruments. Although such specialists are quite important, the committee wishes to emphasize the particular problem of the career paths of technical research support staff who maintain, operate, and manage existing instrumentation. The committee refers to such personnel as PhD-level technical research support staff to emphasize their involvement in research and the advanced nature of their work. Because of the increasingly complex nature of instrumentation and the scope of their duties, such staff often require a high level of education. A doctorate is not requisite, but the support of advanced instruments often demands an equivalent level of skill.

OVERVIEW OF REPORT

As discussed in the preface, the purpose of this study is to examine current federal programs and policies for the acquisition and development of advanced research instrumentation and the status of such instruments on university campuses and to determine whether an interagency instrumentation program is warranted. Chapter 2 of this report describes the significance of instrumentation and provides a definition of ARIF and examples of ARIF in various fields. Chapter 3 presents an overview of the issues regarding instrumentation and ARIF in particular at academic institutions. Chapter 4 provides information on the instrumentation funding practices of various federal agencies: NSF, NIH, DOE, the National Aeronautics and Space Administration, DOD, the Department of Homeland Security, the US Department of Defense, the US Department of Agriculture, and the National Oceanic and Atmospheric Administration. NSF is of particular focus, because this study has its origins in the NSF Authorization Act of 2002. Chapter 5 summarizes the committee's findings and recommendations for making the most effective use of federal resources for ARIF by providing responses to each of the questions in its charge.

FINDINGS

F1-1: In recent years, the nature of S&E research has changed dramatically, as have the instruments that support and advance this research. In addition to many other factors, the rise in interdisciplinary research, with its focus on large-scale problems that require a variety of techniques, demands more advanced instrumentation. As a result,

- The need for particular instruments has broadened, crossing scientific and engineering disciplines.
- Instruments that were once of interest only to specialists are required by a wide array of scientists to solve critical research problems.
- The need for new types of instruments—such as distributed networks, cybertools, longitudinal surveys, and sensor arrays—is increasing.
- Researchers have become increasingly dependent on advanced instruments that require highly specialized knowledge and training for their proper use and greatest effectiveness.

F1-2: According to the 2003 NSB infrastructure report, over $9 billion will be required in FY 2003-2012 for infrastructure projects that each cost between $1 million and $50 million.

F1-3: According to the 2004 NSB S&E indicators report, the share of research equipment expenditures funded by the federal government declined from about 62% to 55% from 1983 to 2001.

F1-4: The funds spent for academic research equipment on the average over the last 5 documented years (1997-2001) were concentrated in three fields: life sciences (41%), engineering (23%), and physical sciences (18%), according to the 2004 NSB S&E indicators report.

F1-5: Because federal agencies use different metrics to track their expenditures, it is difficult to make quantitative comparisons of agency investments in instrumentation. However, it is clear that NIH devotes a much smaller fraction of its research budget to instrumentation than NSF does.

2

Introduction to Instrumentation

This chapter introduces the subject of instrumentation in general; defines the particular instrumentation that is the subject of this report, advanced research instrumentation and facilities (ARIF); and gives examples of ARIF used in various fields.

WHAT IS INSTRUMENTATION, AND WHY IS IT IMPORTANT?

Instruments have revolutionized how we look at the world and refined and extended the range of our senses. From the beginnings of the development of the modern scientific method, its emphasis on testable hypotheses required the ability to make quantitative and ever more accurate measurements—for example, of temperature with the thermometer (1593), of cellular structure with the microscope (1595), of the universe with the telescope (1609), and of time itself (to discern longitude at sea) with the marine chronometer (1759). Instruments have been an integral part of our nation's growth since explorers first set out to map the continent. The establishment of the US Geological Survey had its roots in the exploration of the western United States, and its activities depended critically on advanced surveying instruments.

A large fraction of the differences between 19th century, 20th century, and 21st century science stems directly from the instruments available to explore the world. The scope of research that instrumentation enables has expanded considerably, now encompassing not only the natural (physical and biologic) world but also many facets of human society and behavior. Instrumentation has often been cited as the pacing factor of research; the productivity of researchers is only as great as the tools they have available to observe, measure, and make sense of nature. As one of the committee's survey respondents commented,

> without continued infrastructure support. . . . We will see many young investigators changing the nature of the projects and science they do to areas that have less impact but assure better chances of success. The lack of instruments or the ability to upgrade aging local facilities simply dictates the science done in the future.[1]

Cutting-edge instruments not only enable new discoveries but help to make the production of knowledge more efficient. Many newly developed instruments are important because they enable us to explore phenomena with more precision and speed. The development of instruments maintains a symbiotic relationship with science as a whole; advanced tools enable scientists to answer increasingly complex questions, and new findings in turn enable the development of more powerful, and sometimes novel, instruments.

Instrumentation facilitates interdisciplinary research. Many of the spectacular scientific, engineering, and medical achievements of the last century followed the same simple paradigm of migration from basic to applied science. For example, as the study of basic atomic and molecular physics matured, the instruments developed for those activities were adopted by chemists and applied physicists. That in turn enabled applications in biological, clinical, and environmental science, driven both by universities and by innovative companies. A number of modern tools that are now essential for medical diagnostics, such as magnetic resonance imaging scanners, were originally developed by physicists and chemists for the advancement of basic research.

WHAT IS "ADVANCED RESEARCH INSTRUMENTATION AND FACILITIES"?

Borrowing from the terminology used by Congress in its request, the committee's study focuses on the issues surrounding a particular category of instruments and collections of instruments, referred to as advanced research instrumentation and facilities. In the charge to the committee, ARIF is defined as instrumentation with capital costs between $2 million and several tens of millions of dollars. In that range, there is no general instrumentation program at either the

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[1] Pettitt, Montgomery. Response to Committee Survey on Advanced Research Instrumentation, 2005.

National Science Foundation (NSF) or the National Institutes of Health (NIH), yet they are the primary federal agencies that support instrumentation for research outside the national laboratories. The instruments and facilities in this price range fall under neither NSF's Major Research Instrumentation program nor its Major Research Equipment and Facilities Construction account. The committee found that there are no general ARIF programs at the other federal funding agencies.

The committee identifies other characteristics of ARIF that should be part of its definition. Many qualities distinguish ARIF from more easily acquired instrumentation. The capital cost of ARIF is not its distinguishing factor, and thus many of the characteristics of and challenges associated with ARIF may apply to instruments and facilities costing less than $2 million. ARIF are

- *Difficult for individual investigators to obtain* and more commonly acquired by large-scale centers or research programs; it is often necessary to have the consensus of a field when attempting to find support for such an instrument or collection of instruments.
- *Often in need of a substantial institutional commitment* for its acquisition, including the availability of proper space and continued upkeep. Multiple federal and nonfederal sources are needed to meet the initial acquisition cost, but the costs of operation and maintenance often require a substantial and long-term financial commitment from the host institution. Many academic institutions—even major research universities—have no ARIF, and institutions that do have ARIF generally have no more than a handful of such instruments or facilities.
- *Often dependent on PhD-level technical research support staff* to ensure that researchers are able to take full advantage of the unique capabilities of the instrument and to keep them in proper operating condition.
- *Dependent on relatively high-level decision-making.* The investment process for ARIF is likely to include the head of a directorate of NSF, a division or directorate external advisory committee, and the vice-president or vice-provost of research at a university. Identifying or renovating appropriate space for an instrument may require the approval of a university provost or president.
- *Managed by institutions, not individual investigators,* because their administration requires a large financial commitment.
- *Often funded in ways that cannot be easily tracked.* Acquiring instruments and facilities often requires multiple sources of funding to meet the initial capital cost. As a result, it is difficult to obtain an accurate picture of contributions of institutions, states, federal agencies, and other supporters.

> "Advanced research instrumentation provides a technological platform to answer the hardest, unanswered questions in science. An investment on the order of magnitude of 10 or 100 million dollars will pay off many times over if it opens up opportunities to discover new sources of energy, cures for diseases, etc. Beyond potential revenue generating applications, having access to advanced research instrumentation also opens up avenues for fundamental discoveries, the implications of which may be currently unfathomable."
>
> Melissa L. Knothe Tate
> Associate Professor
> Case Western Reserve University
> Response to Committee Survey on Advanced Research Instrumentation

ARIF includes both commercially available instruments and specially designed and developed instruments and both physical and nonphysical tools. Specially developed instruments are assembled from many less expensive components to make a new, more advanced and powerful instrument. ARIF may be single standalone instruments, networks, computational modeling applications, computer databases, systems of sensors, suites of instruments, and facilities that house ensembles of interrelated instruments. A number of different funding mechanisms support the wide diversity of ARIF.

ARIF can be loosely categorized in two distinct types of use. Some are "workhorse" instruments, essential to everyday research and training. Others are "racehorse" instruments, newly developed or constantly developing, that are perched on the cutting edge of research. Racehorse instruments, because they are novel, are often easier to justify to potential funders. Both workhorse and racehorse instruments are vital for research, and finding the right balance between the two is a challenge.

The "facilities" portion of "ARIF" was incorporated by the committee to emphasize that some research fields and problems require collections of advanced research instrumentation. As has been described earlier, the changing face of research has demanded that a wide array of instruments be brought to bear on a single problem. Collections of instruments are often essential for meaningful research to occur. To solve some types of scientific problems or to engineer new materials, multiple instruments are necessary to carry out a series of steps or processes. Complementary instruments are more effective when housed side by side and may be far more productive than each one is individually.

Historically, centralized facilities have played a large role in research involving

ARIF instrumentation by consolidating resources, increasing collaboration, and making available rare or unique resources to a large number of users. Most publicly funded centralized facilities are located at universities and national laboratories. The state of US research facilities is often cited as an indicator of the nation's long-term international competitiveness in research. For example, a 2000 National Academies Committee on Science, Engineering, and Public Policy study of materials facilities noted that "rapid advances in design and capabilities of instrumentation can create obsolescence in 5–8 years." The study further noted that the overall quality of characterization services provided by materials facilities supporting universities and industry had "lost substantial ground" to Japan and Europe.[2] The committee distinguishes between *facilities* and *centers.* A center is defined as a collection of investigators with a particular research focus. A facility is defined as a collection of equipment, instrumentation, technical support personnel, and physical resources that enables investigators to perform research.

In referring to ARIF, the committee excludes facilities that house large assemblies of unrelated or only loosely related equipment and that generally require no targeted support staff. Different research fields require different types of ARIF, and some fields have a larger demand for ARIF than others. ARIF are not distinguished by the diversity of research fields or geographic regions it supports.

EXAMPLES OF ARIF

The research community recognizes the importance of instruments. The National Science Board (NSB) recently identified eight Nobel prizes in physics that were awarded for the development of new or enhanced instrumentation technologies, including electron and scanning tunneling microscopes, laser and neutron spectroscopy, particle detectors, and the integrated circuit.[3] Nobel prizes for the development of instrumentation have been awarded in chemistry and medicine for instrumentation related to nuclear magnetic resonance (NMR) or magnetic resonance imaging, and many were also awarded at least in part for the development of ARIF. Many of the ground-breaking instruments that qualified for a Nobel prize or contributed to Nobel prize-winning work began as ARIF and through development have become widely available and more affordable.

Table 2-1 lists the types of ARIF reported to the committee in its survey of institutions. The results of this survey are known to be incomplete and not repre-

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[2] National Academies. *Experiments in International Benchmarking of U.S. Research Fields.* Washington, DC: National Academy Press, 2000.

[3] National Science Board. *Science and Engineering Infrastructure for the 21st Century: The Role of the National Science Foundation.* Arlington, Va.: National Science Foundation, 2003.

TABLE 2-1 Examples of ARIF, by Field

Field	Selected Instruments or Facilities	Capital Cost (millions of $)
Astronomy	Telescope, spectrograph, infrared camera for Magellan	3.9-5
Biology	Proteomics-protein structure laboratory	2.7
Cyberinfrastructure	Supercomputer	2.0-5.0
Geosciences	Ion microprobe, earthquake sensor testing laboratory	2.8-3.8
Materials	Electron-beam lithography system, semiconductor production system	2.3-2.5
Human and animal imaging	Magnetic resonance imager, human and animal	2.2-2.8
Spectrometry (NMR)	NMR spectrometer, 800-900 MHz	2.2-4.8
Physics	Infrared camera, pulsed electron accelerator	2.0-15.0
Space	MegaSIMS (isotope analysis)	3.5
Facility-supporting equipment	Helium refrigerator supplying helium for superconducting magnets at the National Superconducting Cyclotron Laboratory	2.9

Source: Committee on Advanced Research Instrumentation survey of academic institutions, 2005.

sentative of the state of ARIF on university campuses. Notably absent from this table, for example, are cybertools other than supercomputers, which cost much to develop but little to use. Computer modeling programs are used often by the chemistry and biology community. The cost of acquiring these computational modeling programs is often negligibly small, but the cost of creating them is often substantial. The computational chemistry program, NWChem, for example, cost around $10 million to create and is distributed free. Further details about the committee's survey and the ARIF reported in it can be found in Appendix C. Table 2-1 is followed by descriptions of several types of ARIF.

Imaging Technologies: From Physics to Biology

Imaging technologies provide many of the best-known examples of the evolution of modern instrumentation. Fifty years ago, studies of the effects of magnetic fields on the nuclear spin states of molecules were at the forefront of esoteric physics research. The earliest magnetic resonance spectrometers were inexpensive to build (they could literally be cobbled together by graduate students from spare radar parts); this was fortunate because measuring nuclear spin properties had no conceivable application. If sensitivity and instrument performance had stayed the same, NMR still would have no conceivable application.

Instead, today magnetic resonance is a fundamental technique for biological imaging and the most important spectroscopic method for chemists, the only one that measures the structure of proteins in their natural environment (in solution). Since 1980, the sensitivity of the best commercially available NMR spectrometers

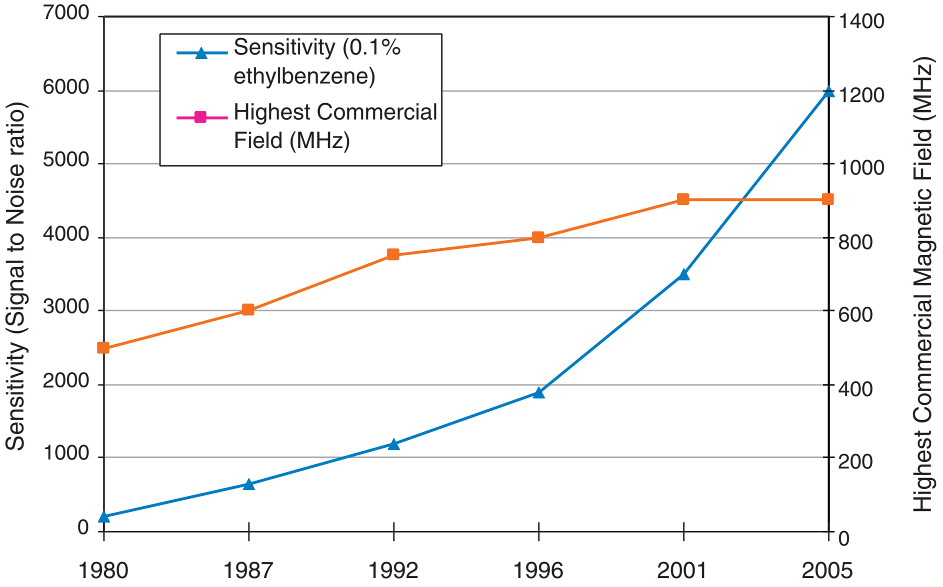

FIGURE 2-1 Historical capability of NMR spectrometers.
Source: Razvan Teodorescu, "Bruker Biospin Magnets." Presentation to the National Research Council Committee on High Magnetic Field Science, December 8, 2003.

has improved by a factor of 30. With that advance alone, NMR spectra could be acquired 900 times faster today than 25 years ago. Improvements in resolution and pulse sequences make the advances in NMR spectrometry even more dramatic. Figure 2-1 shows how NMR resolution and sensitivity have progressed since 1980.

Modern, very-high-field NMR spectrometers (high fields help to resolve the many atoms found in large molecules) are complex instruments; the most advanced machines today cost millions of dollars. The next generation, which pushes to still higher magnetic field strengths, will require a concerted effort in superconductor physics and radiofrequency design but will create even further dramatic extensions of the applicability of the technique.[4]

The pioneers of magnetic resonance would never have dreamed that 50 years later the International Society of Magnetic Resonance in Medicine would have 2,800 papers and 4,500 attendees at its annual meetings. Today, magnetic resonance imaging is a mainstream diagnostic tool, and functional magnetic resonance

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[4] National Research Council. *Opportunities in High Magnetic Field Science.* Washington, DC: National Academies Press, 2005.

900 MHz NMR

NMR Spectrometer

NMR spectrometers probe materials and biological processes at the molecular and nano-scale to give information on the three-dimensional structure and dynamics of molecules. This instrument is routinely used in chemistry, materials science, biology, and clinical medicine. NMR spectrometry is used to study everything from DNA to disease-causing proteins. Information obtained from NMR studies aids in the development of new drugs.

imaging (literally, watching people think) promises to revolutionize neuroscience and neurology. Again, the applications and the expense are intimately coupled to the sophistication of the technology: a modern, commercially available 4 Tesla whole-body magnetic resonance imager can easily cost $10 million to acquire and site, and it requires highly specialized technical staffing to maintain its perfor-

Brain Scan Procedure

Magnetic Resonance Imager

The magnetic resonance imager is used to take pictures of the body. A major current application of such an imager is in brain research. While the general areas of the brain where speech, sensation, memory, and other functions occur are known, the exact locations vary from individual to individual. This instrument is used by neurobiologists in the recently developed high-speed "functional imaging" mode to map out precisely which part of the brain is handling critical functions such as thought, speech, movement, and sensation. These experiments, though not straightforward, have started a revolution in our knowledge of brain function.

mance. For the institutions that responded to the committee's survey, the annual cost of operation for magnetic resonance imagers averaged 10% of the capital cost.

Modern methods in optical and x-ray imaging also reflect the evolution from physics to more applied science. They are not simply descendants of van Leeuwenhoek's crude microscope and Röntgen's x-ray hand picture; they embody and enhance our understanding of molecular and cellular structure and function. It is only a slight exaggeration to say that the most important application of the crude lasers of the 1960s was as inspiration for science-fiction television and movie weapons. Today, advanced laser systems permit microscopy hundreds of times deeper into tissue than would be possible with an ordinary microscope, and they are central to the rapidly growing field of molecular imaging.

The National Cancer Institute has identified molecular imaging as an "extraordinary opportunity" with high scientific priority for cancer research. The most promising approach is the development of new technologies and methods to improve the imaging and molecular-level characterization of biologic systems.

In the committee's surveys of researchers and institutions, NMR spectrometers were among the most commonly cited individual instruments, and advanced models were among the most commonly sought. The availability of ARIF in general was of concern to many researchers for whom access to increasingly advanced instruments was the key to advancing science and providing solutions to societal problems. The NMR spectrometer, as it becomes more and more sophisticated, exemplifies the issue. As one researcher noted,

> there is an increasing need for advanced research instrumentation in many fields. Many instruments that start out appearing to be expensive and esoteric rapidly become mainstream. The good side of this is that these instruments fuel impressive scientific results. The bad side is that scientists who do not have access to these instruments tend to fall behind in terms of their results and in what experiments they can propose in grant applications.
>
> . . . Five or six years ago, few labs had access to very high field spectrometers (750 MHz or above), but now the field has been pushed ahead to where many . . . projects require such instrumentation. A significant number of researchers have access to these machines, but many either don't have access or must drive/fly long distances to obtain access. While on paper it sounds fine to ask a researcher to travel to a high field spectrometer, in practice this is very cumbersome and does not lead to cutting edge results. For any particular NMR project, a dozen or more different NMR experiments must be carried out on a sample. . . . Traveling back and forth to a "richer" or better endowed university is not conducive to getting results.[5]

High-Speed Sequencers and the Human Genome Project

One of the major accomplishments of science in the 20th century was the deciphering of the human genome. That achievement made it possible to understand the molecular basis of human life in unprecedented detail. The potential for

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[5] LiWang, Patricia. In response to National Academies Advanced Research Instrumentation Survey, 2005.

X-ray Crystallography

X-ray crystallography is an experimental technique that uses x-ray scattering off of molecules or atoms in a crystal to make a model of the molecule or crystal. This technology is pivotal for obtaining knowledge of protein structures, which is a prerequisite for rational drug design and for structure-based studies that aid the development of effective drugs.

improving health and curing disease has already been demonstrated, but most of the benefits remain to be seen. The achievement will provide the basis of discoveries far into the future.

The genetic information in DNA is stored as a sequence of bases, and DNA sequencing is the determination of the exact order of the base pairs in a segment of DNA. Two groups, in the United States and the United Kingdom, first accomplished sequencing in 1977 and were awarded the 1980 Nobel prize in chemistry. However, their approaches were time-consuming and labor-intensive. Further

Mass Spectrometer

2-D Electrophoresis System

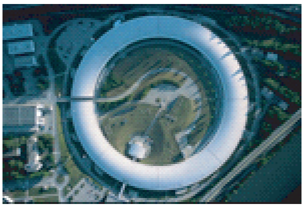
Proteomics

Proteomics is the identification, characterization, and quantification of proteins, and its applications include drug discovery and targeting, whole proteome analysis of any organism, agriculture, and the study of protein complexes, gene expression, and disease. The mass spectrometer is used to determine the structure and chemical nature of molecules, including proteins, and can be used to find the concentration of known molecules and identify unknown ones. Mass spectrometry can identify compounds even if they are present in very low concentrations. It is powerful in a wide range of applications, including the detection of environmental contaminants, establishing the purity of food and industrial products, locating oil deposits, and studying materials brought back from space missions. Two-dimensional electrophoresis is used to isolate proteins for further study with mass spectrometry.

advances came in 1986-1987 with the development of fluorescence-based detection of the bases. That led quickly to automated high-throughput DNA sequencers that were soon commercialized and made generally available to the research community. However, the speed of those devices was still not sufficient to decode the human genome in any reasonable amount of time.

Beginning in 1990, the pressures of approaching the daunting task of sequencing the human genome produced a number of new advances, which resulted in a fully automated high-throughput parallel-processing device that was 10 times faster than the older method. The progress and success of the Human Genome Project constitute a case study in instrumentation and of how, without develop-

APS, USA



ESRF, Europe-France

Spring-8, Japan

Beamlines

A synchrotron is a large machine (about the size of a football field) that accelerates electrons to almost the speed of light. The electrons are deflected through magnetic fields thereby creating extremely bright light. This light is channeled down beamlines to experimental workstations where it is used for research. Beamlines are used to examine samples of microscopic matter, analyze ultradilute solutions, and to observe what happens during chemical or biological reaction over very short timescales. Knowledge gained from synchrotron-based studies could someday lead to pollution-free electric trains levitated by superconductivity, atom-sized factories, and molecular-sized machines.

ment, it can become a pacing factor for research. The leaders of the sequencing efforts at the Department of Energy Office of Science and NIH recognized that the existing technology was not capable of sequencing fast and cost-effectively. As a result, they invested substantially not only in researchers but in the further development of sequencing technologies. The tandem approach proved very successful.

Genome sequencing requires the assembly of millions of fragments into a complete sequence. By itself, the mechanical process of sequencing was not sufficient to map the human genome in a reasonable time. The project was aided by computer algorithms developed by researchers in the late eighties and early nineties. The confluence of hardware and software development made it possible to complete the human genome sequence years before it had been considered possible. It also provided a general approach to large-scale sequencing that has resulted in the understanding of the genomes of a wide variety of organisms. The knowledge of genomes of a number of organisms has vastly accelerated discovery in basic biology research.

The history of the genome project shows how technology development can influence the course of discovery. Hardware and software were both needed and

Supercomputer

Research Databases

Cyberinfrastructure

The term "cyberinfrastructure" refers not only advanced scientific computing but also a comprehensive infrastructure for research and education based upon networks of computers, databases, on-line instruments, and human interfaces. Cyberinfrastructure is increasingly required to understand global climate change, protect our natural environment, apply genomics-proteomics to human health, maintain national security, master the world of nanotechnology, and predict and protect against natural and human disasters. All fields of science from physics to social sciences rely on databases (e.g., ICPSR and SPARC) for research.

were synergistic. The parallel development of sequencers and software demonstrates that not only key insights but also incremental improvements can make a qualitative difference in the progress of science.

Cybertools

Today, computers are vital tools to scientists and engineers. Indispensable for communication and often used in conjunction with many instruments, the computer can also be a scientific instrument itself. This section gives examples of three types of cybertools that are fundamental to several fields of research: software, data collections, and surveys.

Although one of the first scientific applications of digital computers in the 1940s was to try to predict the weather—with grants from the US Weather Service, the Navy, and the Air Force to John von Neumann at the Institute for Advanced Study at Princeton University—scientific applications software aimed at obtaining

Gaussian and the Nobel Prize

In 1998, John A. Pople was awarded the Nobel prize in chemistry (his colaureate was Walter Kohn of the University of California, Santa Barbara). The citation for Professor Pople refered to "his development of computational methods in quantum chemistry." The research "tool" that Professor Pople developed was the **Gaussian** program, which is now one of the most widely used tools in chemical research. The first version of Gaussian was released in 1970 and provided only limited ways of modeling molecular structure and processes. The last release of Gaussian, in 2003, is so advanced it can predict the structure and properties of many molecules to an accuracy that enables chemists to gain a better understanding of the problems they are investigating.

a better understanding of physical phenomena did not become widely available until the 1960s and 1970s. Scientists and engineers have since developed a broad array of scientific software applications that are acknowledged to be indispensable in the scientist's toolkit—the software equivalents of the NMR spectrometer and other instruments described above. Examples of such applications software in use today are Gaussian, a molecular modeling code that is used by experimental and theoretical chemists to understand molecular structure and processes better and more easily by performing computer "experiments" rather than chemistry experiments; the Community Climate System Model, which is used by the climate research community to understand the evolution of past and future climates; and CHARMM and AMBER, used by the biomolecular community to understand the structure and dynamics of proteins and enzymes.

Scientific applications, such as Gaussian, often began as small research projects in the laboratory of a single investigator. However, as the capabilities of computers increased, the applications included models of the physical and chemical processes of higher and higher fidelity, and the software became more and more complex. Today, many of the scientific applications involve hundreds of thousands to millions of lines of code, took hundreds of person-years to design and build, and require substantial continuing support to maintain, port to new computers, and continue to evolve the capabilities of the software as new knowledge accumulates. The cost of developing major new scientific and engineering applications can be more than $10 million, and the cost of continuing maintenance, support, and evolution exceeds $2 million per year. Thus, these software applications are well within the category of advanced research instrumentation being considered in this report.

A Virtual Data Center

Political Science Instrumentation

Instrumentation requirements in political science largely rest in the operation of major longitudinal data series and the maintenance of the institutional support for them, with the peak example being the National Election Studies sustained by the National Science Foundation. A second emerging area is the development of laboratory capacity for computerized political science research. A third area involves archiving, particularly of political communication materials, and the construction of meta-data. Virtual data center projects are also emerging, where marginal costs of use are free but development costs are very expensive. Future instrumentation needs could include: a network of exit polling to validate election outcomes; linking of political-administrative information systems with physical science systems to translate natural disaster warnings into effective systems for sharing life-saving information and implementing public safety plans; and developing collaborations between political scientists and other scientists in brain imaging and genomics.

Digital data collections also provide a fundamentally new approach to research. By gathering data generated in studies on related topics, digital data collections themselves become a new source of knowledge. One of the best examples of a large scientific database that is integral to progress in science and engineering is GenBank, the genetic sequence database maintained for the biomedical research community by NIH. GenBank was born at Los Alamos National Laboratory in 1982, well before the beginning of the Human Genome Project. When the Human Genome Project came into being and the number of available sequences exploded, GenBank became an indispensable repository for the data being generated. Today GenBank contains over 49 billion nucleotide bases in over 45 million sequence records, and the amount of data is increasing exponentially with a doubling time of less than two years. All sequencing data produced by the Human Genome Project must be deposited in GenBank before it can be published in the literature. Because of the unique role now being played by digital data collections in research and education, the NSB recently drafted a report on the subject, finding that such collections are used in most fields of science, from astronomy (as in the Sloan Digital Sky Survey) to biology (as in The Arabidopsis Information Resource).[6] It concluded that "digital data collections serve as an instrument for performing analysis with an accuracy that was not possible previously or, by combining information in new ways, from a perspective that was previously inaccessible." The collections are often fundamental tools of the social sciences, housing extensive survey and census results and archived media.

Especially in the social sciences, the survey itself is a scientific instrument that can cost millions of dollars a year to maintain. Longitudinal surveys, large and often decades-long surveys, are analogs to the telescopes and microscopes of the other sciences. These surveys are not created by single investigators; they are often sources of basic data used by arrays of disciplines. Increasingly, surveys collect not only social data but also biomedical data (e.g., cheek swabs for DNA analysis) or are integrated with satellite down feeds or inputs from air quality sensors. The data from these surveys is expensive to collect and document as well as make publicly accessible to researchers while preserving anonymity and confidentiality. They are very expensive to collect in any given round let alone over time. They are also expensive to document and make accessible as public use files, preserving anonymity and confidentiality. Frequently, the data for such surveys can only be collected by one or two survey research centers in the country, such as the Institute for Social Research at the University of Michigan, that possess the ongoing human and local infrastructure to manage them at affordable scale.

Computational technology has advanced to the point where computers can be used as tools not only for remotely accessing databases and collaborating with other researchers but for remotely accessing and controlling scientific instruments. A 900-MHz virtual NMR facility at the Pacific Northwest National Laboratory, for example, supports a national community of users, roughly half of whom use the instrument remotely. The technology can improve and provide less expensive access to instruments for geographically remote users and can permit more effective use of instruments. The openness of this technology and the ability to book at all hours may be a means to generate more revenue from user fees and thus recoup the facility's operation and maintenance expeditures.

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[6] National Science Board. *Long-Lived Digital Data Collections: Enabling Research and Education in the 21st Century*. NSB-05-40. March 30, 2005, Draft.

Ocean Floor Pressure Sensor

Seismometer

Earth and Ocean Science Sensor Systems

Earth and ocean sciences rely on sensor systems, both to predict natural disasters and to learn about climate, natural phenomena, and weather. Ocean sensors are essential for the predicting when and where a tsunami will strike. New seismometer technology is making earthquake predictions and immediate, accurate damage assessment possible. Orbiting satellites are a part of tsunami and earthquake sensor systems, and are essential for predicting dangerous weather including hurricanes and tornadoes.

Distributed Advanced Research Instrumentation Systems

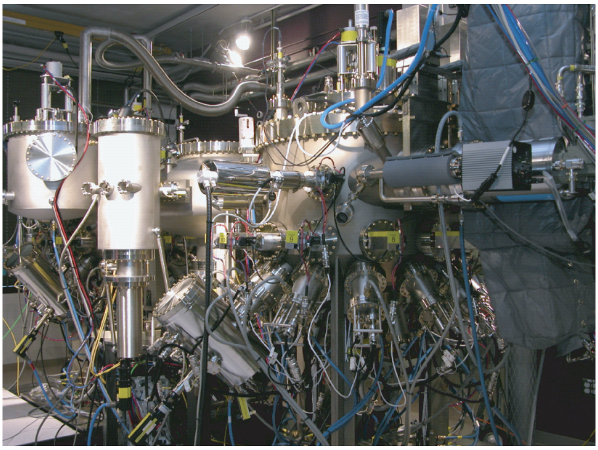
Not all advanced research instrumentation is housed in laboratories. Progress in the physics underlying the technological development of modern scientific instruments and their associated cybertools has given rise to an unprecedented explosion in the scope of basic research in the geosciences and biosciences that relies on field observations. Atmospheric scientists, oceanographers, geophysicists, and ecologists are now tackling and solving fundamental problems that require analysis of large numbers of observations that are both time- and space-dependent. Some of the sensors and tools required to make the necessary measurements can be deployed on familiar mobile instrumental platforms, such as oceanographic ships, research aircraft, and earth-orbiting satellites; but many need to be distributed in sensor networks of local, regional, or even global scale. Both physical and wireless networks can be used to transmit data to off-site storage facilities.

A good example of a distributed sensor network is the Global Seismographic Network (GSN), which consists of 130 seismic stations distributed on continental landmasses, oceanic islands, and the ocean bottom. GSN recording and nearly real-time distribution of seismic-wave parameters measurements at numerous sites over the globe serve the needs of basic research in geophysics (such as seismic tomography of the earth's interior structure) and of applied geosciences (such as earthquake and tsunami monitoring and seismic monitoring of nuclear testing).

Seismometers were originally developed to study earthquakes, but their modern versions, deployed in geographically distributed networks, record data that can be processed with sophisticated computing methods to produce images of the solid earth. The resulting "seismic imaging" is science's most important source of knowledge about the structure of the earth's interior and its consequences for humanity with respect to, for example, mineral and energy resources, earthquakes and volcanic hazards.

Today's seismograph system takes advantage of modern off-the-shelf hardware for many of its components. Global positioning system (GPS) receivers provide the accurate timing required, off-the-shelf electronic amplifiers generate little noise or distortion, and commercial analog-to-digital converters with true 24-bit or higher resolution are an improvement over custom-designed "gain-ranging" systems; but the primary sensor of a modern seismometer still requires unique design to meet a combination of stringent requirements. To detect the smallest signals above the earth's background "hum," the self-excitation of the pendulum sensor by Brownian noise must be less than that caused by shaking the instrument's foundation with an acceleration of 1 nm/s^2 across a wide frequency band of 10^{-4}-100 Hz. Furthermore, to make faithful records of the largest earthquakes, the response across the same frequency band must be linear up to excitation amplitudes that are 10^{12} times greater than the smallest detectable signals. No company in the United States produces sensors with those capabilities, and no US universities train engineers in seismometer design.

Environmental sensor systems must often be installed in remote field locations, and this poses difficulties not encountered in housing instruments in a laboratory setting. For example, seismometers must be installed in ways that isolate them from drafts, temperature changes, and ambient noise and that protect them from damage by animals and vandalism. Low-power, rugged, and high-capacity data-storage systems are required for remote locations where energy must be provided by fuel cells or batteries recharged by solar or wind-based systems. In locations where Internet service is not available, transmission of data must take advantage of satellites or other telemetry technologies that can substantially add to costs. Although data transmission and interrogation of routine instrument functions can be dealt with remotely, periodic maintenance by technicians is needed



Composite Instruments

Instrumentation is often built from a collection of less expensive components that are put together to form a new instrument with unique functions. Composite systems are required to solve many research problems for which there are no commercially available instruments. These systems are ubiquitous in all research fields, from electrical engineering to neutron scattering to ocean research.

and can account for a large fraction of operation and maintenance costs, especially for large networks with worldwide distribution of stations. Although the combined equipment, installation, and a year of operation and maintenance of an individual station typically will cost between $100,000 and several hundred thousand dollars depending on instrumentation specifications and location (polar regions and ocean-bottom locations are obvious examples of expensive locations), it is clear to the committee that distributed network "instruments" fall well within its definition of ARIF.

Tools for Integrated Circuits

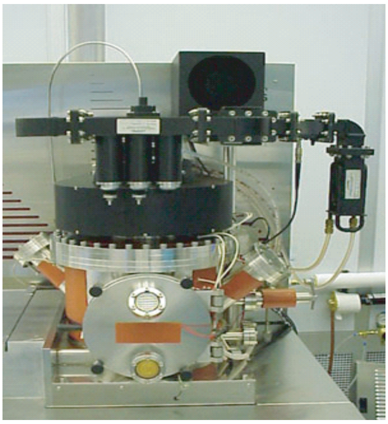
An advanced research instrument may consist of a suite of tools that must be combined to advance a particular field of science and technology and eventually affect society. An excellent example is the microelectronic processing technology that has been developed over the last 50 years to create integrated circuits (ICs). ICs are found in every electronic product purchased by Americans to enhance our day-to-day living. Communication, education, transportation, defense, health care, and recreation, to name a few examples, have been dramatically transformed by the creation of ICs. In 1947, the first point-contact transistor was demonstrated; it consisted of a sizable chunk of germanium with two gold wires to conduct electricity and enable the demonstration of power gain. A few years later, in 1956, Bardeen, Brattain, and Shockley were awarded the Nobel prize in physics for the discovery of the transistor. Throughout the 1950s and 1960s key technological breakthroughs in crystal growth, ion implantation, photolithography, and planar processing paved the way for the creation of the IC. By fabricating the transistor in a planar form, engineers and scientists could envision methods to interconnect the transistors and begin combining them to perform an unlimited number of functions.

In 1971, Intel introduced its 4004 processor that contained 2,300 integrated and interconnected transistors in a 4 × 5 mm area—about 10,000 transistors/cm^2. In 1997, the Intel Pentium II processor contained 7.5 million transistors in an area of about 8 × 8 mm. The Pentium III has 28 million transistors; by 2006, the industry projects a logic transistor density of 40-80 million per square centimeter! In 2000, Kilby was awarded the Nobel prize for the invention of the IC. Today, the microelectronic processing technology industry has sales of over $150 billion per year. To create such amazing ultra-high-density, small-area ICs requires a suite of planar processing tools, each of which can be categorized as an advanced research instrument but all of which are needed to build the IC.

As the capability of an instrument increases, its price also increases. For example, in 1982, a physical vapor-deposition tool cost about $400,000; whereas in 2002 a physical vapor-deposition tool cost $7 million. This rise in cost reflects substantial gains in the precision and repeatability of vapor deposition. Similar increases in equipment costs have occurred for other tools in the suite as resolution has increased, feature size has been reduced, and overlay accuracy has been improved. The incredible gains demonstrated by the microelectronic processing technology industry were facilitated by placing the suite of tools within specially designed space or clean rooms to ensure defect-free high-density ICs; such special space adds further to the cost of ownership of these advanced research instruments.

Nanotechnology

Nanotechnology is a broad field that has stemmed from our recently developed ability to manipulate atomic and molecular objects with dimensions 1-100 nm—a length scale that has become increasingly important in pushing the boundaries of operation and performance. It involves the ability to engineer materials on a



Chemical Vapor Deposition

Ion Etch System

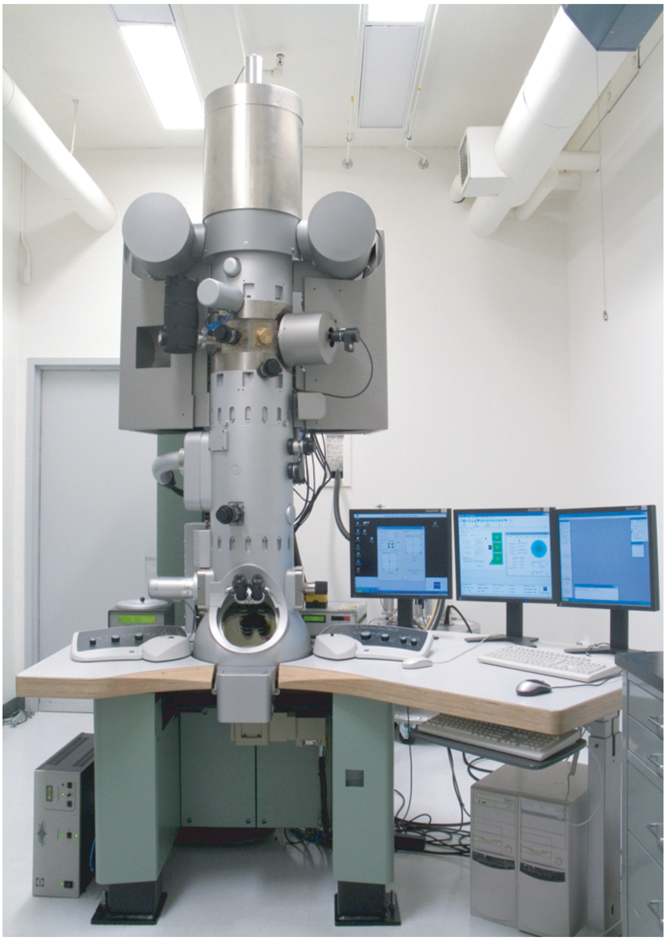
National Nanofabrication Users Network

The National Nanofabrication Users Network (NNUN) is an integrated network of user facilities, providing researchers expertise to fabricate nanometer-scale structures, devices and circuits. NNUN-related instruments perform tasks such as lithography, etching, and spectroscopy. This network aids diverse disciplines from engineering to physics to biology.

nanometer scale by placing atoms into predetermined locations. In light of the broad goals and possible applications of nanotechnology, a large array of synergistic tools has been developed.

A primary need in nanotechnology is the ability to "see" the locations of specific atoms. That has been accomplished largely through the development of scanning probe microscopes. These types of microscopes have the ability to scan or map a surface line by line at atomic resolution. Scanning probe microscopes are distinct from most other microscopes in using mechanical devices, instead of light and lenses, to image surfaces.

The development of scanning probe technology began in 1981 with the scanning tunneling microscope in Zurich. Scanning tunneling microscopes use quantum principles not only to visualize surfaces but also to manipulate them by, for example, initiating chemical reactions. In 1986, the Nobel prize in physics was awarded to the discoverers of this microscopy technique; the remarkably short



Electron Microscope

An electron microscope uses electrons to probe materials at extremely high resolution. This examination can reveal much about an object, including atomic-scale structure and bonding, features of surfaces and interfaces, the shape and size of the object, and its chemical composition or electronic structure. The current development of aberration-corrected electron optics will greatly enhance the spatial, temporal, and energy resolution of electron microscopes. x-ray microscopy could make a major contribution to the understanding of cell function and structure. Microscopes based on electrons, x-rays, and scanning probes are instrumental in expanding knowledge and creation in nanotechnology.

2.3 and 4 Meter Dome Telescopes

UARS Satellite

Telescopes and Global Sensors and Infrastructure

Telescopes, radar, and satellites are frequently employed in science and engineering research. Telescopes are central to the study of our own solar system and to the study of galaxies billions of light-years away. Radar is used to track satellites, detect atmospheric hazards to aircraft, and detect air traffic and runway intruders. We rely on satellites for studies of deep space and deep oceans. Satellites are also essential for the operation of cell phones and GPS devices. The UARS satellite, shown above, measures ozone and chemical compounds found in the ozone layer, which affect ozone chemistry and processes.

time after the initial discovery indicates its importance. Since then, an array of other scanning microcopies have been developed, most notably the atomic-force microscope in 1986 that measured attractive or repulsive forces between a very fine tip and a sample. That approach allowed the imaging of nonconductive surfaces, which the tunneling technique could not do. As is often the case, sophisticated software is required to make sense of the information generated by these tools and to integrate it into a comprehensible image.

The effects of nanotechnology are beginning to be felt, for example, in materials science (nanotubes and nanoparticles), in the development of smaller computer chips, and in the manipulation of biologic components to create nanomotors. Recently, there has been interest in the interaction of "hard" and "soft" materials, which require special facilities where semiconductor fabrication and biomolecular assembly can take place in concert.

Tools for Space Exploration

The exploration of space and the solar system depends on a number of ground-based and space instruments, such as the Supernova Acceleration Probe, a satellite observatory that probes the history of the expansion of the universe over the last 10 billion years. The exploration of space has also become increasingly dependent on diagnostic equipment, whose focus is characterization of samples that have been returned to the earth from space. Such instruments as the MegaSIMS combination spectrometer (see Table 2-1), which was specially designed to analyze GENESIS NASA solar wind samples, are ARIF that bridge space and earth exploration and enable us to understand better the materials that make up the world around us and the processes that govern its development.

FINDINGS

F2-1: Instrumentation is a major pacing factor for research; the productivity of researchers is only as great as the tools they have available to observe, measure, and make sense of nature. Workhorse instruments, once cutting-edge, now enable scientists to perform routine experiments and procedures much faster. Those tools now have efficiency and sensitivity greater by several orders of magnitude than a decade ago. Research that previously took years to conduct now takes hours. Most of the research funded by the federal government today would be impossible with tools that were developed in decades past.

F2-2: As new research questions are answered, more advanced instrumentation needs to be developed to respond to researcher needs. As a result, the useful life of instruments has shortened dramatically in recent decades, and the demand for new instruments has increased. Instruments that used to be relevant to cutting-edge research for a decade or more today last less than half that time. Older instruments are still useful, but the demand for new instruments is greater and greater.

F2-3: ARIF include both workhorse instruments that are used every day by researchers and racehorse instruments that represent the state of the art or are still developing.

F2-4: ARIF often depend on PhD-level technical research support staff for its proper operation and maintenance and to facilitate use by researchers. ARIF require highly specialized knowledge and training for proper operation and use. Nonspecialists increasingly need ARIF for their research and require dedicated personnel to provide expertise.

RECOMMENDATIONS

R2-1: The committee recommends the following definition of ARIF:

> **Advanced research instrumentation and facilities (ARIF) are instrumentation and facilities housing collections of closely related or interacting instruments used for research and includes networks of sensors, data collections, and cyberinfrastructure. ARIF are distinguished from other types of instrumentation by being more commonly acquired by large-scale centers or research programs rather than individual investigators. The acquisition of ARIF by scientists often requires a substantial institutional commitment, depends on high-level decision-making at institutions and federal agencies, and is often managed by institutions. Furthermore, the advanced nature of ARIF often requires expert PhD-level technical research support staff for its operation and maintenance.**

R2-2: Continued and vigorous federal investment in ARIF is essential to enable cutting-edge research in the future.

3

Instrumentation and Universities

Instruments reside in many settings, including universities, industrial laboratories, national laboratories, and independent research institutions. The present committee, in accordance with its charge, is interested primarily in federally funded instrumentation in academic institutions. This chapter discusses the issues that surround instruments in the university setting.

Academic researchers not only use instruments in their work but also develop new kinds of instruments. Further, instruments in academic settings are used not only to conduct research but also to provide education and training for the next generation of practitioners. As a result, they are often used by undergraduate students, graduate students, and postdoctoral fellows as well as by staff scientists and faculty. Instrumentation and facilities at universities are often also of service to local research companies, which might not otherwise have access to such instruments and technical expertise. And, although instruments may be designed originally for one field of research, they will be often be used by researchers in many other fields, once their potential is known.

INVESTING IN INSTRUMENTATION IN UNIVERSITIES

As research progresses, improved and novel instruments become necessary to enable new discoveries and enhance scientific productivity. In the 19th century, the government was not an important patron of science in universities, and researchers turned to philanthropists and private organizations to fund an increasing need for new and more powerful instruments. The 100-in. telescope at the Mount Wilson Observatory and the 200-in. telescope at the Mount Palomar Observatory were both funded by the Carnegie Institution of Washington. In the 20th century, the need for federal support of science and the instruments that enable it became a fact of life. Maintaining a balance between supporting investigators and supporting the tools they require is a long-standing concern.[1]

The investment in instrumentation in universities typically involves several kinds of costs, which vary from instrument to instrument, including,

- *Capital:* The direct cost required for the purchase of a commercially available instrument or, often, the components for assembling an instrument that has advanced or unique capabilities not available commercially.
- *Construction:* The costs associated with installing or assembling an instrument.
- *Development:* These costs may include associated basic research and researcher salaries.
- *Siting:* The cost of locating an instrument in a facility, which may involve renovation and the purchase of peripheral equipment, such as clean rooms or shielding.
- *Operation and maintenance:* The costs associated with continual upkeep of the instrument, which may include continuing siting costs, energy costs, service contracts, and repair costs.
- *PhD-level technical research support staff:* The costs associated with the employment of staff to operate the instrument and assist researchers.
- *Upgrade:* The costs associated with updating an instrument as opposed to replacing it.
- *Compliance:* The costs associated with meeting ever higher health, safety, and environmental standards, including upgrades and re-engineering to maintain operation.
- *Decommissioning:* The costs associated with the disposal or repurposing of an instrument that is no longer of use.

Among the important factors to consider, from the perspective both of the researcher and of the patron, is the lifetime of an instrument. The lifetime of an instrument will depend not only on the type of instrument but also on its continuing utility as a cutting-edge research tool. Some instruments are useful for decades; others become outdated in only 5-10 years. The lifetime of an instrument will also

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[1] Stine, J. K., and G. A. Good. 1986. Government funding of scientific instrumentation: A review of U.S. policy debates since World War II. *Science, Technology & Human Values* 11(3):34-46.

vary with how it is used. Some workhorse instruments in universities may have greater wear and tear because of student use.

The factors outlined above are important for nearly all major scientific instruments, even those costing as little as several hundred thousand dollars. But as the cost of an instrument increases, they become more and more critical. At the level of advanced research instrumentation and facilities (ARIF), instruments must be handled in a manner that does not compromise the investment. As the investment in instrumentation reaches into the millions of dollars, it is imperative that maximal benefit be derived from the instrument. Accomplishing that may rest on several key factors.

First, it is important that downtime is minimized. Because of high demand, many ARIF are operated 24 hr/day 7 days/week, and downtime means a loss of efficiency and opportunity. In some cases, a long experiment will be compromised if an instrument breaks down in the middle. Downtime affects the productivity of researchers in a manner that costs money and competitiveness.

Second, careful attention must be paid to maintaining ARIF at published specifications because often these expensive instruments are acquired precisely because they have resolution, sensitivity, or throughput that surpasses that of less expensive instruments. If an instrument is not operating at its specified limits, the investigators are not acting responsibly and are not gaining the advantage that such a large investment was intended to achieve in the first place.

Third, it is critical that the instrument capabilities are constantly upgraded, whether with hardware or with software improvements, to ensure that it is kept up with advances in the field and related technology development. Doing so can

Instrumentation and the Challenge of User Fees

Many universities rely on user fees to cover maintenance contracts and operating support for advanced research instrumentation. If instrument use declines for any reason, the hourly user fee must be increased to pay for the fixed cost of operation and maintenance. That creates an unstable situation, which allows the cost of instrument use to increase to the point where the instrument becomes inaccessible to researchers. A dependence on user fees to offset ongoing costs thus has the potential to shape the direction of research. Even a temporary decline in use can initiate a cycle of spiraling cost, insufficient maintenance, or lack of upgrades that can paralyze operation. Only when universities have found creative solutions to the problem of user fees have major instrument resources remained available for research.

substantially extend the lifetime of ARIF and requires a sophisticated operator who thoroughly understands the technology and is fully acquainted with the needs and goals of the researchers.

These factors related to operation and maintenance directly affect the productivity and effectiveness of the research. ARIF are essential to the success of many investigators who depend heavily on the results that can be obtained with these instruments. Ineffective operation, downtime, and underperformance all lead to a waste of time and money for each research program that depends on the instrument or facility. Thus, not only is the investment in the instrumentation itself compromised but all the grants that depend on it are themselves affected, to say nothing of the many investigators whose work is compromised.

For those and similar reasons, it is important to pay careful attention to the detailed plans for operation and maintenance of ARIF and to ensure that adequate funds are built into the budget for this aspect not to be a limiting factor in the operation of the facility and for the investment to be properly protected.

MANAGEMENT OF INSTRUMENTATION IN UNIVERSITIES

From a university administrator's perspective, the acquisition of instrumentation may be the responsibility of either the researcher or the university, depending on its capital cost. Generally, the principal investigator is responsible when instrumentation is of such a small scale that it can be located in the researcher's laboratory and it has a capital cost of less than about $50,000. Such instruments can be acquired as part of a research grant or with startup funds provided by the institution when a researcher sets up a laboratory.

Instrumentation with capital cost beyond $50,000 usually requires the involvement of the university administration. The degree to which the leadership of a university is involved with instrumentation decision-making and fund-raising depends mainly on three factors:

- Cost of the instrument.
- Operation and maintenance costs.
- Space requirements, including renovation of rooms in existing structures and possibly a new building.

If any of those factors is substantial, decision making regarding the instrument generally moves up the decision-making chain of the university, from department chair to dean to university vice-president, vice-provost, or vice-chancellor for research. Most ARIF would follow this decision-making path.

Cost of Advanced Research Instrumentation and Facilities

The path that universities must follow to obtain ARIF has been extremely rocky in recent years for several reasons. First, especially at the National Science Foundation (NSF) but also to a smaller degree at some other agencies, there was a policy for a time that required universities to provide matching funds for major research programs. For example, NSF required 30% matching on all Major Research Instrumentation[2] awards. That meant that an institution was obligated to contribute a substantial amount of funding each year if it wanted to use the award to acquire such instrumentation. This depleted the already constricted research budgets of universities and often pitted faculty against the administration. Last year, NSF changed its policy, and it no longer requires the large matching contributions.

Second, the continuing erosion of state budgets for public universities (and the decline of the endowments of some private universities) has in many cases largely eliminated line-item equipment budgets. Some public universities receive no equipment allocation of any kind or receive only very small and highly restricted research funding.

Third, as the focus of research, especially in engineering and the life sciences, has shifted to the microscopic level, the demand for sophisticated instrumentation

Costs and Requirements Associated with an 800-MHz NMR with Cryoprobe

- Part of a facility housing instrumentation with total capital costs of $5 million
- Capital cost: $1.9 million
- Siting cost:
    - o New construction (not including environmental infrastructure): $900,000
    - o Cost of installation: $60,000
- Annual cost of operation (excluding support staff): $40,000
    - o Cryogens: $10,000
    - o Spectrometer repairs and upgrades: $10,000
    - o Cryoprobe annual maintenance: $15,000
    - o Administrative expenses: $5,000
    - o Service contract for spectrometer: $25,000
    - o Service contract for cryoprobe: $25,000
- Annual Support staff salaries (before fringe benefits): $143,000
- Expected lifetime: 25 years

continued

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[2] This program is described in Chapter 4.

- User fees cover 100% of the operating costs, but less than 5% of the facility salary costs. The institution pays over 80% of the total facility salary costs, and the remainder comes from grants.
- Supported by a PhD-level laboratory director and a BS-level research assistant
- Space Requirements:
    - 1,000 square foot room (size of room subject to level of shielding)
    - Two additional 250 square foot rooms, one for electronic equipment and another for the operators and computer control.
- Environmental requirements:
    - Very good temperature stability, with less than 1 degree Fahrenheit of drift per hour.
    - Low vibration—the magnet is supported by a vibration-isolated slab cut away from the rest of the building and supported by concrete piers sunk into the bedrock.
    - No ferrous metals close to the magnet, even embedded in the concrete. In a wider range, there can be no moving ferrous metals during an experiment.
    - Space around instrument needs to be shielded. For a low-field NMR this is inexpensive, adding about $7,000 to the cost of a 400-MHz NMR, but $300,000 to the cost of a 800-MHz NMR.

Source: David Vander Velde
Director
University of Kansas NMR Laboratory
Response to Committee Survey on Advanced Research Instrumentation

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"Unfortunately, public institutions have been seeing a downward trend in funding from the State, and the first place that is cut is funds for instrumentation. It would also be advantageous if NIH comes up with another instrumentation grant to cover bundled instruments (i.e. a number of lower cost items, e.g. centrifuges, fluorescence spectroscopy or microscopy). The higher cost instrument grants program was also not activated this year, equipment over $750,000. This needs to be reinstated. In order for investigators to continue quality research they need access to state of the art equipment. . . . [W]e are a growing institution adding new faculty. New instrumentation is not only needed but essential to attract the best and most promising scientists."

Thomas Yorio
Vice President for Research
Dean of the Graduate School of Biomedical Sciences
University of North Texas Health Science Center
Response to Committee Survey on Advanced Research Instrumentation

> "Acquisition of advanced research instrumentation with these capital costs must be part of a strategic plan that encompasses the academic, research and economic development missions of the university."
>
> Anonymous source who is a
> Vice Provost for Research at a public university in New York
> Response to Committee Survey on Advanced Research Instrumentation

(once the domain largely of physics and chemistry programs) has expanded dramatically. Today, the need for expensive and complex instrumentation capable of probing phenomena at the molecular level—to say nothing of the expansion of astronomical observations across the entire electromagnetic spectrum—is straining institutional budgets to the breaking point.

Fourth, instruments today include not only hardware but also software, databanks, and automated aids for data analysis and interpretation—collectively known as cyberinfrastructure. Cyberinfrastructure has become a major component of such costs in all fields of research.

As a result of such pressures, it is extremely challenging for a university to assemble sufficient funding for ARIF. This lack of access to ARIF can severely hamper research and teaching activities.

Operation and Maintenance Costs

Operation and maintenance of ARIF require commitments for service contracts, space and utilities, and technical and scientific support staff. Any plan for

> "To obtain such instruments is way beyond the time single researchers can commit for the cause of common good. The maintenance fees will represent the second level of unforeseen difficulties. We do not have any means/mechanism to raise, in addition to the purchase and maintenance costs, running and operating budgets and resources to provide for well-trained personnel to run such instruments and provide service to multiple investigators."
>
> Katalin Csiszar
> Professor
> University of Hawaii
> Response to Committee Survey on Advanced Research Instrumentation

operation of a major item of instrumentation must address those issues in order to clearly establish the degree and character of the institutional commitment associated with the proposed acquisition.

- Most commercial instruments, such as a high-field nuclear magnetic resonance (NMR) or an electron microscope, need a maintenance contract for service and repair and insurance against catastrophic failure. At an annual cost of about 5% of the capital expense, that is an important factor over the lifetime of an instrument.
- Space, utilities, and consumables can add considerably to the cost of a major piece of instrumentation.
- To achieve consistent high-level performance, PhD-level technical research support staff are essential to maintain the instrument in top operating condition, manage scheduling, evaluate and prioritize use, perform daily alignments and periodic calibrations, collaborate on research projects, implement upgrades and enhancements, train students, trouble-shoot, and coordinate service calls.

A recently released National Academies report on midsize materials science research facilities and larger university-based facilities found a substantial number of facilities with annual operating budgets between $250,000 and $2 million, shown in Figure 3-1. Federal agencies were the most common source of support for those operating budgets (35%) followed by user fees (35%) and host institutions (27%).[3] The facilities had from one to thirty staff; 30% had one to five staff.

Figure 3-2 shows how annual operation cost can accumulate each year to be comparable to the initial capital cost of the instrument, with the example of an average field emission transmission electron microscope.[4] The costs shown exclude support staff and refer only to an annual service contract with the instrument manufacturer. The contract costs the same every year.

Space

Almost all ARIF have special siting requirements. Institutional involvement is often needed in order to secure space as well as infrastructure for appropriate utilities—expenditures often not factored into the original acquisition cost.

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[3] National Research Council. *Midsize Facilities: The Infrastructure for Materials Research*. Washington, DC: National Academies Press, 2006.

[4] National Research Council. *Connecting and Sustaining Midsize Materials Research Facilities*. In review.

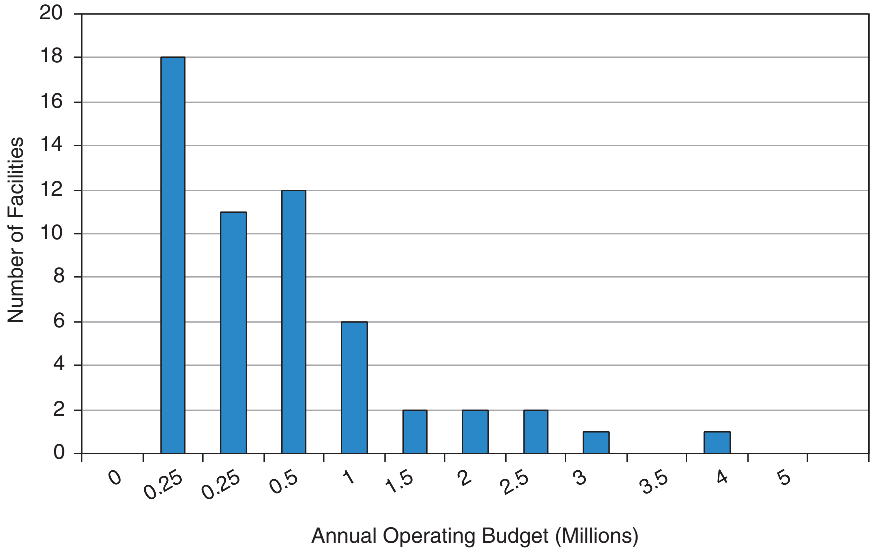

FIGURE 3-1 Midsize materials science facility operating budgets.
Source: National Academies, Board on Physics and Astronomy, *Midsize Facilities: The Infrastructure for Materials Research,* 2006.

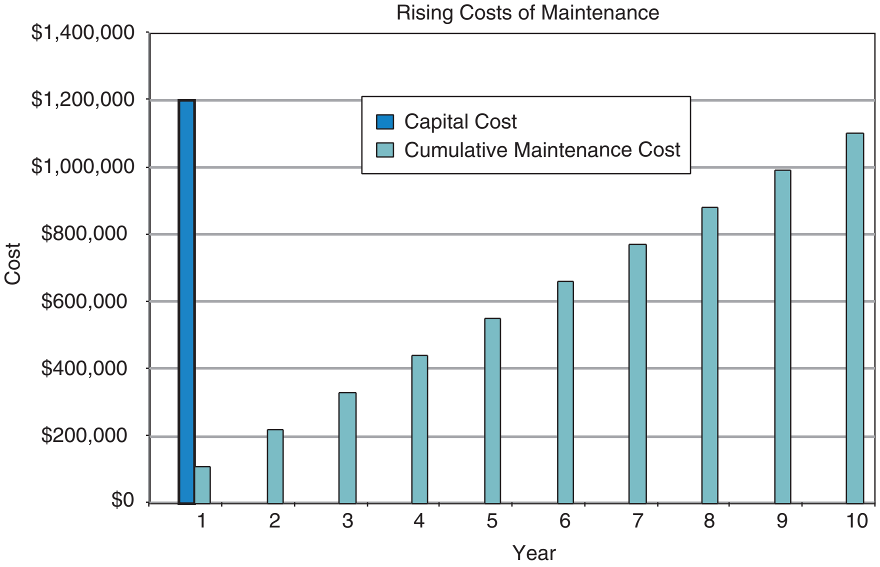

FIGURE 3-2 Accumulation of operating costs for a transmission electron microscope.
Source: National Academies, Board on Physics and Astronomy, *Midsize Facilities: The Infrastructure for Materials Research,* 2006.

Many ARIF need special environments that are essential for their operation. For example, high-performance electron microscopes require extremely stable laboratory spaces with special controls to reduce vibration, acoustic noise, electromagnetic interference, and thermal gradients. The cost to construct a suitable laboratory space or modify an existing one cannot be neglected. Likewise, utilities and consumables can add substantially to the cost of operation and maintenance. Many academic institutions suffer from a shortage of space, and accommodations for ARIF must be negotiated with the administration and be specially justified.

PhD-Level Technical Research Support Staff

Technical support is an important element of advanced instrumentation. Staff members can provide expertise for optimal use, for development of techniques and instrumentation, and for assistance with data analysis and interpretation. Those functions are especially important for multidisciplinary and interdisciplinary use of such equipment, which involves many researchers who are not expert with the instrumentation in question.

Sometimes support functions are left to graduate students. That is often inefficient, in that their expertise is variable, the service level is uneven, and such work is of limited pedagogic value to the students. The cost of equipment downtime scales roughly with the capital cost, so major research instrumentation requires dedicated technical research support staff for efficient operation.

For many types of ARIF, it is essential that a skilled PhD-level researcher be in charge because of the instrumentation's high cost and sophistication. Such a person can ensure that the latest enhancements are implemented, that the software is kept up to date, and that experiments are optimally designed to get the best results. It is, of course, important that students learn to use such instrumentation, so it is critical that skilled staff be available for training and advice. In addition to training students and keeping instruments up to date, technical research support staff are common collaborators in research projects, often serving as coauthors of papers, and play a key role in managing instruments and setting prioritites for use.

Few universities have well-defined policies for supporting such staff; most make no provisions for it at all. It commonly falls to the individual faculty member to patch together funding from various other users and funding sources to try to support technical help. That is often a time-consuming and frustrating process for the researcher; all too often, these ad hoc arrangements fall apart after a year or two and have to be painfully reconstructed.

"Instrumentation in this price range is often accompanied by the need for specialized facilities. Funding agencies should require that institutions demonstrate the ability to provide appropriate facilities, have a mechanism to insure multiple PI access, and have a plan to provide on-going support and maintenance of the instrument."

Anonymous source who is a
director of special projects at a public university in California
Response to Committee Survey on Advanced Research Instrumentation

CENTRALIZED UNIVERSITY FACILITIES

A criticism sometimes raised about major research facilities in universities is that they tend to be the province of one department or one college even though they may have been established as multidisciplinary facilities (with multiple contributions to the initial proposal). That sometimes leads to a concern that either accessibility of those outside the responsible unit is not adequate or support for other users is inadequate or not readily available. Furthermore, the support staff have a more limited role and less engagement with other investigators throughout the institution.

It has been suggested that one way to remedy the situation is to create more centralized instrumentation resources by placing them under a centralized office,

"The purchase of expensive instrumentation must recognize the long-term commitment that is incurred in staffing the facility with adequately skilled operators. The user pays model does not always produce the needed revenue, so that a back-up mechanism needs to be explored. Whether to buy our own instrument or enter into a service agreement with a national lab, or some other entity, should be debated on a case-by-case basis."

Digby Macdonald
Professor
Pennsylvania State University
Response to Committee Survey on Advanced Research Instrumentation

such as a university office of research. Such placement might provide for more even-handed treatment of all users, would tend to make the instrumentation more visible to the central administration, would give the support staff wider visibility and potentially a more promising career path, and might reduce duplication and underuse. It could also provide more assistance to novice users who might want to learn how the instrumentation could facilitate their research. A highly skilled staff member could facilitate broader cross-fertilization of approaches and ideas by introducing users to each other and by disseminating novel ideas and techniques to the user community.

Possible disadvantages are that the office of research does not control space, does not have adequate budget control, does not have adequate staff to oversee technical staff, does not have the expertise, and does not have the interest. Furthermore, such centralization might be resisted by the dominant users who would have first-line responsibility and interest in ensuring the success of the facilities (their research success depends on it). Those users would most likely have invested more resources than others and would therefore expect to have more control. They might argue that a facility that is designed to serve all serves none well.

In contrast, when a facility is in a school or college, access by and service to other units often are not commensurate with the needs of the research community or the demands of the research programs involved. Hence, however organized in an institution, there should be, at a minimum, an institutionwide oversight group that ensures effective use of expensive instrumentation resources.

These are complex issues that need to be carefully addressed, but as the cost of instrumentation continues to rise and the demand expands, some institutional attention to these issues may yield a more satisfactory strategy than not having access to such instrumentation at all.

The recent (2005) National Academies Committee on Science, Engineering, and Public Policy report *Facilitating Interdisciplinary Research* (IDR) discussed this issue and recommended[5] that

> Institutions should develop equitable and flexible budgetary and cost-sharing policies that support IDR.
>
> For example, institutions can
>
> - Streamline fair and equitable budgeting procedures across department or school lines to allocate resources to interdisciplinary units outside the departments or schools.
> - Create a campuswide inventory of equipment to enhance sharing and underwrite

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[5] National Academies. *Facilitating Interdisciplinary Research.* Washington, DC: National Academies Press, 2004.

centralized equipment and instrument facilities for use by IDR projects and by multiple disciplines.

- Credit a percentage of a project's indirect cost to support the infrastructure of research activities that cross departmental and school boundaries.
- Allocate research space to projects, as well as departments.
- Deploy a substantial fraction of flexible resources—such as seed money, support staff, and space.

The committee supports the findings of the report and believes that adopting the outlined recommendations would greatly enhance the effectiveness and productivity of ARIF facilities.

INSTRUMENTATION FUNDING

Locating sufficient funding in a government grant to pay for a major instrument and its operation and maintenance costs is extremely challenging. When funding for instrumentation on university campuses is assembled, it is typically a combination of external funding (federal and nonfederal) and funding from the university itself. In some cases, those who use an instrument that is not part of their own laboratory may be required to pay user fees; funds to pay user fees may be part of a federal grant that supports the research being conducted.

For example, the federal government might be willing to support the capital cost of an instrument, but not its operation and maintenance costs. Operation and maintenance costs are typically paid by the institution. User fees may also offset a portion of those costs.

In the case of institutions that support instrument capital, operation, and maintenance costs, one option for doing so is through the institution's facilities and administration (F&A) mechanism[6] (see box). That can be challenging, how-

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[6] Some might argue that F&A costs already provide for building renewal and space upgrades. This is problematic. First, the allowed building component in the F&A rate may be only 5 percentage points or so of the 50% for the F&A rate (or 10% of total indirect cost if the rate is 50%). An institution with $500 million a year in grant activity will typically collect somewhere around $100 million in F&A reimbursements. At 10% for facilities this amounts to about $10 million to maintain, upgrade, and replace a research-intensive physical plant that may have a replacement value of $2-$5 billion or more. The $10 million or so for the buildings and improvements cost pool is an important contribution but pales in comparison with the costs of maintaining the physical plant that supports the research enterprise. (A related problem is the low cost basis for buildings that are 30-50 years old, whose original construction cost may have been only a few million dollars. Hence, the depreciation-related cost recovery is negligible compared with the cost of replacement.)

What Are Facilities and Administrative Costs?

Federally funded research is a prominent feature at all major American research universities today. Before World War II, however, federal support for research as we know it was virtually nonexistent. The situation changed dramatically during the war as the federal government invested heavily in the discovery and development of new technologic tools to support the war effort.

During and after the war, the Office of Naval Research engaged faculty members at universities to carry out contract research for special projects. In the process, institutional costs (known as overhead, indirect, or F&A costs today) were addressed. It became apparent that a successful university-based research infrastructure could expand and improve only if the costs incurred in connection with these Navy contracts—beyond the obvious direct costs of research—were reimbursed.

After World War II, discussions of F&A cost rates continued between universities and the federal government. In 1958, a formal and extensive set of guidelines for determining F&A costs was issued as Bureau of the Budget (today's Office of Management and Budget) Circular A-21. Circular A-21 has been revised over the years.

F&A costs are those involving resources (such as utilities and space) used mutually by different individuals and groups, so it is difficult to assess precisely which uses should pay what share. Direct costs are easily assigned to a specific research project and paid by its direct grant funding.

The F&A cost rate is calculated as follows. First, all F&A costs in the institutions are assigned to one of nine cost-pool groups related to primary functions. These include

ever; in 1991, the Office of Management and Budget placed a cap on the administrative costs for which universities can be reimbursed, an amount substantially less than the actual cost of research.[7] In addition, federal, as well as institutional, policy

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Likewise, the equipment pool may be 3-5 percentage points (of the 50% rate) and therefore generate $6-$10 million a year for all equipment needed to support the research enterprise, including the computing infrastructure of the institution, as well as such mundane things as desks, chairs, and filing cabinets for staff, new computers for employees (every 3-5 years), and vehicles for service personnel. Although some of those items have been reclassified technically as "supplies" in the last few years, the fact remains that the funds have to come out of the cost pools. In other words, although there is some money in the pools for equipment, the demands are so diverse and large that the pleas of the researcher often go unnoticed.

[7] Comments of Columbia University to National Science and Technology Council Research Business Models Subcommittee.

Facilities cost

- Buildings and improvements.
- Interest (on debt associated with certain buildings, and so on).
- Equipment (which includes only items of equipment purchased with nonfederal funds).
- Operation and maintenance (utilities and so on).
- Library.

Administration cost

- General administration (personnel, purchasing offices, and so on).
- Department administration (college and department staff).
- Sponsored projects administration.
- Student services administration.

Once all F&A costs attributable to research are identified and calculated for a fiscal year, the sum becomes the numerator in the F&A cost rate. The modified total direct costs for the corresponding year are the denominator. A component rate is calculated for each of the nine cost-pool groups.

For example, the University of Washington's on-campus organized F&A cost research rate in FY 2000 was 52%. That includes 26% for facilities and 26% for administration costs.

Source: Adapted from Kwiram, A. L. An overview of indirect costs. *Journal for Higher Education Strategists* 1(4):387-436.

may prohibit flexible strategies that would make acquisition of such instrumentation more feasible (for example, applying user fees to a sinking fund).

In a period of ever more constrained resources, there are no obvious solutions to the issue of whose responsibility it is to support the operation and maintenance of ARIF that are on university campuses but used for activities supported by federal agencies. The Research Business Models subcommittee of the Office of Science and Technology Policy's National Science and Technology Council provides a venue for such issues to be discussed by academic institution leaders, researchers and federal research agencies, although policies exclude consideration of financial changes to the current system.

SURVEY RESULTS

As part of its work, the committee conducted a survey of academic institutions to get a better understanding of the issues surrounding major instruments on university campuses. For the full results, see Appendix C. A few key items of interest are highlighted here. As discussed more fully in Appendix C, the committee does not consider the results of the survey to be representative of universities as a whole. The results underestimate the number of ARIF on university campuses and should not be used for budgeting purposes.

Of the institutions that responded to the commitee's survey, many did not have any ARIF. As shown in Figure 3-3, more than half the respondents do not have any ARIF that has been purchased or constructed in the last 5 years, and institutions that do have ARIF have only a handful.

The types of ARIF that were reported by institutions were in a wide array of science and engineering fields. Figure 3-4 shows the types of ARIF at the universities that responded to the survey, categorized by instrument or field. The most common individual instruments were magnetic resonance imagers and NMR spectrometers. A full list of the instruments and facilities reported can be found in Appendix C.

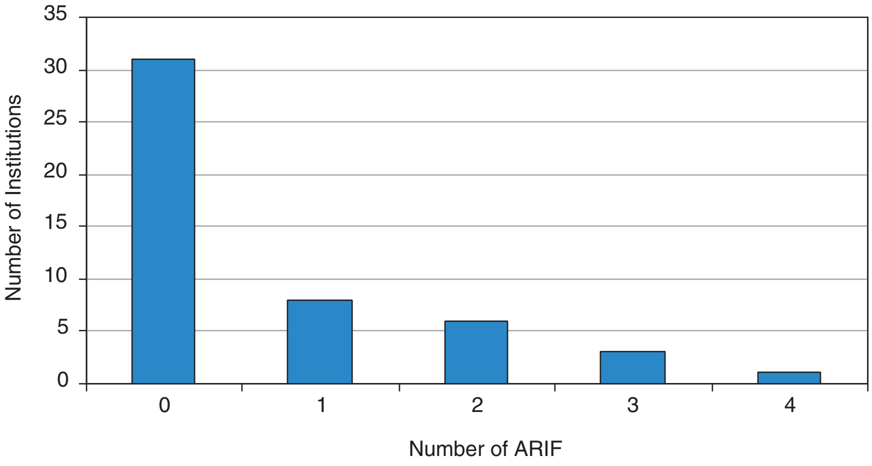

FIGURE 3-3 Number of ARIF reported by institutional survey respondents.
Source: Committee Survey on Advanced Research Instrumentation.

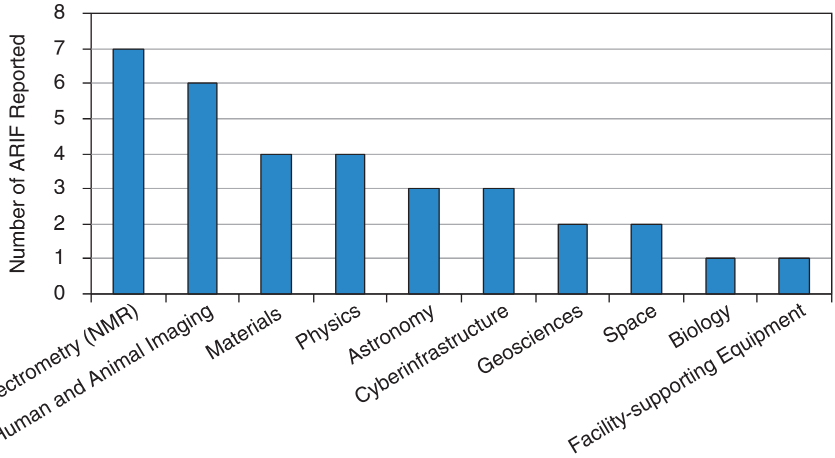

FIGURE 3-4 ARIF at institutions, by field.
Source: Committee Survey on Advanced Research Instrumentation.

The university administrators and instrument or facility managers were asked by the committee whether they had any thoughts concerning ARIF and whether they face any particular challenges with respect to ARIF. Figure 3-5 shows the frequency of the major categories of concern expressed by institutions. Most institutions commented on continuing costs or administrative challenges regarding the instrument.

Perhaps the most surprising results of the university survey concern the sources of support listed for the ARIF reported. Probably because of the high cost, 62% of the institutions reported more than one source of funding for the initial cost of ARIF acquisition. The distribution of numbers of funding sources is shown in Figure 3-6.

The host institution was the most common source of funding for ARIF. For almost half (48%) of the ARIF reported in the survey responses, the host institution was one of the sources of support. If all institutions and ARIF are totaled, host institutions were also the largest contributors of support for the initial capital cost for ARIF. Figure 3-7 shows the distribution of sources of support for ARIF. The largest and most common contributors were the host institution, NSF, and state governments.

As can be seen in Figure 3-8, the instrumentation reported in the survey falls into two categories. Most acquisitions fall just beyond the range of the present NSF

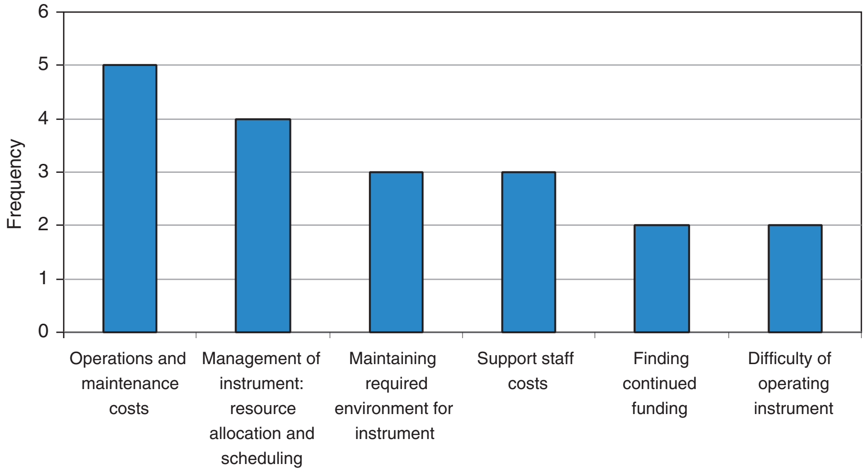

FIGURE 3-5 Major challenges that institutions face with regard to ARIF.
Source: Committee Survey on Advanced Research Instrumentation.

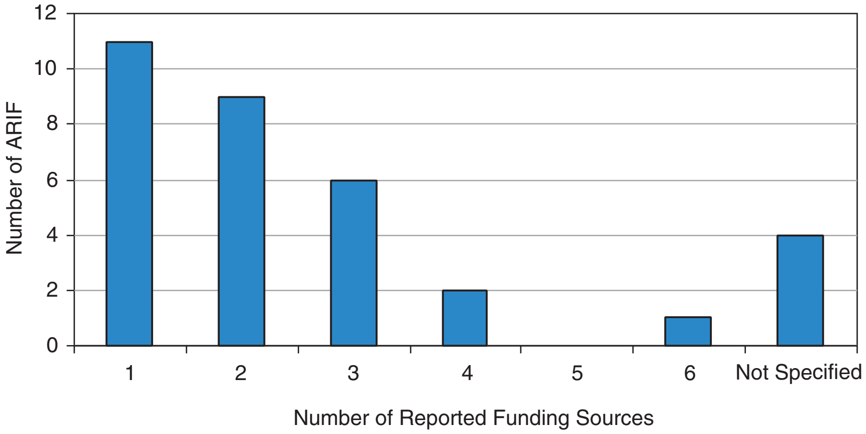

FIGURE 3-6 Number of funding sources specified.
Source: Committee Survey on Advanced Research Instrumentation.

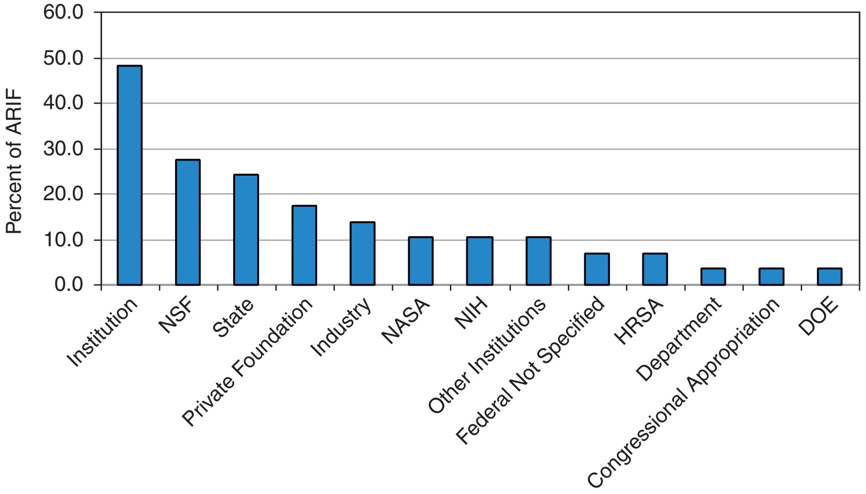

FIGURE 3-7 Frequency of ARIF capital cost sources of support.
Note: The fraction of ARIF supported by various funding sources. For example, institutions contributed to the capital costs of 48% of the ARIF reported.
Source: Committee Survey on Advanced Research Instrumentation.

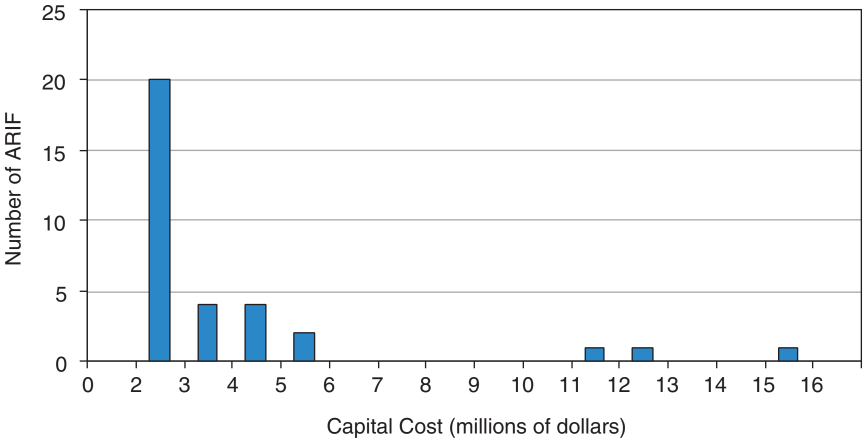

FIGURE 3-8 Itemized ARIF, by capital cost.
Source: Committee Survey on Advanced Research Instrumentation.

and National Institutes of Health limit of $2 million, with few special cases in the $10 million-$20 million window. The distribution suggests that there is a serious need for ARIF installations but that institutions can acquire them only if the price is within $1 million or so of the federal limit. No doubt other ARIF-category installations exist that were not reported, but it is likely that most of them required multiple funding sources. Moreover, often the true costs are significantly greater than the available funding, and frequently budget compromises are made at the expense of the technical support staff that is essential for effective operation.

The near-future needs for ARIF in the $2 million-$5 million range in universities are substantial, including tools for materials science and nanoscience, high-resolution transmission electron microscopes, NMR spectrometers, and beam lines for high-energy physics and biological and chemical applications. The full list (see Appendix C) no doubt underrepresents the need for instruments costing over $5 million; that few instruments in this category show up in the survey indicates that most institutions cannot fulfill such needs with their own resources. Thus, a serious task that lies ahead is to develop a more comprehensive catalog of genuine needs for the advancement of scientific research, to establish a priority ranking of the needs, and then to develop a systematic budget and scientific strategy for them.

FINDINGS

F3-1: ARIF are used by researchers in many science and engineering fields; reside in many settings, including universities and colleges, industrial laboratories, national laboratories, and independent research institutions; and are used by undergraduate students, graduate students, postdoctoral fellows, staff scientists, and faculty. Both workhorse and racehorse instruments play a critical role in educating and training the next generation of scientists and engineers for future employment opportunities.

F3-2: Anecdotal evidence suggests that development of new instrumentation in the academic setting is declining. A decrease in instrument development has the potential to hinder the overall advancement of ARIF, the research that uses ARIF, and the ability to provide the next generation of researchers with the skills and resources they need to use their imaginations to develop new kinds of instruments and techniques.

F3-3: Obtaining full support for ARIF can be challenging, because the costs involved include not only capital cost but costs of construction, development, siting, operation, maintenance, PhD-level technical research support staff, upgrading, and decommissioning. As a result, internal academic institution

funds are a major source of financial support for ARIF. Investing in such instruments requires relatively high-level decision-making. Locating funding for ARIF is difficult, so support often must be cobbled together from multiple sources, both federal and nonfederal, including academic institutions, independent research institutions, private foundations, and state legislatures.

Because of the need for substantial institutional resources, decision-making for most ARIF generally moves from department chair to dean to institution vice-president or vice-provost for research. That path has been extremely rocky in recent years because of federal agency practices, such as the requirement for matching funds (no longer the case), and the continuing erosion of state budgets for public institutions, which has in many cases largely eliminated line-item equipment budgets.

F3-4: Few academic institutions have well-defined policies or systematic provisions for career paths for PhD-level technical research support staff. A lack of administrative support places a burden on individual faculty members to locate resources for salaries. Maintenance of ARIF by graduate students or postdoctoral scholars is not cost effective; the expertise and thus the service level are too variable. Furthermore, the pedagogic value to graduate students charged with instrument support is limited, and the tenure of postdoctoral scholars is too short to provide continuity.

F3-5: Space for ARIF places special demands on an institution and can be quite expensive. Many ARIF require special environments that demand the renovation of existing space or the construction of new space. The costs of installation and appropriate utilities for ARIF often are not factored into the original acquisition cost and are thus difficult to support.

F3-6: When the federal government provides support for the capital cost of an instrument, it typically does not support the continuing operation and maintenance costs. Those costs are often borne by the academic institution or individual researchers. In some cases, operation and maintenance may be able to be supported through the general federal grants that offset the institution's overhead costs.

RECOMMENDATIONS

R3-1: Academic institutions should review their financial support and their planning and budgeting processes for ARIF to ensure that funds are identified to support existing instrumentation properly—including such elements as op-

eration and maintenance costs, technical research support staff, and space—and to provide the institutional resources necessary for researchers interested in developing instruments.

R3-2: Given that most ARIF are used for multidisciplinary and interdisciplinary research, the funding and management of such instrumentation should be structured so that it has institution-wide, or even user community-wide, characteristics and should be reviewed regularly in a performance-based manner. That could involve a more centralized management structure in an administrative office for research. Facilities organized in an academic institution may benefit from having an institution-wide oversight group.

R3-3: Academic institutions should enhance the career paths of PhD-level technical research support staff essential for ARIF by establishing long-term and stable staff positions for the lifetime of the instruments. These experts are vital to research involving ARIF, and their continued support would greatly enhance institutional and federal investment in ARIF.

R3-4: Academic institutions should continue to discuss the issue of federal agency support for operation and maintenance costs for instruments with the Research Business Models Subcommittee of the Office of Science and Technology Policy's National Science and Technology Council.

4

Federal Agency and Interagency Programs and Activities

This chapter describes current federal agency and interagency programs and activities for the support of instrumentation, particularly advanced research instrumentation and facilities (ARIF). The focus of this chapter is on federal programs and activities that support extramural instrumentation acquisition and development. Most of the federal programs described in this chapter use a peer-review process to evaluate proposals. This process differs among agencies and programs and is described most in depth in the section on the National Science Foundation (NSF).

HISTORICAL OVERVIEW OF FEDERAL FUNDING OF INSTRUMENTATION

The federal government has supported science for over 150 years, but World War II served as a great transition point in federal sponsorship of basic and applied research. With the government's support, the nation's science and engineering enterprises, especially in universities, made large strides and saw great growth. With the changing landscape of scientific research and the new discoveries that accompanied it, instrumentation became an increasingly important component of federal support of research.

A 1947 report from President Truman's Scientific Research Board, led by John R. Steelman, observed that complex instrumentation had become a vital component of modern science. The Steelman report noted that equipment, libraries, and laboratory space were all needed "not only in terms of the contemplated program of basic research, but to train scientists for research and development programs in the future." It also observed that the facilities and instruments needed for science were shifting "from mere shelter and relatively uncomplicated instruments to elaborate structures and expensive specialized equipment." Federal support of instrumentation has waxed and waned over the last 60 years. The late 1960s ended a period of expansion in science, but in the 1970s and 1980s instrumentation was singled out for federal attention as an important issue in science policy.

NATIONAL SCIENCE FOUNDATION PROGRAMS AND ACTIVITIES

In the first 10 years after the 1950 founding of the NSF, the agency increasingly recognized that costs of scientific instruments were outpacing the resources of universities and private patrons, and there arose an appreciation of a need for more federal support. NSF's 1957 report *Basic Research: A National Resource* highlighted a further issue: that the "continuing costs for operation and maintenance of large research equipment raise more problems than original construction costs."

National Science Board Findings on National Science Foundation Support for Infrastructure

In 2003, the National Science Board (NSB) released a report based in part on a survey of the needs of the individual NSF directorates and the Office of Polar Programs,[1] recognizing that the demand for advanced research instrumentation depends on research field. The NSB estimated that 22% of the NSF budget is devoted to infrastructure, a designation that includes hardware, software, technical support, and physical spaces or facilities. Among its key recommendations, the board called for increased investment in small- and medium-scale infrastructure and in cyberinfrastructure. It further recommended the development of new "funding mechanisms, as needed" to support midsize projects. The NSB estimates that 20% of infrastructure needs in FY 2003-FY 2012 will be for midsize projects (in the $1 million-$10 million range, totaling $3.95 billion).

To underscore the outstanding, high-priority advanced research instrumentation needs that remain unfunded, the board cited such examples as a replacement Artic-regional research vessel, the replacement or upgrade of submersibles, beam-

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[1] Computer and Information Science and Engineering (CISE); Mathematical and Physical Sciences (MPS); Geosciences (GEO); Biological Sciences (BIO); Engineering (ENG); Education and Human Resources; Social, Behavioral and Economic Sciences (SBE).

line instrumentation for radiation sources, upgrades of computational resources, and an incoherent scatter radar for atmospheric research.

The Major Research Instrumentation Program

NSF has one instrumentation program that is administered by the agency as a whole. The Major Research Instrumentation (MRI) program supports both instrument acquisition and development with awards that range from $100,000 to $2 million and aims to "increase access to scientific and engineering equipment for research and research training."[2] The program covers single instruments, large systems of instruments, sets of instruments that share a common research focus, and cyberinfrastructure. MRI-supported instrumentation is intended for "research-intensive learning environments".[3] Eligible institutions include both academic and non-degree-granting research institutions, such as independent nonprofit institutions, museums, and legally incorporated consortia of eligible institutions. Proposals that request a grant below the low end of the funding range ($100,000) are considered if they are from "small" academic institutions that award fewer than 20 PhD or DSci degrees per year or if they are for mathematical science, economics, or the behavioral or social sciences. Proposals that exceed $2 million are not eligible. In the past, the MRI program set aside funding for "small" academic institutions that awarded fewer than 20 PhD or DSci degrees per year. This is the first year in which the MRI program has received no congressional guidance on how much support should go to those institutions.

In FY 2005, the estimated budget for the MRI program is $90 million, down from the $112 million awarded in FY 2004. Table 4-1 shows the trends in proposals and awards for the last 6 fiscal years. In FY 2004, the last year for which there are data, the success rate for proposals was 39%, and the average award amount was $344,000. In total, 464 institutions submitted 837 proposals, and 260 institutions received 326 awards. NSF tracks the traditionally minority-group-serving and non-PhD-granting institutions as well. In FY 2004, the MRI program received 56 proposals from traditionally minority-group-serving institutions and 311 proposals from non-PhD-granting institutions. Those institutions had success rates of 43% and 44%, respectively, only slightly higher than the average of all institutions.

Despite a $2 million cap, the MRI program seldom funds projects at the upper end of its eligibility. The program priorities demand funding many instruments of lower capital cost. Of the 205 currently active NSF MRI awards, only 25 (12%) are

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[2] National Science Foundation, *Major Research Instrumentation Program (MRI)*. NSF 05-515. 2004.

[3] National Science Foundation, *Major Research Instrumentation Program (MRI)*. NSF 05-515. 2004.

TABLE 4-1 Major Research Instrumentation Program Proposals and Awards

Fiscal Year	Number of Proposals	Total Amount Requested (millions of dollars)	Number of Awards	Total Amount Awarded (millions of dollars)
1998	479	249	165	56
1999	472	262	166	57
2000	476	252	156	53
2001	741	304	310	79
2002	692	296	279	81
2003	757	352	280	91
2004	837	421	326	112
2005	*Not yet known*	*Not yet known*	*Not yet known*	*90*

Source: Brzakovic, D. "Major Research Instrumentation," Presentation to Council on Undergraduate Research, DIALOGUES 2005, April 18, 2005.

for amounts over $750,000.[4] Although the MRI program sometimes cofunds awards with other NSF instrumentation programs (typically five or six awards/year), none of these exceeds the $2 million limit.

The MRI program is centrally administered by the NSF Office of Integrative Activities (OIA). Proposals are prescreened by OIA to determine whether they are satisfactory and meet MRI proposal guidelines; there is a 5-10% return rate of proposals that are deemed either inappropriate or out of the scope of NSF support.[5] After that, review of proposals is divided among the individual NSF directorates.

Proposals are evaluated in a peer-review process carried out by interdisciplinary external review panels. Two merit-review criteria for the MRI program have been approved by the NSB: intellectual merit and the broader impact of the proposed activity. Consideration of broader impact includes evaluation of how well the NSF missions of research and education have been integrated and of the overall level of diversity of all proposed activity. Investigators are expected to address those issues in their proposals. The plan for use in education and training and, in the case of instrument development, the justification for the new instrument are also considered.[6]

Award funding is distributed to the directorates in proportion to demand. Figure 4-1 shows the distribution of the FY 2004 awards by directorate. The MRI program solicitation asserts that the program is intended to assist "in the acquisition or development of major research instrumentation by organizations that is, in

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[4] Results of an NSF Award Search conducted by the committee's staff online at http://www.nsf.gov/awardsearch/ on March 16, 2005.

[5] In 2005 the MRI program received 850 proposals, and 780 passed the initial OIA prescreening.

[6] Brzakovic, D. "Overview of the National Science Foundation (NSF) and the Major Research Instrumentation (MRI) Program," October 22, 2004. QEM Proposal Development and Evaluation Workshop, Atlanta, Ga.

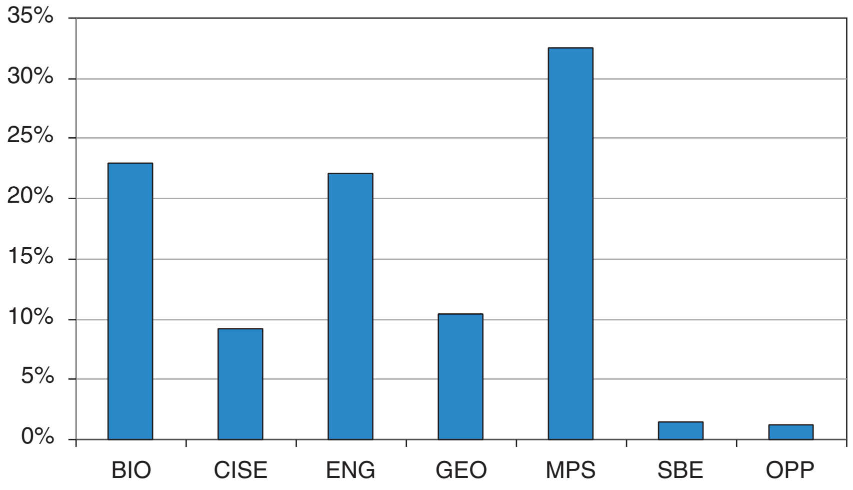

FIGURE 4-1 Major Research Instrumentation program FY 2004 awards by directorate.
NOTE: BIO: Biological Sciences; CISE: Computer and Information Science and Engineering; ENG: Engineering; GEO: Geosciences; MPS: Mathematical and Physical Sciences; SBE: Social, Behavioral and Economic Sciences; OPP: Office of Polar Programs.
Source: Brzakovic, D. "Major Research Instrumentation," Presentation to Council on Undergraduate Research, DIALOGUES 2005, April 18, 2005.

general, too costly for support through other NSF programs." Some directorates and divisions use the program in different ways to meet the needs of their scientific communities. CISE uses MRI program awards to support cyberinfrastructure, which can make incremental gains through smaller grants given every year. The Division for Materials Research (DMR) in the MPS sometimes splits grants between the DMR Instrumentation and Facilities program and the MRI program.

Historically, the MRI program allowed operation and maintenance costs to be included in the total amount of funding proposed for instrument acquisition. In addition, it was required that institutions contribute matching support totaling 30% of the award amount. In October 2004, NSF eliminated program-specific cost-sharing; in exchange, however, operation and maintenance costs are no longer provided for in MRI awards.

The MRI program still requires that a management plan be included with a proposal, and this plan is considered in the review process. In the case of an acquisition proposal, the management plan is reviewed with an eye to whether it includes sufficient infrastructure and technical expertise to allow effective use of the instrument and whether there is an institutional commitment for the continued operation and maintenance costs. In considering an instrument development proposal, reviewers evaluate whether the plan has a realistic schedule and whether mechanisms are in place to deal with potential risks.

An institution is limited to two MRI proposals per year, although a third may be allowed if it is for instrument development. Collaborating universities that wish to submit an MRI proposal jointly will each have one slot taken, unless the collaboration is legally incorporated. Researchers are sometimes placed in the position of negotiating with university administration if multiple MRI proposals are competing for the opportunity to be submitted to NSF. That is especially problematic in such fields as the social sciences, whose work depends heavily on shared databases and other such cyberinfrastructure.[7] In those fields, the MRI program is not particularly useful inasmuch as the continuing operation and maintenance costs are much higher than the initial capital investment.

The Major Research Equipment and Facilities Construction Account

NSF maintains an agencywide program for instrumentation and facilities called the Major Research Equipment and Facilities Construction (MREFC) account, which supports the “acquisition, construction, commissioning, and upgrading of major research equipment, facilities, and other such capital assets” costing more than several tens of millions of dollars.[8] Awards made through the MREFC account usually span several years. Proposals for new starts are first reviewed by an MREFC panel consisting of senior staff and are then approved and subjected to priority-setting by the NSB. MREFC awards are typically in the hundreds of millions of dollars and include such facilities as the Network for Earthquake Engineering Simulation, the Atacama Large Millimeter Array, the Laser Interferometer Gravitational-Wave Observatory, and Terascale Computing Systems. Unlike MRI proposals, MREFC proposals are reviewed by a special MREFC committee and by the NSB. Funding for construction is supplied centrally, and the operation and maintenance budget comes from an individual directorate. Because of the financial commitment involved, the review process for MREFC proposals is especially competitive, and NSF has a number of commitments that have been approved through the MREFC process but are still awaiting funding. In response to the National Academies report on large facilities, the NSB is reviewing its MREFC procedures.[9]

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[7] Committee’s staff conversation with Norman Bradburn, of the University of Chicago.

[8] National Research Council. *Setting Priorities for Large Research Facility Projects Supported by the National Science Foundation*. Washington, DC: National Academies Press, 2004.

[9] National Science Board, *Science and Engineering Infrastructure for the 21st Century: The Role of the National Science Foundation*. Arlington, Va.: National Science Foundation, 2003.

The NSB found that the total budgets of the MRI and MREFC programs account for less than one-third of the agency's support for infrastructure.[10] Most instrumentation support occurs in individual NSF directorates. Because of the differing instrumentation needs of the research communities they support, some directorates depend on these agencywide programs more than others.

Support for Advanced Research Instrumentation and Facilities

NSF has no agencywide program for instrumentation or facility needs that fall in between those met by the MRI program and those met by the MREFC account, that is, for ARIF. Support offered for ARIF differs widely among the various NSF directorates. The following analysis is based on the committee's staff's conversations with NSF staff.

The NSF directorates and their divisions support ARIF in a number of ways. Some divisions have accounts specifically set aside for ARIF; proposals go through a peer-review process that may or may not be publicized through solicitations for competition. Most ARIF projects are funded through a combination of NSF programs. The most straightforward examples of ARIF support are outlined in the following two sections.

The Instrumentation for Materials Research–Major Instrumentation Projects Program

The MPS DMR releases the only solicitation, or request for proposals, for an advanced research instrumentation program. The Instrumentation for Materials Research–Major Instrumentation Projects (IMR-MIP) program is similar to the MRI program in that it supports the construction or acquisition of instrumentation but not its continuing operations and maintenance.[11] Traditionally, the researcher who builds the instrument is able to use it for 25% of the time. Use of the remaining time available is determined by the institution, which may charge user fees to researchers who wish to use the instrument. The program's budget is \$3-\$4 million but, on the basis of an assessment of need, DMR argues that \$25 million at steady state would be more appropriate. Among the instruments that DMR has supported under this program are a specially constructed 900-MHz wide-bore nuclear magnetic resonance (NMR) (about \$16 million) that resides at the Na-

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[10] See Figure 1-1 for 2004-2006 statistics.

[11] National Science Foundation, *Instrumentation for Materials Research–Major Instrumentation Projects (IMR-MIP)*. NSF 05-513. 2004.

tional High Magnetic Field Laboratory and new beamlines for neutron sources. An IMR-MIP grant partially funded a recently constructed National Institute of Standards and Technology beamline with additional support from the NSF MRI program and supplemental funding from Johns Hopkins University.

Geosciences Support for Advanced Research Instrumentation and Facilities

The 2003 NSB report on science and engineering infrastructure specifies that GEO spends about 36% of its total budget on infrastructure, well above the NSF average of 22%.[12] The unusually large dependence on infrastructure is due to the inherently observational nature of geoscience research, which requires modern research vessels, aircraft, and ground-based deployment of networks of sensors, such as seismometers, global positioning system stations, and strain meters. The high cost of some of those needs must be met through NSF's MREFC account, but many fall in the category of ARIF.

To meet the rising need for instrumentation and facilities in the $2 million-$20 million range in the earth, ocean, and atmospheric sciences, the three divisions of GEO each recently created accounts for the support of ARIF. Those accounts, each of $7 million-$12 million, were created in the last 3 years by diverting existing funding in response to pressure from the scientific community. Operation budgets are not included in awards made from the accounts. Project ideas are sometimes developed through workshops at NSF. Although no program solicitations are released to advertise the accounts, the need in the three research communities is sufficient that proposals are carefully planned by groups and submitted proposals are subject to a competitive, peer-reviewed process. Because of the coordinated, observation-based nature of the geosciences and the conservative budgetary climate, GEO prefers this approach to the release of grant solicitations. GEO estimates the total present need for ARIF funding in geosciences to be $500 million.

The Atmospheric Sciences Division is funding the Advanced Modular Incoherent Scatter Radar (AMISR) with its ARIF account. A phased-array radar system for studying the upper reaches of the earth's atmosphere and ionosphere has a total cost of $44 million and is treated with the same rigor and planning as MREFC projects. The division plans to have a separate 5-year award for operation for the AMISR project. The Earth Sciences Division had used its account primarily for large cyberinfrastructure projects. In both divisions, networks of distributed sensor systems constitute instrumentation that requires additional support.

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[12] National Science Board. *Science and Engineering Infrastructure for the 21st Century: The Role of the National Science Foundation.* Arlington, Va.: National Science Foundation, 2003.

The Earth Sciences Division also has an instrumentation program, Instrumentation and Facilities, with a budget of $30 million per year, with roughly $7 million for new awards for instrumentation acquisition every year.[13] The Instrumentation and Facilities program supports the acquisition of new research equipment, instrumentation and technique development, shared facilities, and technical staff. About 60% of the Instrumentation and Facilities program budget goes to 15 national and regional multiuser facilities managed by university consortia with annual budgets of $200,000 to $15 million. Most of those facilities depend on the program for the support of continuing costs, including costs for personnel, although some are still being set up and require more support for instrumentation acquisition. The remaining 40% of the Instrumentation and Facilities program budget goes to individual awards. There is no budgetary limit on proposals for instrumentation acquisition, but investigators who want to request more than $500,000 are asked to contact the program directors before submitting proposals. Technical staff support awards are made for at least 3 years and may be continued for an additional 2 years. The awards for salaries are set at a maximum of $80,000/year, and many go to PhD-level staff. A number of institutions have established permanent positions for personnel supported through those awards.

NATIONAL INSTITUTES OF HEALTH PROGRAMS AND ACTIVITIES

An estimated 1.4% ($400 million) of the National Institutes of Health (NIH) budget went to instrumentation in FY 2004. That estimate includes instrumentation purchased by investigators through NIH R01 research grants under $250,000; these no longer require itemized budgets, so it is difficult to determine how much has been spent on equipment. NIH has two established instrumentation programs, both of which are below the threshold for ARIF. The programs, which are both intended for acquisition and are thus a year in duration, do not support operation and maintenance. The Shared Instrumentation Grant Program supports instrumentation in the $100,000-$500,000 range and has an annual budget of $49 million. The High End Instrumentation (HEI) program, announced every 2 years, supports instrumentation in the $750,000-$2 million range and has an annual budget of $21 million. Combined, the programs constitute less than 20% of the estimated NIH investment in instrumentation. Both programs require that a proposal be submitted by a group of at least three NIH-funded or NIH-recognized investigators. Note that NIH's primary mechanism for directly funding the con-

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[13] National Science Foundation, *Earth Sciences: Instrumentation and Facilities (EAR/IF)*. NSF 05-587. 2004.

struction or renovation of biomedical research facilities is the Research Facilities Improvement Program. Grants from this program fund only the "bricks and mortar" of facilities construction and renovation and cannot be used to purchase research equipment or instrumentation.[14]

Although the $2 million cap on the HEI program excludes complete support of purchase costs of advanced research instrumentation, NIH uses several practices to fund instruments valued over $2 million. The HEI program will partially fund instrumentation that exceeds the limit. That has been done in the case of synchrotron beamline end stations, biomedical imagers, high-end computing clusters, and high-voltage electron microscopes. If the price of an instrument exceeds $2 million, funding is usually sought elsewhere. Additional support typically comes from the principal investigator's institution or from private agencies.

NIH will also set aside money for specific instruments when it sees a need. That was the case for the 900-MHz NMR, the most expensive commercially available NMR. The NIH National Institute of General Medical Sciences has, in years past, released two requests for applications specifically for the 900-MHz NMR, and NIH sees no additional demand for such machines in the biomedical research community.

NIH has no MREFC-like program, although two units (the National Center for Research Resources and the National Institute for Biomedical Imaging and Bioengineering) fund about 70 research centers through the Biomedical Technology Resource Center Program (P41). With an annual budget of about $100 million, these facilities focus mainly on the development of new technologies and instrumentation. The P41 centers provide complex and expensive instruments that are difficult for individual institutions to acquire and maintain. Each center provides a multidisciplinary environment that fosters collaboration among investigators and maintains staff scientists. The centers work closely with industry on NMR, electron paramagnetic resonance, magnetic resonance imaging, and electron microscopy. Requirements for continued support include a technology development program that can be evaluated, external collaboration for input on development, provision of access to researchers, training, and dissemination to ensure that the tools and technologies that a center develops reach the widest possible array of users. The annual budget ceiling for a P41 center is $700,000 in direct costs, excluding instrumentation. A budget ceiling of $500,000 for instruments is in place for any given project grant. Support from other sources is often required for equipment purchases that exceed that limit.

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[14] National Institutes of Health Working Group on Construction of Research Facilities. *A Report to the Advisory Committee of the Director, National Institutes of Health.* July 6, 2001.

DEPARTMENT OF ENERGY PROGRAMS AND ACTIVITIES

The Department of Energy (DOE) Office of Science has six program offices[15] that sponsor basic research primarily with support and oversight by the national laboratories. Each of the program offices informally supports research at universities that supplements work done at the national laboratories.

The Office of Basic Energy Sciences (BES), for example, had a FY 2005 budget of $1.1 billion. About half of the budget is dedicated to research, and $500 million goes to the construction, operation, and maintenance of national research facilities. BES does not have any dedicated programs for instrumentation, but it funds instrumentation of all sizes through its programs, particularly through its support of facilities, including in FY 2005

- $2 million for instrumentation upgrades at the High Flux Isotope Reactor Facility.
- $5.5 million for the development of a next-generation Transmission Electron Aberration-corrected Microscope. This is coordination among five electron beam microscopy efforts—four at national laboratories and one at the Frederick Seitz Materials Research Laboratory at the University of Illinois at Urbana-Champaign. The total budget for the project is $25 million.
- $300 million for the Nanoscale Science Research Centers at five DOE-funded national laboratories. The first occupancy at one of these facilities will be in April 2005.
- $50 million-$60 million Linear Coherent Light Source (over many years).
- $7.5 million for seven new instruments at the Spallation Neutron Source ($75 million over 10 years).
- Continued support of beamlines.

BES both builds and operates its national laboratories and facilities. In taking on the construction of facilities, it also takes on responsibility for the facility after commission, supporting operation, maintenance, and upgrades as needed. BES funds operations at the Advanced Photon Source, which was also managed during construction by BES on a separate project line. There are similar plans for the Spallation Neutron Source once construction is completed.

Historically, if the university retained the title to a facility, BES provided grant

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[15] The six program offices are the offices of Advanced Scientific Computing Research, Basic Energy Sciences, Biological and Environmental Research, Fusion Energy Sciences, High Energy Physics, and Nuclear Physics. Each of the program offices informally supports research at universities that supplements work done at the national laboratories.

support to the university to maintain it. It was found that consortia of universities and industry responsible for the management of a facility often broke down after 5-10 years. BES has modified its policies, and each facility now has administrative staff who are directly responsible for the management of operation and maintenance.

DEPARTMENT OF DEFENSE PROGRAMS AND ACTIVITIES

The Department of Defense maintains one program that supports the acquisition of research equipment, the Defense University Research Instrumentation Program (DURIP). The objective of the program is to improve the capability of academic research institutions to conduct research in fields important to national defense, and to educate scientists and engineers in those fields. In FY 2004, the program had $44 million available for awards.[16] About 100-120 awards are given each year, and the average grant size is about $700,000. Individual grants supported by DURIP range from $50,000 to $1 million, although the upper limit is flexible and may accommodate proposals up to $1.5 million. The program also allows for the partial funding of instruments. The success rate of proposals is roughly 20%. Award money is divided among the Army, Navy, and Air Force.

DURIP awards support the installation of instruments, excluding building renovation and construction, in addition to capital costs. The program does not support operation and maintenance. If the instrument is part of a user facility, there are no restrictions on user fees as long as the plan to charge them has been included in the proposal. The program supports both multipurpose and state-of-the-art instruments. There are no review restrictions related to geographic location.

The Defense Advanced Research Projects Agency does not have any programs for the support of instrumentation and evaluates requests for support case by case.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION PROGRAMS AND ACTIVITIES

The National Aeronautics and Space Administration (NASA) allows universities and research groups at NASA centers to compete for instrument development projects. Because of NASA's mission, many advanced instruments are specially designed for space and atmospheric missions and vehicles, and the agency is more likely to support instrument development projects than acquisition of commercially available ARIF. Both the Science Mission Directorate (which manages missions for space satellites, planes, and balloons) and Human Spaceflight (which

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[16] Department of Defense. *Defense University Research and Instrumentation Program (DURIP).* AFOSR BAA 2004-3. FY 2005.

manages the shuttle missions) release solicitations for proposals for instruments to be developed for such missions. Sometimes, the Science Mission Directorate solicits proposals for entire missions, including the development of the spacecraft in which instruments will be housed, and operation after the launch. Investigators who are interested in developing an instrument and who need several millions of dollars to do so often partner with industry to secure the initial research and development funding in the hope that this will later lead to flight opportunities and support by the agency.

NASA also supports longer-term research not tied to specific missions. The Science Mission Directorate regularly releases solicitations for Cooperative Agreement Notices that entail partnering with an academic institution, with awards reaching $1 million per year for five years. The NASA Astrobiology Institute currently supports sixteen "nodes" through this mechanism. The Exploration Systems Mission Directorate also grants such awards for University Research Engineering and Technology Institutes in various disciplines, such as nanotechnology.

The NASA Science Mission Directorate also maintains the Research Opportunities in Space and Earth Science (ROSES) program, which releases 60 solicitations each year supporting basic research, including such topics as land use and cover, ecology, ocean biology, atmospheric science and satellites, earth surface and interior science, Mars data, sample returns, solar science, and x-ray astronomy.[17] The ROSES program includes several solicitations for proposals for instrument development, acquisition, and improvements. The median grant size for ROSES programs is $50,000-$100,000. Technology development awards can range from $500,000 to $750,000 per year for 3 years, and some can be as much as $2 million.

ROSES includes the Sample Return Laboratory Instrument and Data Analysis (SRLIDA) program, with a budget of $6.7 million in FY 2005. SRLIDA seeks to maximize the scientific yields from sample return missions by funding projects to develop new analytic instrumentation or to improve existing instrumentation. SRLIDA requires cost-sharing and highly values evidence of a long-term institutional commitment.

DEPARTMENT OF HOMELAND SECURITY PROGRAMS AND ACTIVITIES

The Department of Homeland Security (DHS) supports research through its Directorate of Science and Technology to enhance the nation's security. The pri-

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[17] National Aeronautics and Space Administration. *Research Opportunities in Space and Earth Science—2005* (ROSES-2005).

mary focus of the directorate is the development and improvement of instrumentation and equipment that can prevent, detect, diagnose, and facilitate responses to chemical, biological, radiological, nuclear, and explosive threats. Because of its mission, the agency is more likely to fund instrument development projects than instrument acquisition.

Investigators who desire to begin an instrument development project have three primary ways to pursue support from DHS. An investigator can directly solicit one of the seven Homeland Security Centers for Excellence, which are in universities. The Homeland Security Centers for Excellence have annual research budgets of $4 million-$5 million.

An investigator may also contact one of the portfolio directors at the DHS Directorate of Science and Technology. Fields supported include the development of countermeasures (biological, chemical, radiological and nuclear, and high-explosive) and such fields as cybersecurity, transportation security, and emergency response. Urgently needed technology may be supported under the Rapid Prototyping portfolio.

A third option is to contact the Homeland Security Advanced Research Projects Agency, which may release a Broad Area Announcement (BAA) publicly requesting proposals for the project in question. A BAA is often left as an open-ended solicitation with no budgetary limit specified, so relevant development proposals that qualify as ARIF would be allowed.

US DEPARTMENT OF AGRICULTURE PROGRAMS AND ACTIVITIES

The US Department of Agriculture (USDA) includes the Agricultural Research Service (ARS) as its intramural research agency and the Cooperative Research Education and Extension Service (CREES) as its extramural research agency. Both support agricultural and environmental research, including plant, animal, natural resource, food, and human nutrition research. Because of the mission-driven nature of the agency, it is more likely to support instrumentation development projects. A researcher interested in an instrumentation development project may unofficially solicit ARS or apply for a grant through CSREES. ARS and CSREES also work together on occasion to support collaborative arrangements.

Roughly 85% of USDA's $2 billion research budget is for intramural research, which occurs in ARS. The 100 ARS centers are around the country and employ over 2,000 scientists. Half the centers are on college or university campuses. ARS has no specific mechanism for grants to university laboratories and investigators, although the ARS centers on academic campuses often have cooperative agreements that govern such factors as space, instrument use, and graduate students. A number of congressional directives and allocations govern the direction of the ARS budget.

CREES administers competitive grants for research and education in addition to direct funding for research at land-grant and other institutions and congressionally allocated funding for research, education, and other local activities. Among the competitive grants managed by CREES is the National Research Initiative, which is a broad research grant supporting scientific activities related to agriculture, food, and the environment.

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION PROGRAMS AND ACTIVITIES

The majority of the research and development budget of the National Oceanic and Atmospheric Administration (NOAA) goes to intramural research. ARIF is used for NOAA's ecosystem, climate, water, and weather missions and for mission support. Examples include the Aquarius Undersea Laboratory (about $5 million), the distributed Climate Reference Network (about $2 million), and a phased-array radar (about $10 million). Most extramural research grants are for research activities related to NOAA's mission rather than the purchase of instrumentation or facilities. Given the observational nature of NOAA's research and the objective of making resources as widely available as possible, the agency funds and manages more of its instruments and facilities. Most advanced research instrumentation funded by NOAA is not commercially available but is developed by the agency, often in conjunction with others, including the US Navy, the Federal Aviation Administration (FAA), universities, industry, NSF, and NASA. Commercially available instruments are sometimes modified and used as part of larger instrumentation.

INTERAGENCY ACTIVITIES

Today, the frontiers of science and engineering are increasingly interdisciplinary. Neutron and synchrotron radiation, for example, was once just the domain of physicists. Now, new instrumentation makes it possible to provide neutron scattering techniques for use in condensed matter physics, materials science, chemistry, biology, molecular characterization, and geophysics.[18] Synchrotron radiation facilities are now used heavily by biomedical researchers for many purposes, including the development of protease inhibitors for the treatment of HIV.[19]

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[18] OSTP Working Group on Neutron Science. *Report on the Status and Needs of Major Neutron Scattering Facilities and Instruments in the United States*. Washington, DC: Office of Science and Technology Policy, June 2002.

[19] NIH News Release. NIH and DOE to upgrade synchrotron X-ray research facilities in California and New York, July 21, 1999.

Largely stewarded by DOE, the nation's neutron and synchrotron facilities receive the support of NSF and NIH for upgrades and development. In addition to instrumentation that has evolved to serve many distinct research needs, there are fields, such as nanoscience and supercomputing, that bring together many traditionally disparate scientific disciplines. With an increasing need for instrumentation and cross-disciplinary science, federal agencies are finding more and more reasons to work together. Agencies collaborate to evaluate need in particular disciplines and to coordinate investments and jointly fund programs. There are no particular models for interagency collaboration.

Agencies have coordinated in a number of ways to evaluate the needs of particular scientific fields and the efficacy of existing programs. DOE and NSF share the High-Energy Physics Advisory Panel, an external advisory committee composed of researchers that advises agencies about pressing issues and long-range concerns related to high-energy physics. The Networking and IT R&D Program and Next-Generation Internet, both large efforts to improve the nation's cyberinfrastructure as a whole, involve interagency coordination and evaluation. Specialized programs—such as the Alliance Workshops on Propulsion and Power Systems involving NASA, Department of Defense (DOD), DOE, FAA, and industry—exist to accumulate and share research results and directions. The Global Climate Science Program of NOAA, DOE, and NSF was organized to coordinate individual agency investments with an eye to the field at large. On the basis of its findings, NOAA, DOE, and NSF made investments in their institutions to look at the ecological effects of climate change.

In addition to efforts spearheaded by federal research agencies, the Office of Science and Technology Policy (OSTP) and the cabinet-level National Science and Technology Council (NSTC), chaired by the president, serve as mechanisms for monitoring current and pressing issues in science and planning for the future. OSTP organizes interagency working groups that bring representatives together from various federal agencies to evaluate needs in particular fields of study. Among recent groups were the Working Group on Structural Biology at Synchrotron Radiation Facilities, the Working Group on Physics of the Universe, and the Working Group on Earth Observations. In 2002, the Working Group on Neutron Science released a report on the status and needs of neutron facilities that recommended that there be continued interagency collaboration through OSTP and increased coordination between national user facilities and between researchers in related groups and disciplinary societies. It identified the needs of neutron science to include the upgrade and enhancement of instruments and the development of new source technologies and scattering methods. The report further identified expanding the scope of neutron scattering to other fields as a worthwhile goal.

OSTP has stated that it does not have the resources to administer interagency coordination, although in cases of special need it has done so. The office was involved in collaboration between DOE and NSF for the Large Hadron Collider, and it has participated in the International Fusion Project. Another factor that limits OSTP's ability to foster interagency collaboration is the shift in priorities between presidential administrations. The interagency Climate Change Science Program has had many sponsors over the years. Originally informal in the 1980s, it later officially came under the purview of the US Global Change Research Program (USGCRP). During the Clinton administration, responsibility for the USGCRP shifted to OSTP, and it is now led by the Department of Commerce.

Under the purview of the NSTC Committee on Technology, the Subcommittee on Nanoscale Science, Engineering, and Technology (NSET) meets to coordinate the National Nanotechnology Initiative. Its scope includes "planning, budgeting, implementation, and review" of agency efforts in research and development for NSET.[20] The subcommittee is composed of representatives of 20 federal agencies and departments. In addition to functioning in an advisory capacity and providing technical expertise, the subcommittee helps to implement the recommendations of other advisory organizations, including the President's Council of Advisors on Science and Technology and the National Research Council.

The NSTC Research Business Models (RBM) Subcommittee is a standing group that examines the effectiveness of the federal research and development enterprise. Under RBM, the Working Group on Alignment of Funding Mechanisms and Scientific Opportunity is examining agency mechanisms for the support of instrumentation.

In addition to interagency efforts that focus on evaluation, agencies have collaborated on projects and programs. In 1999, DOE and NIH cosponsored an upgrade of two DOE synchrotron facilities. Recognizing the need for such facilities in the biology community, NIH funded half of a $58 million upgrade of the Stanford Synchrotron Radiation Laboratory at the Stanford Linear Accelerator Center and provided $4 million for upgrades at the National Synchrotron Light Source at Brookhaven National Laboratory. DOE and NIH also cosponsored the longer-term Human Genome Project. Begun in 1990 and completed ahead of schedule in 2003, the success and early completion of this project were due in part to the investments in technologies for more efficient DNA sequencers. Databases and analysis algorithms were also developed to store and parse results.

One type of interagency coordination is a memorandum of understanding, a recognition of individual agency funding efforts with an eye to maximizing the benefit. For a number of years, NSF and NIH maintained a memorandum of

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[20] NSTC/NSET Terms of Reference.

understanding to jointly fund deserving awards up to $900,000. Researchers, including those who may have required funding for projects categorized as advanced research instrumentation, were welcome to apply to both the NIH HEI program and the NSF MRI program for partial instrumentation support. The arrangement was discontinued by NSF in 2004 because of concerns that such efforts were too distant from the NSF mission and strained an agency budget that was small compared with that of NIH.

FEDERAL PHD-LEVEL TECHNICAL RESEARCH SUPPORT STAFF CAREER DEVELOPMENT AND SUPPORT PROGRAMS

To obtain better efficiency and reliable results, researchers and laboratories often require a knowledgeable staff to maintain and operate instruments and facilitate the use of instruments by nonspecialists. That is especially true in the case of ARIF. PhD-level technical research support staff are increasingly important to the research enterprise, not only to keep important instrumentation functioning but often to assist in the development of new instrumentation and techniques.

Among the federal research agencies, few programs recognize and support technical research staff in university laboratories. The NSF Earth Sciences Division of GEO provides awards for technical staff salaries through its Instrumentation and Facilities program, as described earlier. The DOE supports nonfaculty staff with advancement programs similar to the tenure-track system. Outside of those, however, there are few ways for university laboratories to obtain federal support for the salaries of research and technical staff. Furthermore, no awards are given by agencies to outstanding staff at university laboratories to serve as a mechanism for career recognition and advancement.

SUMMARY AND ANALYSIS

This chapter has described the various federal agency programs and mechanisms by which instrumentation for extramural research is supported. On the basis of the public information provided by the agencies and discussions with agency staff, the committee has found that a number of federal instrumentation programs support the acquisition and development of instrumentation, although few are designed specifically for ARIF. Many ARIF are funded on an ad hoc basis through informal mechanisms for support, usually involving discussions with agency staff and a considerable amount of time and knowledge on the part of the investigator. Agency programs and practices that may support extramural acquisition and development of instrumentation are summarized in Table 4-2.

In addition to meeting with agency officials, the committee benefited in its

TABLE 4-2 Federal Agency Programs and Practices for the Support of Instrumentation

Agency	Instrumentation Program	Description
National Science Foundation	Major Research Instrumentation (MRI) program	$100,000-$2 million for instrument acquisition and development; capable of partially funding ARIF, although such support is unlikely; support does not include continuing costs
	Major Research Equipment and Facilities Construction (MREFC) account	Supports major facilities in the tens of millions of dollars and above
	Instrumentation for Materials Research–Major Instrumentation Projects (IMR-MIP)	Supports ARIF, although program's budget is small ($3-$4 million); support does not include continuing costs
	Earth Sciences Instrumentation and Facilities (EAR-IF)	$7 million for new awards; support available for instrument acquisition and development, technical staff; there is no budgetary limit on awards other than those designated for staff
	Other programs	Other NSF programs support instrumentation and facilities with limits much less than $2 million, although partial and coordinated funding is possible
	Informal	Researchers may discuss with staff in various divisions; communities expressing great need may be accommodated with workshops and discussions leading to further support
National Institutes of Health	High-End Instrumentation (HEI) program	Capable of partially funding ARIF with $750,000-$2 million awards for instrumentation acquisition; proposals must be from a group of at least three NIH-funded investigators; does not support continuing costs
	Shared Instrumentation Grant (SIG) Program	$100,000-$500,000 for instrumentation acquisition; proposals must be from a group of at least three NIH-funded investigators; does not support continuing costs
	Informal	If need for particular instrument is sufficiently expressed by research community, a special request for proposals may be released
Department of Energy	Informal and principally at national laboratories	Supports instrumentation needs at national laboratories and at universities supporting national laboratory efforts
Department of Defense	Defense University Research Instrumentation Program (DURIP)	$50,000-$1 million in individual grants for acquisition of research equipment; does not support continuing costs

continued

TABLE 4-2 Continued

Agency	Instrumentation Program	Description
National Aeronautics and Space Administration	Research Opportunities in Space and Earth Science (ROSES)	Average $100,000 research grants, including instrumentation development, acquisition and improvements under specific solicitations
	Cooperative Agreement Notices	Grants to institutions that can be in the $1 million range over a period of five years. Support research, including instrument acquisition.
	Mission-specific solicitations for proposals	Investigators interested in developing instrumentation for use in missions on space shuttles, satellites, planes, and balloons can respond to specific solicitations sent out by Science Mission Directorate and Human Spaceflight
National Oceanic and Atmospheric Administration	None for university laboratories	Supports instrumentation for intramural research, which includes collaboration with universities
Department of Homeland Security	Homeland Security Advanced Research Projects Agency (HSARPA) broad-area announcement	Grants for research in particular fields, most likely to obtain support for instrument development projects in particular fields needing new security technologies
	Informal	Instrument development projects are more in line with the agency's mission; researchers may discuss with science and technology portfolio directors
	Homeland Security Centers for Excellence	University centers that receive DHS grants that may be available for collaboration
US Department of Agriculture	National Research Initiative (NRI)	General research grants that can support instrument development projects
	Informal	Researchers may discuss with staff

understanding of federal agency support of ARIF from responses to its survey of research institutions, primarily colleges and universities. While the committee is aware that the survey results are not representative of ARIF on university campuses, the data on sources of support for individual ARIF proved to be helpful.[21] Figure 4-2 shows the proportion of ARIF at institutions that were supported by various sources; more than half the ARIF reported had more than one sponsor.

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[21] More information on the survey and its limitations is located in Appendix C.

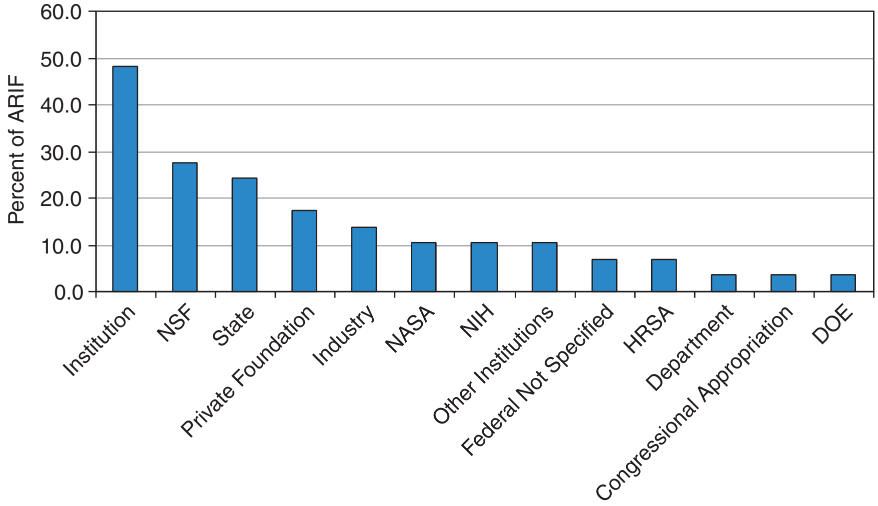

FIGURE 4-2 Frequency of ARIF capital cost sources of support.
Note: The fraction of the ARIF supported by various funding sources. For example, institutions contributed to the capital costs of 48% of the ARIF reported.
Source: Committee Survey on Advanced Research Instrumentation.

The most common sources of funding for ARIF were the host institutions, NSF, and the states. Figure 4-3 indicates the total amount (over all survey responses) of funding from each reported source.

Data on ARIF support from NSF were particularly surprising. Three instruments had NSF support for well over $2 million ($3.9, $4.4, and $2.7 million). That yielded an average award amount of $2.3 million. Particular programs by which this NSF funding was acquired were not listed. We speculate that the support was obtained through individual NSF divisions.

FINDINGS

F4-1: Long-term, sustained support of ARIF is a critical element of effective investment in research. Unstable investment in instrumentation negatively impacts research as well as the attractiveness of technical research support careers vital to research involving ARIF.

F4-2: A rapidly increasing number of instruments essential for the research enterprise are crossing the $2 million capital-cost maximum of federal instru-

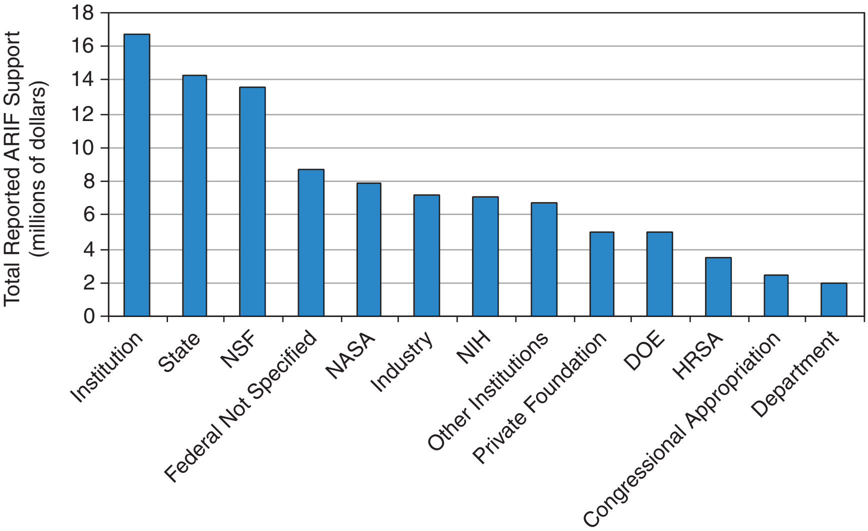

FIGURE 4-3 Total ARIF capital cost support, by source.
Source: Committee Survey on Advanced Research Instrumentation.

mentation programs at NIH and NSF. The cost of many essential next-generation instruments is moving across the $2 million boundary, including 900-MHz and 1-GHz NMRs and electron microscopes. Increased costs and specialization have created a void in federal programs inasmuch as only a few disciplinary programs permit proposals greater than that limit.

F4-3: Obtaining support for the operation and maintenance of ARIF is even more challenging than obtaining the initial capital investment. On the basis of its survey, the committee saw that finding funding for the continuing operation of an instrument or facility is difficult. For many types of ARIF, such as cyberinfrastructure, that is especially problematic, because the continuing costs may be much higher than the initial capital investment.

F4-4: Current federal agency planning and budgeting information is inadequate, given the level of resources involved. Because agencies generally respond to requests for ARIF on an ad hoc basis, the mechanism by which researchers can apply for support for the acquisition or construction of instrumentation is not clear. Few formal programs that can serve as models have been developed.

F4-5: The lack of formal programs for ARIF leads to inconsistent evaluation criteria and makes it harder for agencies to incorporate agency goals—such as research-field, geographic, institution, and researcher diversity—or requirements that instruments be shared in ways that maximize their utility. A well-planned peer-review system is essential to this process.

F4-6: Few federal research agency programs are in place for the support of PhD-level technical research support staff, who are critical to research involving ARIF.

F4-7: OSTP, via the NSTC, provides a mechanism for enhancing coordination, planning, and budgeting among federal agencies in that it can organize regular meetings that may serve as a clearinghouse for ARIF program ideas. Coordination is needed among federal agencies when

- Resources that are beyond the capabilities of a single agency are required.
- Large, diverse research communities need an advanced research instrument or facility.
- The focus is in a field of research that is relevant to the missions of two or more agencies (for example, a roadmap for software) and there is mutual interest and value in the research to be supported. (The committee is aware of situations in which agencies have jointly funded both small and large ARIF.)

F4-8: ARIF does not require the creation of a centralized interagency program for its funding, management, and oversight, as such a program would be impractical, and sufficient multiagency coordination is possible through the NSTC. Because the missions of the research-supporting federal agencies differ greatly, as do the mechanisms by which they report to the Office of Management and Budget and congressional committees, it would be difficult to maintain such a continuous funding program. The committee is aware that when agency missions have overlapped, the agencies have found ways to work together on joint activities; including instrumentation. An interagency-sponsored program for the acquisition of ARIF is neither necessary nor practicable.

RECOMMENDATIONS

R4-1: Each federal research agency[22] should devote more attention to ARIF by evaluating the needs of its investigators and explicitly planning and budgeting for their support. Given the need for these ARIF and the limited resources available, federal research agencies need to develop better models for dealing with the ARIF needs of the community. Such evaluation should include the development of a formal definition of ARIF to distinguish it from bricks-and-mortar facilities and from facilities that fall under the NSF MREFC designation.

R4-2: Each federal research agency should re-evaluate the appropriate balance between instrumentation and research grants and, within instrumentation programs, the appropriate balance between small-, middle, and large-scale instrumentation and facilities.

R4-3: Each federal research agency should establish centralized, transparent, and peer-reviewed programs for ARIF that publicly solicit proposals.

Such programs should

- Fund the operation and maintenance costs associated with approved proposals that demonstrate sufficient need.
- Sustain proportion of support for ARIF even when agency funding is stagnant or declining.
- Develop a set of selection criteria that respond to agency goals, such as effectively sharing and efficiently using instrumentation both inside and outside the institution and supporting research-field, geographic, institution, and research diversity.
- Coordinate whenever possible with ARIF programs at other agencies; joint solicitations and reviews will increase the cost effectiveness of the support and reduce the burden on researchers.

R4-4: The federal research agencies should require that proposals for ARIF from institutions contain a business and management plan that includes information on space, technical staffing, and source of funding for operation and maintenance costs. The business plan should include a mechanism for performance review and reporting.

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[22] The committee designates the following as federal research agencies: NSF, NIH, DOE, USDA, NOAA, NASA, DOD, and DHS.

- Federal research agencies should view the management and operation of ARIF at academic institutions in a manner similar to the approach used for the NSF MREFC program or the user facilities at national laboratories.
- Proposal review should include the management and sharing of the proposed instrumentation and facility so that the resource will be effectively used and readily accessible to a wide array of users, if appropriate, and the level of attention to operation and maintenance issues will be sufficient.

R4-5: The federal research agencies should establish career development and support programs for technical research support staff for instrumentation. Such programs will help to advance the careers of PhD-level specialists, who are vital to ARIF-related research, as well as enhance the utility of federal research investments.

In particular,

- NIH should expand its K-level career development awards to include technical instrument staff; such awards would provide both support and needed recognition.
- At NSF, a model is the Earth Science Division Instrumentation and Facilities program, which supports the establishment of new full-time positions for technical support staff through awards for up to 5 years that can cover salary, fringe benefits, and related indirect costs.

R4-6: NSF should expand its existing MRI program so that it includes instrumentation with capital costs greater than $2 million but less than the amount that makes it eligible for the MREFC account. Proposals from consortia that are not legally incorporated should be allowed to further encourage collaboration and sharing among institutions.

R4-7: NIH should eliminate the capital cost limit of the HEI program, reevaluate its balance between support for ARIF and research grants, and substantially increase its instrumentation investment. The nature of the research that NIH funds is increasingly similar to that in physics; this leads to the need for tools that are able to measure at the molecular level. The dominant role of NIH in funding for science argues for its playing a major role in making up for the backlog that was identified by the NSB. As a result, NIH should evaluate the percentage of its budget that it devotes toward instrumentation. On the basis of its survey, the committee believes that the current percentage of NIH's budget devoted to instruments constitutes a substantial underinvestment.

R4-8: The NSTC should elevate ARIF as a particular topic for coordination and cooperation among the federal research agencies.

The NSTC should

- Foster discussion among agencies of the amount to be allocated for federal ARIF programs on the basis of consideration of the appropriate balance among people, tools, and ideas. The proceedings of such discussion could become part of the regular OMB-OSTP budget memorandum.
- Serve as a clearinghouse for agencies to discuss best practices for the support of ARIF.
- Allow researchers in diverse disciplines to present to multiple agencies simultaneously their case for ARIF that would be used in many fields.
- Encourage the federal research agencies to work together to develop joint solicitations for proposals.

5

Overview of Conclusions, Findings, and Recommendations

In this chapter, the committee summarizes its responses to the questions in its charge on the basis of the findings and recommendations presented in earlier chapters.

GENERAL FINDINGS

Instrumentation is essential to research in that it enables scientists to observe and measure the world in ways far beyond the capabilities of our senses. It is a major pacing factor for research; the productivity of researchers is only as great as the tools they have available to observe, measure, and make sense of nature.

In recent years, the instrumentation needs of the nation's research communities have changed. Instrumentation is increasingly advanced, pushing the boundaries of our science and engineering knowledge and our technologic capabilities.

The need for particular types of instruments and facilities has broadened, crossing scientific, engineering, and medical disciplines. The growth of interdisciplinary research that focuses on large-scale problems demands more instrumentation. Instruments that were once of interest only to specialists are required by a wide array of scientists to solve critical research problems. The need for new types of instruments—such as distributed networks, cybertools, and sensor arrays—is increasing. Researchers are increasingly dependent on advanced instruments that require highly specialized knowledge and training for their proper use.

The committee developed the following definition for the instrumentation and facilities that are the subject of this study—*advanced research instrumentation and facilities* (ARIF)—which encompasses instrumentation used for research, including collections of closely related or interacting instruments, networks of sensors, databases, and cyberinfrastructure.

ARIF is distinguished from other types of instrumentation by the capital cost and in that it is commonly acquired by large-scale centers or research programs rather than individual investigators. The acquisition of ARIF by scientists often requires a substantial institutional commitment, depends on high-level decision-making at both institutions and federal agencies, and is often managed by institutions.

Furthermore, the advanced nature of ARIF often requires an expert technical staff for its operation and maintenance.

The following sections provide the committee's response to its charge.

CONGRESSIONAL CHARGE

Congress requested the study in the following language in Section 13(b) of the National Science Foundation (NSF) Authorization Act of 2002:

> **NATIONAL ACADEMY OF SCIENCES ASSESSMENT ON INTERDISCIPLINARY RESEARCH AND ADVANCED INSTRUMENTATION CENTERS.**
>
> (1) Assessment—Not later than 3 months after the date of enactment of this Act, the Director shall enter into an arrangement with the National Academy of Sciences to assess the need for an interagency program to establish and support fully equipped, state-of-the-art university-based centers for interdisciplinary research and advanced instrumentation development.
>
> (2) Transmittal to Congress.—Not later than 15 months after the date of the enactment of this Act, the Director shall transmit to the Committee on Science of the House of Representatives, the Committee on Commerce, Science, and Transportation of the Senate, and the Committee on Health, Education, Labor, and Pensions of the Senate the assessment conducted by the National Academy of Sciences together with the Foundation's reaction to the assessment authorized under paragraph (1).

In assessing the question of interagency activity, the committee found that the acquisition of ARIF often requires support from multiple funding sources, and this poses a substantial burden on the researchers and institutions seeking federal funding for such instruments and facilities. The committee recommends that the White House Office of Science and Technology Policy (OSTP), as part of its National Science and Technology Council (NSTC) activities, enhance federal research agency coordination and cooperation with respect to ARIF to reduce the burden on these researchers and institutions and enable agencies to leverage their resources whenever possible and learn from each other. Through NSTC, OSTP should

- Foster discussion between agencies of the amount to be allocated for federal ARIF programs on the basis of consideration of the appropriate balance between people, tools, and ideas. The proceedings of such discussion could become part of the regular OSTP-Office of Management and Budget budget memorandum.
- Serve as a clearinghouse for agencies to discuss best practices for the support of ARIF.
- Allow researchers in diverse disciplines to present their case for ARIF that would be used in many fields to multiple agencies simultaneously.
- Encourage the federal research agencies to work together to develop joint solicitations for proposals.

The committee does not see a need for "an interagency program to establish and support fully equipped, state-of-the-art university-based centers for interdisciplinary research and advanced instrumentation development." A mandatory interagency program is not practical; it is challenging for federal agencies to coordinate their efforts, because their missions and support mechanisms differ greatly. The establishment of a mandatory interagency program also is not necessary because research agencies already cooperate to some extent by cofunding ARIF.

RESPONSE TO CHARGE QUESTIONS

This section presents the committee's response to the specific questions that were part of its charge.

1. What are the current programs and policies of the major federal research agencies for advanced research instrumentation?

The NSF Major Research Instrumentation (MRI) program and the National Institutes of Health (NIH) High End Instrumentation (HEI) program each support instrumentation with capital costs of up to $2 million, although award amounts are frequently far less in NSF's case. In FY 2004, the last year for which there are data, the success rate for proposals was 39%, and the average award amount was $344,000.

NSF's Major Research Equipment and Facilities Construction (MREFC) account funds research equipment whose capital costs are in the ten to hundreds of millions of dollars (spread over many years). Between those two cost ranges, several NSF division programs support instrumentation with capital costs over $2 million in particular research fields and programs that are capable of partial funding and less formal mechanisms for support. There is no MREFC program at NIH for major equipment and facilities, but NIH supports biomedical technology resource centers (P41), which focus on the development of new technologies and instrumentation.

The Department of Defense, through its Defense University Research Instrumentation Program, funds projects whose capital costs are up to $1 million. The average grant size in the National Aeronautics and Space Administration's Research Opportunities in Space and Earth Science program is about $100,000, with instrumentation development awards as high as $2 million. The Department of Homeland Security and the US Department of Agriculture support relevant instrumentation development projects through formal and informal proposal processes.

The Department of Energy (DOE) and the National Oceanic and Atmospheric Administration (NOAA) focus their instrumentation funds on their national research facilities, which include a number of instruments categorized as major research equipment. Because of the missions of the two agencies, support for ARIF instruments is more likely go to upgrades to existing facilities and instrument development. DOE and, to a lesser extent, NOAA support research in universities in support of agency missions and goals.

2. **What is the current status of advanced midsized research instrumentation on university campuses? How are such instruments currently designed, built, funded, operated, and maintained?**

The committee performed a preliminary survey of academic research institutions, requesting information on recently acquired ARIF and any issues and concerns regarding ARIF. The committee was surprised by a low response rate from the nation's largest research universities, which may not have had sufficient time to complete the survey or perhaps receive the funding for their instruments from nonfederal sources because of a lack of appropriate federal funding. Few of the responding academic institutions reported having recently acquired ARIF; of 51 respondents, only 18 (35%) had any ARIF. More than three-fourths of institutions with ARIF have only one or two such instruments or facilities, and none has more than four.

Because of the high number of responses from smaller institutions and some incomplete surveys from institutions with which the committee is familiar, the committee has no reason to believe that the statistical results of this survey are representative of the nation's universities. The committee did give weight to the concerns raised by universities responding to the survey and to common elements among the ARIF reported, particularly the operations and maintenance costs, the sources of initial capital cost, and the ubiquitous need for support personnel. In the same congressional act that authorized this study, the NSF has been asked to conduct a more thorough survey. The committee looks forward to the results of this effort.

Of the instruments reported in the committee's survey, 63% were purchased and 30% of the instruments and facilities were designed and built by institutions or through contracts with manufacturers. Among the future needs anticipated by institutions were many instruments that straddle the $2 million mark and whose state-of-the-art versions are becoming more expensive, including high-resolution transmission electron microscopes, high-frequency nuclear magnetic resonance spectrometers, and tools for materials and nanoscience, such as lithography systems.

The capital cost of the ARIF reported ranged from $2 million (for an infrared camera) to $15 million (for a pulsed electron accelerator, funded by DOE), although more than half the instruments reported had capital costs between $2 million and $3 million, and over 90% of the instruments cost $5 million or less. For more than half the ARIF reported, at least two funding sources were needed to meet the initial capital costs. Almost half (48%) of the ARIF listed detailed the institution as a source of funding, averaging $1.25 million per instrument or facility. The next most common contributors were NSF (28%) and states (24%).

The annual cost of operation was generally $100,000-$500,000; a few ARIF cost $1 million-$2 million per year. Most federal agencies do not provide the operation and maintenance costs for ARIF. Support for those continuing costs instead comes from institutional funds and user fees. Obtaining operation and maintenance funding for ARIF was the most common concern expressed in the survey responses. Almost all ARIF require PhD-level technical support staff to achieve consistent high-level performance and facilitate use by researchers. Providing viable career paths for those essential personnel is a critical issue facing universities with ARIF.

3. What challenges do federal agencies and universities identify regarding such instruments?

The following are the chief challenges identified by institutions in response to the committee's survey (in decreasing order by number of institutions indicating the issue):

- Locating sources of funding for operation and maintenance costs.
- Managing the instrumentation. Some institutions remarked that, because of high demand, the administration of instrumentation was particularly challenging—especially resource allocation and scheduling.
- Maintaining the required environment for the instrument. Many of the instruments reported by institutions require a specially controlled environment for proper operation.
- Locating sources of funding to support staff costs.
- Operating an instrument. Some institutions reported that an instrument itself was difficult to run and keep at peak performance.

In presentations and interviews with federal agencies, the following major challenges were identified:

- Balancing the need for instrumentation and research grants in a budget that is stagnant while instrumentation costs are increasing rapidly.
- Insufficient financial resources to meet demand.

A key bone of contention between federal agencies and universities is that federal agencies believe that operation and maintenance costs should be paid by institutions and researchers and academic institutions believe that federal agencies should pay the operation and maintenance costs (including support for staff who operate and maintain an instrument) for a least a few years as part of the initial grant.

4. **Would an interagency program to fund midsized advanced research instruments that are used by researchers funded by many agencies help respond to these challenges? If so, what should be the components of such a program?**

The committee does not believe that an interagency program is necessary. The committee does, however, believe that that NSTC should elevate ARIF as a topic for particular interagency attention to enhance agency coordination and cooperation.

5. **Are sufficient federal programs available to provide the intellectual and financial resources necessary to develop new midsized instruments that respond to research community needs?**

There is an enormous gap in federal programs for ARIF. Although federal agency instrumentation programs exist, only rarely are researchers able to submit proposals when the capital cost is greater than $2 million. There are no agencywide ARIF programs.

Existing instrumentation programs are poorly supported, do not provide funds for continuing technical support and maintenance, and are rarely considered in the context of broad scientific needs. The shortfalls for instrumentation have built up, are met by spasmodic programs that address short-term issues but rarely the long-term problem, and are poorly integrated between or even within agencies.

Existing ad hoc ARIF programs are neither well organized nor visible to most investigators, and they do not adequately match the research community's increasing need for ARIF.

Federal agencies need to pay more attention to ARIF than they do now. When a program does not exist for a major need of the research community, the result can be two activities that do not always lead to the best investment of federal research—direct congressional allocations (otherwise known as earmarking) and backroom politics (those who are well known to agency officials are able to lobby individually or as a group). Those outcomes stand in opposition to a well-thought-out program that takes into consideration balance among different fields of research, among different types of tools, and between support for tools and research grants and that affords all proposals an equal chance through a peer-review process.

6. **What federal policies could be put into place to enhance the design, building, funding, sharing, operations, and maintenance of midsized advanced research instruments?**

The committee believes that mechanisms to enhance federal policies are in three categories:

- Program establishment and centralization.
- Proposal processing and transparency.
- PhD-level technical support staff career development and support programs.

In the case of program establishment and centralization, the committee believes that *each federal research agency* should

- Establish centralized, transparent, and peer-reviewed programs for ARIF that publicly solicit proposals.
- Fund the operation and maintenance costs associated with approved proposals that demonstrate sufficient need.

- Sustain proportional support for ARIF even when agency funding levels are stagnant or declining.
- Coordinate whenever possible with ARIF programs at other agencies. Joint solicitations and reviews will increase the cost effectiveness of the support and reduce the burden on researchers.

In particular,

- NSF should expand its MRI program so that it includes ARIF instrumentation whose capital costs are greater than $2 million but less than the amount that makes it eligible for the MREFC account.
- NIH should eliminate the capital cost limit of the HEI program, re-evaluate its balance between support for the ARIF and research grants, and substantially increase its instrumentation investment. The OSTP and NSTC should enhance federal research agency coordination and cooperation with respect to ARIF.

In considering and evaluating proposals, *each federal research agency* should

- Require that proposals from institutions for ARIF contain a business and management plan that includes information on space, technical staffing, and the source of funding for operation and maintenance costs for the instrument. Develop a set of selection criteria that respond to agency goals, such as effectively sharing instrumentation and supporting research field, geographic, institution, and research diversity.
- Make it possible for researchers to present proposals to multiple agencies simultaneously.
- Establish career development and support programs for PhD-level technical research support staff so that instrumentation is optimized and maintained.

Although this question is directed toward federal policies, the committee also believes that university policy regarding ARIF can be enhanced, specifically, by

- Reviewing an institution's financial support, in addition to its planning and budgeting processes for ARIF, to ensure that funds are identified to support existing instrumentation properly.
- Structuring the funding and management of ARIF so that they have institution-wide or even user community-wide characteristics and are reviewed regularly on the basis of performance.

- Enhancing the career paths of the technical research support staff essential for ARIF by establishing long-term and stable staff positions for the lifetime of an instrument.
- Continuing to discuss the issue of federal agency support for operation and maintenance costs for instruments with the Research Business Models Subcommittee of OSTP's NSTC.

SUMMARY

The health and progress of the science and technology research enterprise depend on many types of instrumentation, including the advanced instrumentation and facilities discussed in this report. The committee believes that by taking the steps recommended here, the nation will optimize its investment in research and thus the benefits that research provides to society.

Appendixes

A

Biographic Information on Members and Staff of Committee on Advanced Research Instrumentation

MARTHA A. KREBS (Chair) is the director of the energy R&D division at the California Energy Commission and the past president of Science Strategies, a consulting firm that works with academic and private organizations to identify and address critical issues and opportunities in science and technology that will affect their research and development and business activities. She was an associate vice chancellor for research and founding institute director of the California Nanosystems Institute, where she was responsible for establishing initial leadership, strategic direction, and administration. Dr. Krebs served as director and assistant secretary of the Office for Science for the Department of Energy from 1993 to 2000. She received her bachelor's degree and PhD in physics from the Catholic University of America. She is a member of Phi Beta Kappa, a fellow of the American Physical Society, a fellow of the American Association for the Advancement of Science, and a fellow of the Association of Women in Science.

DAVID JOHN BISHOP is president of the New Jersey Nanotechnology Consortium and vice president of nanotechnology research at Lucent Technologies–Bell Laboratories. In 1973, he received a BS in physics from Syracuse University. In 1977 and 1978, he received an MS and a PhD, respectively, in physics from Cornell University. In 1978, he became a postdoctoral member of the staff at AT&T-Bell Laboratories; in 1979 he was made a member of the technical staff. In 1988, he was made a distinguished member of the technical staff and later that year was promoted to department head, Bell Laboratories. Dr. Bishop is a Bell Laboratories fellow. He has held a number of managerial positions at Bell Laboratories, including director of the Liquid Crystal Physics Research Department, director of the Microstructure Research Department, director of the MEMS Research Department, optical research vice president, and physical sciences research vice president. He has written and given over 500 papers and talks. He also has applied for or been issued more than 50 patents.

MARVIN CASSMAN is an independent consultant. He was the executive director of the Institute for Quantitative Biomedical Research (QB3) at the University of California. Previously, he served as director of the National Institute of General Medical Sciences of the National Institutes of Health (NIH). Dr. Cassman received his bachelor's and master's degrees from the University of Chicago and a doctoral degree in biochemistry from Albert Einstein College of Medicine of Yeshiva University of New York. He was a California resident for 10 years, first as an NIH postdoctoral fellow at the University of California (UC), Berkeley, in the middle 1960s and then for 7 years on the UC, Santa Barbara, biology faculty before accepting his first post at NIH in 1975. Dr. Cassman has a particular interest in advancing biomedical research beyond its primary focus on individual molecules and genes.

ULRICH DAHMEN is director of the National Center for Electron Microscopy (NCEM) at Lawrence Berkeley National Laboratory. Founded in 1983, NCEM is a Department of Energy user facility that provides scientific researchers with essential resources for electronic-beam microcharacterization of materials. Dr. Dahmen came to the United States from Germany in 1974 and received his PhD from the University of California, Berkeley, in 1979. He uses advanced techniques of electron microscopy to investigate size- and shape-dependent behavior of inclusions in alloys and interfaces in solids. His research interests encompass the crystallography of microstrutures; structural phase transformations in solids and interfaces; and orientation relationships and the role of symmetry, shape, and defects in solid state reactions. He has published extensively on the structure of interfaces, the evolution of precipitate morphologies, and the effects of size on the behavior of embedded particles.

THOM H. DUNNING, JR., is the director of the National Center for Supercomputing Applications at the University of Illinois at Urbana-Champaign. Dr. Dunning was the director of the Joint Institute for Computational Sciences in Oak Ridge, Tennessee, and a distinguished scientist in computing and computational sciences at Oak Ridge National Laboratory. Before working in Tennessee, Dr. Dunning was responsible for supercomputing and networking for the University of North Carolina system and was a professor of chemistry at the University of

North Carolina at Chapel Hill. He received his bachelor's degree in chemistry in 1965 from the University of Missouri-Rolla and his doctorate in chemical physics from the California Institute of Technology in 1970. He has written nearly 150 scientific publications on topics ranging from advanced computational techniques for molecular calculations to computational studies of the spectroscopy of high-power lasers and the chemical reactions involved in combustion. He was the scientific leader of the Department of Energy's first "Grand Challenge" in computational chemistry.

MARILYN L. FOGEL is a staff member in the Geophysical Laboratory at the Carnegie Institution of Washington and an adjunct professor at the University of Delaware College of Marine Studies. She uses sophisticated mass-spectrometry techniques and ion microprobes to study evolutionary biology and the history of the earth. She received a BS from Pennsylvania State University in 1973 and a PhD in botany (marine science) from the University of Texas at Austin in 1977. While holding her position at the Carnegie Institution of Washington, she has held various professorial and research appointments at the Smithsonian Institution, Dartmouth College, and George Washington University. She was elected a geochemistry fellow of the Geochemical Society and European Association of Geochemistry in 2003.

LESLIE A. KOLODZIEJSKI is a professor of electrical engineering and computer science at the Massachusetts Institute for Technology (MIT) and leads MIT's Research Laboratory of Electronics Integrated Photonic Materials and Devices Group. She received her PhD from Purdue University in 1986 and then joined the Purdue faculty as an assistant professor. In 1988, Dr. Kolodziejski joined MIT's Department of Electrical Engineering and Computer Science as an assistant professor. She has been a recipient of the Office of Naval Research Young Investigator Award and the National Science Foundation Presidential Young Investigator Award. Dr. Kolodziejski held the Kar Van Tassel and Esther and Harold E. Edgerton professorships before her promotion to full professor in 1999.

ALVIN L. KWIRAM is a professor of chemistry at the University of Washington; he has taught since 1964. He held the position of vice provost for research in 1990. He serves as executive director of a new National Science Foundation science and technology center in photonics and optoelectronics. His research, in physical chemistry, emphases the development of novel magnetic resonance techniques designed to probe the electronic structure of molecular systems in the solid state. Dr. Kwiram has received numerous honors and awards and is a fellow of the American Physical Society and the American Association for the Advancement of

Science, a member of the Graduate Education Advisory Board of the American Chemical Society (ACS), and a member of the Executive Committee of the ACS Division of Physical Chemistry. He is a recipient of the Council for Chemical Research Award for the Promotion of University-Industry Relations, a John Simon Guggenheim Memorial Foundation fellowship, and an Alfred P. Sloan Foundation fellowship. He is the US liaison for the Worldwide University Network, a consortium of international research universities. Dr. Kwiram received his BA in physics and BS in chemistry from Walla Walla College in 1958, and he received a PhD in chemistry from the California Institute of Technology in 1962.

WARREN S. WARREN is the Ralph W. Dornte Professor of Chemistry at Princeton University. He is also on the affiliated faculty in physics, electrical engineering, molecular biology, and neuroscience at the Frick Chemical Laboratory. He is the director of the New Jersey Center for Molecular and Biomolecular Imaging, an adjunct professor of radiology at the University of Pennsylvania School of Medicine, and on the affiliated faculty of the Department of Bioengineering at the University of Pennsylvania. From 1996 to 2001, he was director of the New Jersey Center for Ultrafast Laser Applications. From 1981 to 1982, he was a postdoctoral fellow under Ahmed Zewail at the California Institute of Technology. He received an AB in chemistry and physics from Harvard University in 1977 and a PhD in chemistry from the University of California, Berkeley in 1980. He is a fellow of the American Association for the Advancement of Science and the American Physical Society. As of July 2005, he is professor of chemistry and professor of radiology at Duke University.

DANIEL F. WEILL is retired. From 2001 to 2002, he was director of the Ocean Drilling Program at the Joint Oceanographic Institutions. From 1985 to 2001 he directed the Instrumentation and Facilities Program in the National Science Foundation's Division of Earth Sciences. From 1983 to 1985, he managed the Geosciences Program in the Office of Basic Energy Sciences of the Department of Energy. He received a PhD in geochemistry from UC, Berkeley, in 1962. From 1963 to 1983, he taught and led research programs at UC, San Diego, and the University of Oregon. His research made fundamental contributions in the areas of mineral equilibria, analysis and interpretation of lunar samples, and the physical and thermodynamic properties of silicate liquids. He is a fellow of the Mineralogical Society of America and the 2002 recipient of the Edward A. Flinn III Award from the American Geophysical Union.

PROFESSIONAL STAFF

DEBORAH D. STINE (Study Director) is associate director of the Committee on Science, Engineering, and Public Policy; director of the National Academies Christine Mirzayan Science and Technology Policy Fellowship Program; and director of the Office of Special Projects. Dr. Stine has been working on various projects throughout the National Academies since 1989. She has directed studies and other activities on science and security in an age of terrorism, human reproductive cloning, presidential and federal advisory committee science and technology appointments, facilitating interdisciplinary research, setting priorities for the National Science Foundation's large research facilities, evaluating federal research programs, international benchmarking of US research, and many other issues. Before coming to the National Academies, she was a mathematician for the Air Force, an air-pollution engineer for the state of Texas, and an air-issues manager for the Chemical Manufacturers Association. She holds a BS in Mechanical and Environmental Engineering from the University of California, Irvine, an MBA from what is now Texas A&M at Corpus Christi, and a PhD in public administration with a focus on science and technology policy analysis from American University. She received the Mitchell Prize Young Scholar Award for her research on international environmental decision-making.

RACHEL COURTLAND is a research associate for the National Academies Committee on Science, Engineering, and Public Policy. She earned her BA in physics from the University of Pennsylvania in May 2003 and her MS in physics from Emory University in 2004. In graduate school, she studied the local perturbation of supercooled colloidal suspensions using two-dimensional confocal microscopy and conducted preparatory work for a National Aeronautics Space Administration PCS payload project. As an undergraduate, she led Women Interested in the Study of Physics, an organization created to help to foster a more comfortable environment for women scientists at undergraduate and graduate levels and dedicated to raising awareness of issues facing women in academe.

B

Charge to the Committee

An ad hoc committee overseen by the Committee on Science, Engineering, and Public Policy will examine federal programs and policies related to advanced research instrumentation (including cyberinfrastructure) used for interdisciplinary, multidisciplinary, and disciplinary research.

The study, in response to Section 13(b) of the National Science Foundation (NSF) Authorization Act of 2002, will focus on instrumentation that is not categorized by NSF as Major Research Instrumentation ($100K to $2 million) or Major Research Equipment (more than several tens of millions of dollars) but the equipment that falls in between these two categories ("midsized instruments").

If needed, the committee will propose policies to make the most effective use of federal agency resources to fund such instruments. Such instruments are and would be located at a broad spectrum of academic institutions.

Specific questions that will be addressed regarding advanced research instruments include:

- What are the current programs and policies of the major federal research agencies for advanced research instrumentation?
- What is the current status of advanced midsized research instrumentation on university campuses? How are such instruments currently designed, built, funded, operated, and maintained?
- What challenges do federal agencies and universities identify regarding such instruments?

- Would an interagency program to fund midsized advanced research instruments that are used by researchers funded by many agencies help respond to these challenges? If so, what should be the components of such a program?
- Are sufficient federal programs available to provide the intellectual and financial resources necessary to develop new midsized instruments that respond to research community needs?
- What federal policies could be put into place to enhance the design, building, funding, sharing, operations and maintenance of midsized advanced research instruments?

CONGRESSIONAL LANGUAGE

Congress requested this study in the following language in Section 13(b) of the NSF Authorization Act of 2002:

> **NATIONAL ACADEMY OF SCIENCES ASSESSMENT ON INTERDISCIPLINARY RESEARCH AND ADVANCED INSTRUMENTATION CENTERS.**
>
> (1) Assessment—Not later than 3 months after the date of enactment of this Act, the Director shall enter into an arrangement with the National Academy of Sciences to assess the need for an interagency program to establish and support fully equipped, state-of-the-art university-based centers for interdisciplinary research and advanced instrumentation development.
>
> (2) Transmittal to Congress.—Not later than 15 months after the date of the enactment of this Act, the Director shall transmit to the Committee on Science of the House of Representatives, the Committee on Commerce, Science, and Transportation of the Senate, and the Committee on Health, Education, Labor, and Pensions of the Senate the assessment conducted by the National Academy of Sciences together with the Foundation's reaction to the assessment authorized under paragraph (1).

C

Summary of Institutional Survey Results

CONTENTS

OVERVIEW

The question of the centralization of instrumentation on university campuses figures prominently in the committee's charge, so the committee was interested in finding out more about the instrumentation and facilities with capital costs over $2 million that exist on university campuses. To obtain this information, a survey was drafted and sent to university administrators—namely vice provosts, presidents, and chancellors of research.

The survey, included at the end of this summary, included a request for demographic information regarding the responding institution, questions to the administrator regarding current concerns and future needs, and a detailed chart of existing advanced research instrumentation and facilities (ARIF) that had been acquired in the preceding 5 years. The survey was distributed to all doctorate-granting universities classified by the Carnegie Foundation as *extensive*, as well as a wide array of universities falling under the Carnegie *intensive* classification and to selected historically black colleges and universities.

In total, the committee queried over 300 universities and received responses from 51 universities and one independent research institution. Of these, 42 institutions completed the survey, and the remainder indicated only that they did not have any ARIF. A list of respondents is included at the end of this appendix. Although the committee finds the information collected in the survey useful, because of the low response rate the committee believes that the results of the survey provide only examples of the state of ARIF at the specific universities and do not represent the full population. The National Science Foundation (NSF) Authorization Act that requested this study also requested a survey of ARIF instruments. That survey is to be begun in 2005 and will provide a fuller and much more accurate picture of the true state of ARIF at the nation's universities. The committee believes that the results of this survey underestimate the number of ARIF on university campuses, particularly because a number of the largest research universities, which would be most likely to have many ARIF, did not respond to the survey. Additionally, the committee is familiar with a number of the institutions that did complete the survey but did not report all recently acquired ARIF. Thus, the committee strongly advises that the results of the survey be considered judiciously and that the data not be used for budgeting purposes. Although statistical results concerning the overall number of ARIF and the distribution of ARIF types and costs are not representative, the committee seriously weighed the concerns expressed by universities regarding ARIF. The committee also considered common elements among the ARIF reported, particularly the operation and maintenance costs, the sources of initial capital cost, and the ubiquitous need for support personnel.

Of the 42 institutions that completed the survey, 80% were public universities. The total annual budgets of the individual institutions ranged from \$47 million to \$3 billion. Six institutions reported that they did not have any ARIF without completing the survey.

Most (63%) of the 51 respondents indicated that they had not purchased ARIF in the preceding 5 years. Figure C-1 shows the distribution of ARIF reported by the institutions. In total, 33 ARIF were reported.

Several institutions reported instruments and facilities older than the requested period or below the \$2 million mark; such instruments and facilities are not included in this analysis. One institution also reported a \$3 million Defense Advanced

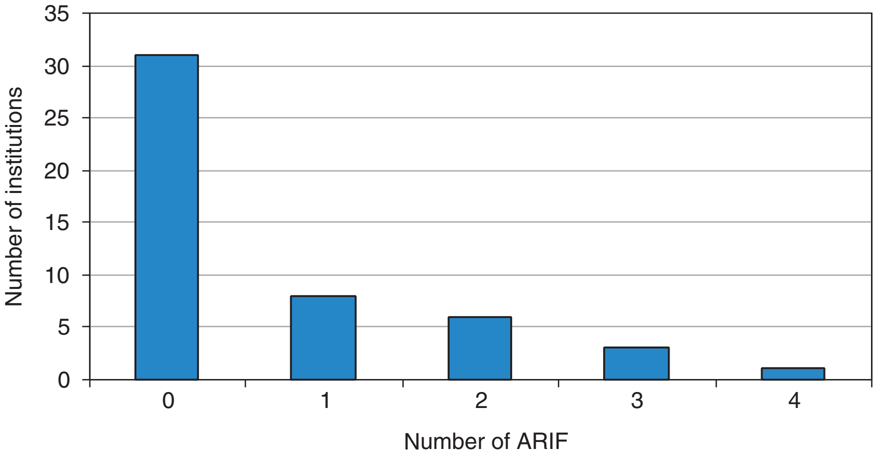

FIGURE C-1 Number of ARIF reported by institutional survey respondents.

Research Project Agency development project that is likewise not included because the survey was directed more to ARIF acquisition and construction that the development of new ARIF.

With the exception of two institutions, the total capital cost of the ARIF at an institution was below 6% of the total amount of basic and applied (nonclinical) federal research funding it received in FY 2004.

TYPES OF ARIF AT INSTITUTIONS

The survey charts itemize 33 ARIF purchased or constructed in the preceding 5 years. Of them, 9 were either specially designed or constructed in house, 19 were purchased from commercial vendors, 2 were donated by the government or industry, and 3 were of unspecified origin. Figure C-2 shows the distribution of ARIF reported by field or type, and Table C-1 lists sample instruments for each category and the range of capital costs. The most commonly reported individual instruments were advanced magnetic resonance imagers and nuclear magnetic resonance spectrometers. Table C-2 lists all the instruments identified by survey respondents.

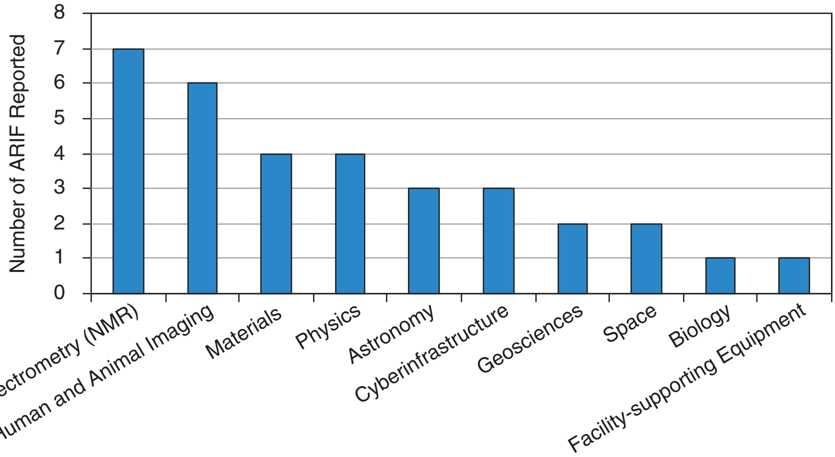

FIGURE C-2 ARIF at institutions, by field or type.

TABLE C-1 Existing ARIF at Institutions, Research Field

Field	Selected Instruments or Facilities	Capital Cost (millions of $)
Astronomy	Telescope, spectrograph, infrared camera for Magellan	3.9-5
Biology	Proteomics-protein structure laboratory	2.7
Cyberinfrastructure	Supercomputer	2.0-5.0
Geosciences	Ion microprobe, earthquake sensor testing laboratory	2.8-3.8
Materials	Electron-beam lithography system, semiconductor production system	2.3-2.5
Human and animal imaging	Magnetic resonance imager, human and animal	2.2-2.8
Spectrometry (NMR)	NMR spectrometer, 800-900 MHz	2.2-4.8
Physics	Infrared camera, pulsed electron accelerator	2.0-15.0
Space	MegaSIMS (isotope analysis)	3.5
Facility-supporting equipment	Helium refrigerator supplying helium for superconducting magnets at the National Superconducting Cyclotron Laboratory	2.9

ARIF CAPITAL COSTS

As shown in Figure C-3, almost all (over 90%) of the ARIF reported by institutions had capital costs of $5 million or less. Almost two-thirds (61%) had capital costs of $2-$3 million.

TABLE C-2 Itemized ARIF, by Price

Capital Cost (millions of dollars)	Siting Cost (millions of dollars)	Annual O&M Cost (millions of dollars)	Instrument or Facility	Institution
2			Spartan IR Camera	Michigan State University
2.2	0.9	0.04	800-MHz NMR and modifications to 600	University of Kansas Center for Research
2.2	1.28	0.25	Magnetom 3T Allegra system (functional magnetic resonance imager)	Princeton University
2.204	1.715	0.025	800-MHz NMR	University of California, Los Angeles
2.2416			Philips Inera 3.0T magnetic resonance imager	Boston University
2.3	0.025	0.2	JEOL 6000 electron beam lithography system	University of Tennessee
2.37	0.04969	0.03345	Semiconductor production system	University of California, Berkeley
2.4	0.03	0.02	600-MHz NMR	University of Illinois, Chicago
2.4	0.08694	0.225	IBM supercomputer	Boston University
2.5	0.38	0.115	Varian 9.4T magnetic resonance imager	Kansas University Medical Center
2.5	0.32	0.125	Seimens 3T magnetic resonance imager	Kansas University Medical Center
2.5	0.2	0.15	JEOL 6000 electron beam lithography system	University of Texas, Austin
2.7	2.2	0.07	Proteomics/protein structure laboratory	University of Kansas Center for Research
2.7	0.1	0.2	Magnetic resonance imager	University of Cincinnati
2.793			Ground data system	University of California, Berkeley
2.81	0.48	0.22	CTF magnetoencephalography (cortical and fetal)	Kansas University Medical Center
2.8132	0.25	0.05	NanoSIMS 50L ion microprobe	Carnegie Institution of Washington
2.85			Helium refrigerator	Michigan State University
3.1			Lower extremity enhancer	University of California, Berkeley
3.5	0.5	0.3	MegaSIMS	University of California, Los Angeles
3.675	0.2	0.35	Atacama cosmology telescope	Princeton University
4.5	0.02	0.075	FourStar: wide-field IR survey camera for Magellan	Carnegie Institution of Washington
4.83			Bruker AVANCE 900-MHz NMR	Michigan State University
5	0.03	0.03	900-MHz NMR spectrometer	University of Illinois, Chicago
5			SALT spectrograph	University of Wisconsin,
Madison				
11	2	0.5	Fast-Pulsed Linac User Facility (DOE designed and owned and housed at ISU)	Idaho State University
12.5	15.45	2	HPCAT	Carnegie Institution of Washington
15	1.8	1	Pulsed electron accelerator	Idaho State University

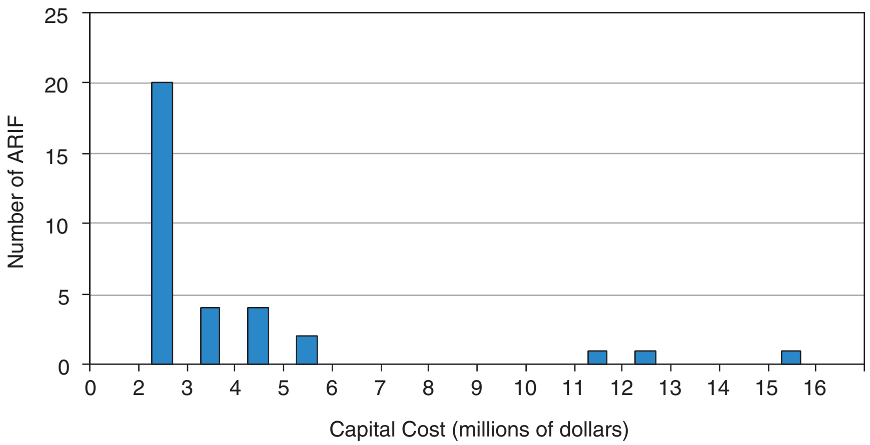

FIGURE C-3 Itemized ARIF, by price.

INSTITUTION CONCERNS REGARDING ARIF

Institutions had two opportunities in the survey to document their concerns regarding ARIF: in the general survey and for each instrument. On the whole, not many comments were given in the general survey. Figure C-4 shows a histogram of the common comments regarding ARIF listed in the itemized ARIF charts. The most prevalent concern was the difficulty of finding continuing support for the operation and maintenance of ARIF.

SUPPORT FOR ARIF

Among the ARIF detailed in the survey charts, an array of sources of support for capital costs were listed, from state governments, to the Department of Health and Human Services, to universities and individual university departments. Probably because of the expense, 62% of the ARIF reported had more than one funding source (see Figure C-5). Most (52%) had some institutional commitment, averaging $1.25 million per instrument or facility (see Figure C-6).

Data on the ARIF support from NSF were particularly surprising. Eight reported ARIF had NSF as a source of funding, including six for which the amount of funding was explicitly listed. Three of those were for amounts well over $2 million ($3.875, $4.35, and $2.68 million). That yielded an average award amount reported from NSF of $2.29 million. The respondents did not list the particular programs through which the NSF funding was acquired. We speculate that it was obtained through individual NSF divisions.

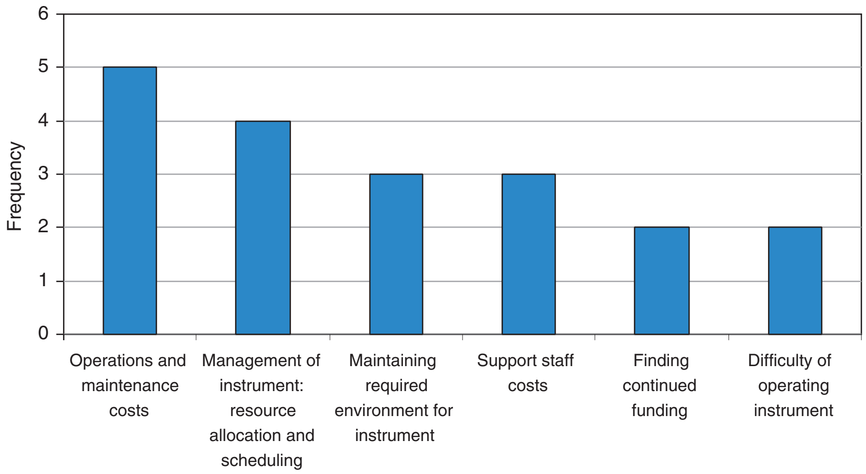

FIGURE C-4 Major challenges that institutions face with regard to ARIF.

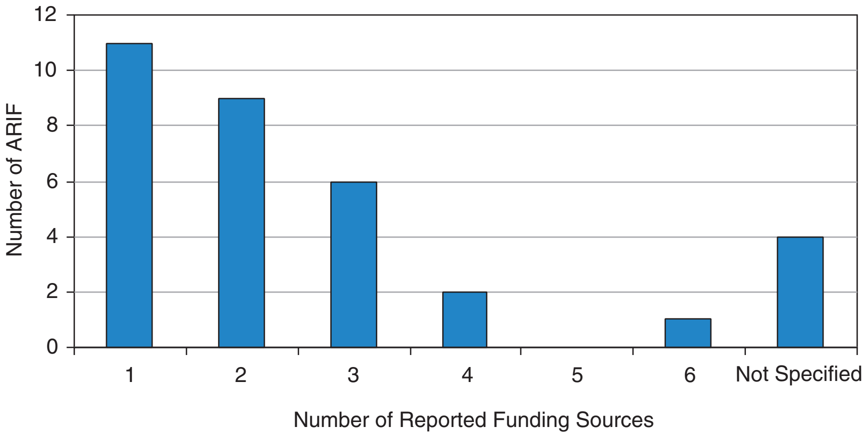

FIGURE C-5 Number of funding sources specified.

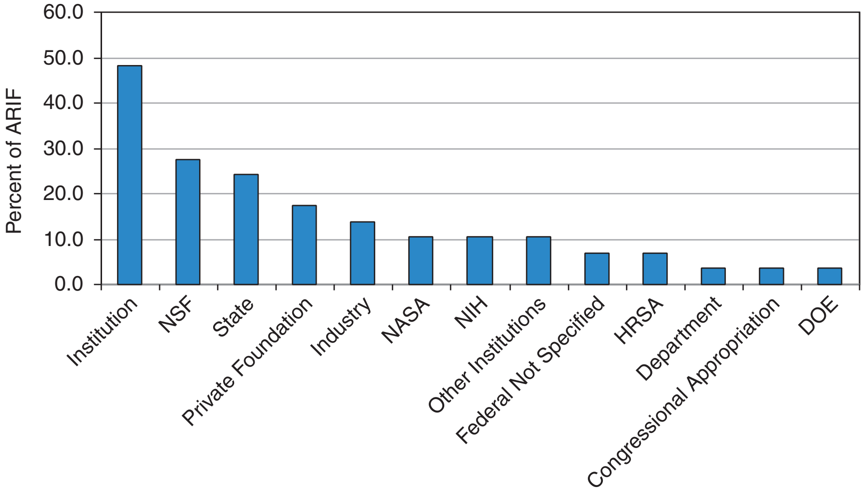

FIGURE C-6 Frequency of ARIF capital cost sources of support. (The fraction of ARIF supported by various funding sources. For example, institutions contributed to the capital costs of 48% of the ARIF reported.)

OPERATIONS AND MAINTENANCE COSTS

Of the instruments detailed in survey charts, 20 had estimates of capital cost, siting cost, and estimated operation and maintenance (O&M) cost. Figure C-7 shows the reported O&M costs as a function of capital costs.

The survey did not define O&M costs, nor did it request that institutions do so. It is likely that most institutions are going by the guidelines of OMB Circular A-21, which defines operations and maintenance costs strictly as the costs associated with housing and maintaining an instrument, including utilities. The one clear exception was Boston University, which reported that the annual O&M costs of its IBM supercomputer refer to maintenance but not power. Some institutions included the costs of service contracts and personnel salaries in their estimates of O&M, and others did not.

ANTICIPATED ARIF NEEDS OF INSTITUTIONS

Many institutions, whether or not they had ARIF, expressed a desire for ARIF. Some detailed ARIF had been proposed but still lacked support. Figure C-8 and the text following it detail the ARIF needs expressed by institutions. Most of these

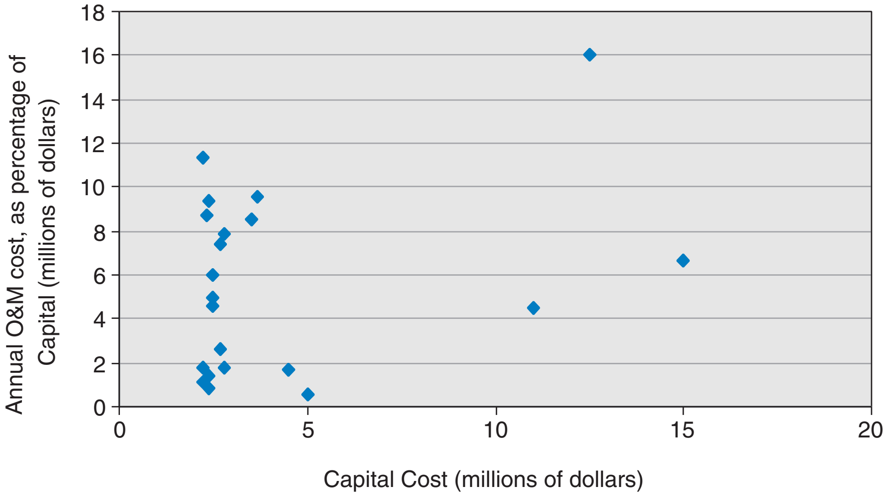

FIGURE C-7 Reported annual O&M costs for ARIF as a percentage of the capital costs.

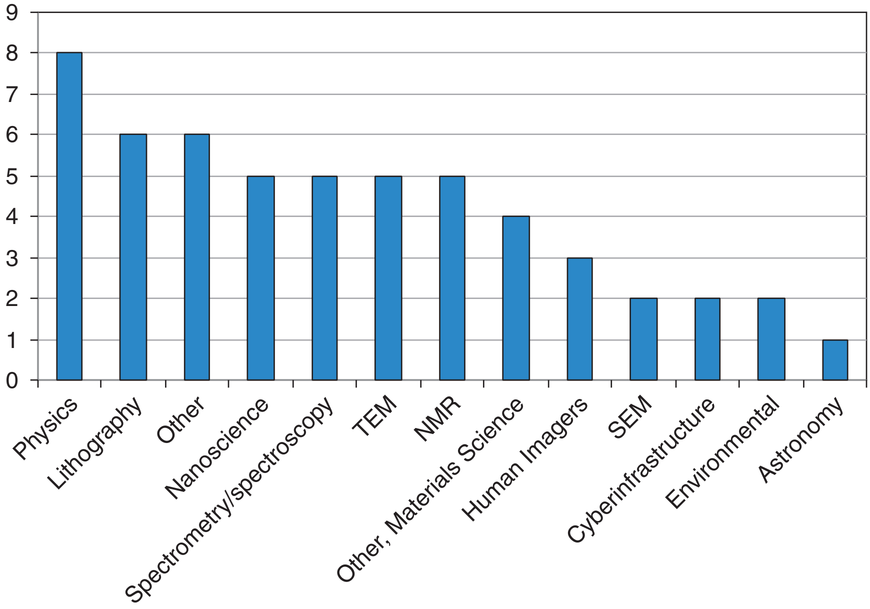

FIGURE C-8 Anticipated ARIF needs of institutions, by instrument or field.

needs are categorized by field, with the exception of the nuclear magnetic resonance spectrometer (NMR), transmission electron microscope (TEM), and the scanning electron microscope (SEM), which, because of their frequency and multidisciplinary nature, are listed as individual instruments. Several institutions reported that they experience difficulty acquiring the instruments the need due to a sort of chicken-and-egg problem, noting that they need more faculty who can push for the acquisition of the instrument, but they need the instrument in order to attract the faculty. See Table C-3.

List of Anticipated ARIF Needs, by Instrument or Field

Physics (from two institutions)

- A high-performance synchrotron beamline $3-$5M
- A new injection system for the storage ring $2-$7M
- A whole new accelerator that would complement the existing accelerator/storage ring $90M
- Cyclotron for the production of isotopes for medicine and research as well as for the production of particles for detector development
- Proton or heavy particle accelerator to expand the nuclear science and engineering research activities
- Linear Collider
- High energy physics
- If the Linear Collider becomes a reality NIU High Energy Physics would be interested in calorimeters that are in the tens of millions. Also, Fermi National Accelerator Laboratory is promoting a Super Conducting Module Test Facility preparatory to RIA and the LC. This will be an $80 million facility, which would benefit from such an instrumentation program. In total, accelerator structures and refrigeration equipment would fall within the cost range.

Lithography

- E-beam lithography
- DUV Lithography Tool
- Electron beam lithography ($2M)
- focus ion beam lithography ($2M-$5M)
- State-of-the-art electron beam lithography system
- Possible extreme ultraviolet lithography

Other
- New, more powerful imaging magnets with enhanced resolution
- Genotyping and sequencing equipment
- Vacuum test facility
- Carbon 14 Accelerator
- Molten metal/salt cooled thermohydraulics loop for engineering scale demonstrations and experiments
- Biocontainment

Nanoscience
- Integrated nano-electro-mechanical system (NEMS) processor to fabricate nanodevices that integrate electronic and mechanical components on a routine basis
- Third Generation "Maskless" exposure instrument to fabricate nanoelectronic devices
- Nanoscience and nanotechnology tools
- Nanoscience/bioscience
- Nanotechnology (clean room)

Spectrometry/spectroscopy
- Ion microprobe, using secondary ion mass spectrometry (SIMS)
- SIMS system
- Dispersive x-ray spectroscopy
- Electron energy loss spectroscopy
- Mass spectometry

Transmission Electron Microscope
- Ultra-high-resolution (2 Angstrom) TEM of anticipated cost $2.5M
- TEM with low temperature
- Aberration-corrected TEM with scanning capabilities and auxiliary detectors for energy ultra-high-performance analytical TEM (materials science)
- HRTEM (high resolution transmission electron microscope)
- A TEM costing approx. $2M

NMR
- A 900-MHz NMR costing approx. $4.5M
- High-field, or ultra-high-field, NMR spectrometer (in the 850-950 MHz range)
- A high-field (800 MHz) NMR machine. Such a machine with a cryoprobe that works for both solids and liquids cost $2.2 million

- The TAMUSHSC is collaborating with Texas A&M University in the development of several major core facilities, including a nuclear magnetic resonance facility
- NMR
- One additional relatively low-field NMR, ideally a 700-MHz or 800-MHz system

Other, Materials Science
- MBE (molecular beam epitaxy)
- Advanced plasma etching tools
- Atomic layer deposition tool
- Microarray technology

Human Imagers
- High-field clinical magnetic resonance imaging unit
- Combined computed tomography (CT)/PET unit
- Positron emission tomography (PET) imaging unit
- MRI

Scanning Electron Microscope
- Scanning electron microscope
- Combined STM and SEM (chart)

Cyberinfrastructure
- High-speed supercomputing clusters
- Large computer

Environmental
- Carnegie Airborne Observatory ~$5M for large-scale ecological research
- National Ecological Observing Network (UC Boulder)

Astronomy
- A 2.4m telescope at $7.1M
- Renewable fuel and chemical pilot facility to study the chemistry, thermodynamics, and reaction parameters for optimizing alternative fuels and chemicals from renewable resources.

TABLE C-3 Institutional Comments Regarding ARIF

Category	Comment
Nature of ARIF	Instrumentation in this price range is often accompanied by the need for specialized facilities. Funding agencies should require that institutions demonstrate the ability to provide appropriate facilities, have a mechanism to insure multiple PI access, and have a plan to provide on-going support and maintenance of the instrument. (University of California, Berkeley)
$2 million limit	We would like to make the point that advanced instrumentation below $2 million is itself very difficult to get through grants; thus advanced should not be confused or equated with expensive. We have trouble getting advanced equipment in grants below $2 million—indeed, even in the $250,000 and below range. (Pennsylvania State University)
	Primary needs in $0.5M-$1.5M (University of Arkansas)
	The development of new instruments is an important aspect of science. Larger, cutting-edge instruments often fall into the $2-$100M range, and currently the NSF is not well set up for accommodating this need. The artificial barrier between MRI and MRE should be eliminated—that may go a long way to meet the needs. At the very least this step would allow the NSF to manage the situation rather than having an administratively imposed self-blockage. A percentage reduction of grants may be advisable, but I have no quantitative information that would allow me to make an argument. All I know is that grants are already under undue pressure.
	. . . the entirely artificial gap between MRI and MREs needs to be closed. For example, the NSCL upgrade (which provided the best US rare isotope user capability) would cost some $25-$30M in total. This is too small for an MRE and too large for an MRI. Of course this could be broken down into smaller components, but only as a system did it make sense. (Konrad Gelbke, Director of National Superconducting Cyclotron Laboratory)
Additional costs	Allowing operations and maintenance costs, even if only for a specified number of years, to be included as part of the original acquisition award would be beneficial to institutions. This would facilitate the movement of the instrument from the acquisition stage into the operations stage, allowing for more rapid implementation and use in research projects. (University of California, Berkeley)
	The purchase of expensive instrumentation must recognize the long-term commitment that is incurred in staffing the facility with adequately skilled operators. The “user pays” model does not always produce the needed revenue, so that a back-up mechanism needs to be explored. Whether to buy our own instrument or enter into a service agreement with a national lab, or some other entity, should be debated on a case-by-case basis. (Pennsylvania State University)

TABLE C-3 Continued

Category	Comment
Additional costs (cont'd)	Ongoing maintenance costs are becoming a significant problem for institutions. (University of Tennessee)
	Our instrumentation problems fall into three areas: (1) resources for new faculty equipment startup costs, which are in the range of $350K-$1M (not including lab renovation); (2) facilities appropriate for shifting from individual faculty lab-based research to interdisciplinary team research. Our facilities consist of many newly renovated faculty labs, but funds are currently not available for the construction of larger core facilities desired by our faculty and conducive for larger-scale interdisciplinary research; (3) funding for staff to operate and maintain expensive equipment that could be shared by investigators. (University of Maryland Baltimore County)
	Thorough study needed of raising costs associated with maintenance, facilities, technicians, and student training through user fees, college or university subsidies, grants, and industrial contracts. (University of Arkansas)
Gap	There is a funding gap that needs to be filled. Moderate projects are now cobbled together with MRIs and ITRs. The funding should not be taken from the base program. (Northern Illinois University)
Distribution of resources	NSF, NIH, NASA, DOE, DOD, and others should collaborate to create and fund a new program to make available large shared computational resources at major research universities. (Pennsylvania State University)
	I support the model of shared use facilities in which expensive instrumentation is shared by a broad research community within the university and with external collaborators. (Pennsylvania State University)
	Thorough study for best practices in sharing needed. (University of Arkansas)
Proof of feasability in proposals	Funding agencies should require that institutions demonstrate the ability to provide appropriate facilities, has a mechanism to insure multiple PI access, and has a plan to provide on-going support and maintenance of the instrument. (University of California, Berkeley)
Vendor/facility relationship	For some specialized tools, equipment vendors are placing unrealistic facility demands on institutions to provide a "liability release" in the event that the tool does not meet inflated vendor performance claims (e.g., Raith ebeam tools now require a facility with vibration control beyond the limits provided by the best facility at the National Institute of Standards and Technologies 1-A vibration criteria). A realistic balance between facility demands and tool performance must be developed. (University of California, Berkeley)

INSTITUTIONAL SURVEY ON ADVANCED RESEARCH INSTRUMENTATION

Today, instrumentation plays a critical role in scientific research and exploration. We would like to get your help in gaining a better understanding of the issues related to instrumentation on your campus and your thoughts on federal policies. This survey is part of a study being conducted by the National Academies Committee on Advanced Research Instrumentation in response to Section 13(b) of the NSF Authorization Act of 2002. The Instrumentation Committee is under the aegis of the Committee on Science, Engineering, and Public Policy (COSEPUP). COSEPUP, chaired by Dr. Maxine Singer, is the only joint committee of the three honorific academies: the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. Its overall charge is to address cross-cutting issues in science and technology policy that affect the health of the national research enterprise.

The study is examining federal programs and policies related to advanced research instrumentation used for interdisciplinary, multidisciplinary, and disciplinary research. If needed, the Committee will propose policies to make the most effective use of federal agency resources to fund such instruments. Advanced research instrumentation, for the purposes of this survey, is defined as instrumentation that is not categorized by NSF as Major Research Instrumentation ($100,000 to $2 million in capital cost) or as Major Research Equipment (more than several tens of millions of dollars), but instead falls in between these two designations. At present, no general program at the NSF exists to support this category of instrumentation.

To respond to its charge from Congress and NSF, the Committee needs to learn more about the way your institution proposes and funds new instrumentation was how it supports and maintains it after installation. The Committee is also interested in your thoughts about current and possible future federal programs and policies for advanced research instrumentation.

We hope you will be willing to participate in this important information-gathering effort. *We recognize that answering all the questions in this survey may be challenging. We only ask that you do the best you can in providing the information requested.* If another person at your institution is better suited to answer this survey, please forward it to them, but please let us know to whom you sent it. We also encourage you to send this survey to any researchers at your institution who may have additional thoughts. Their comments may be sent either to you for compilation or directly to *instrumentation@nas.edu.*

We would appreciate receiving your response by Friday, April 1, 2005. Please return the completed survey via e-mail as an attachment to *instrumentation@nas.edu* or by fax to 202-334-1667. If you have any questions, please contact the study director, Dr. Deborah Stine, at *dstine@nas.edu* or 202-334-3239.

Thank you for your time and participation. For more information on the study, please visit our website at *http://www7.nationalacademies.org/instrumentation/*.

National Academies Committee on Advanced Research Instrumentation

MARTHA KREBS (Chair), President, Science Strategies
DAVID BISHOP, VP Nanotechnology Research, President, NJNC, Bell Labs
MARVIN CASSMAN, Independent Consultant
ULRICH DAHMAN, Director, National Center for Electron Microscopy, Lawrence Berkeley National Laboratory
THOM H. DUNNING, Jr., Director, National Center for Supercomputing Applications, University of Illinois, Urbana-Champaign
FRANK FERNANDEZ, Distinguished Instititute Technical Advisor, Stevens Institute of Technology
MARILYN L. FOGEL, Staff Member, Geophysical Laboratory, Carnegie Institution of Washington
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ALVIN KWIRAM, Professor of Chemistry, University of Washington, Vice Provost for Research Emeritus
WARREN S. WARREN, Professor of Chemistry, Director, NJ Center for Ultrafast Laser Applications, Princeton University
DANIEL WEILL, Professor (by courtesy), University of Oregon, Department of Geological Sciences

National Academies Committee
on Advanced Research Instrumentation
Institutional Survey of Instrumentation Funding and Support

Respondent Name: ________________________________
Title: ________________________________
Institution Name: ________________________________
Street Address: ________________________________
City, State, Zip: ________________________________
Daytime Phone: ________________________________
E-mail: ________________________________

1. Which of the following best describes your institution (check one)?
   _____ a. Public Academic
   _____ b. Private Academic
   _____ c. Independent Research Institute (not affiliated with a university)
   _____ d. Other (please describe): ______________________________
2. What is the total annual budget of your institution?
   ____
3. What was the total amount of basic and applied (nonclinical) research funding received by your institution from the following federal agencies?

Agency	FY2003	FY2004
NSF	__________	__________
NIH	__________	__________
NASA	__________	__________
DOE	__________	__________
DOD	__________	__________
DHS	__________	__________
Other (please specify)	__________	__________

4. Does your institution have any instruments whose capital cost at the time of purchase was greater than $2M and less than $100M?
   a. If not, does your institution hope to acquire any?
   b. If so, in the tables that follow, please provide details regarding instruments in this range on your campus that were either purchased or proposed *in the last five years.* If additional tables are required, please duplicate as necessary.
5. If no additional federal funding was available, do you think the need for instrumentation in this range is sufficient that funding should be diverted from research grants to instruments? If so, what % of funds should be diverted? Should some of the focus be on developing new instruments? If so, what % of funds?
6. What new kinds of instrumentation in the $2M-$100M price range do you think your institution will be interested in five years from now?
7. Do you have any additional thoughts regarding advanced research instrumentation which you would like to share with the Committee?

Confidentiality: **Unless permission is otherwise given, the responses provided in this survey will only be used in an aggregated fashion in the Committee report. Your institution will be listed as a respondent to the survey.**

8. May we use the comments you have provided verbatim in the report?
   Yes _____ No _____

9. May we attribute these comments to you?
Yes _____ No _____

10. *Additional Contacts:* Please identify anyone at your institution who may have unique anecdotal information regarding their experience with funding new or supporting existing instrumentation.

Name	Title	E-mail Address	Phone Number	Issue

Existing or Proposed Instrumentation: ______________________________

a) Capital cost ____________________
b) Siting cost (for remodeling existing facility) ____________________
c) Annual cost of operation (estimated or known)? ____________________
d) Total expected lifetime (years) and cost? ____________________
d) Date need recognized (Month/Year)? ____________________
e) Date fundraising began (Month/Year)? ____________________
f) Funding sources solicited (list specific programs within sources if applicable). Funding sources may include industry, government agencies, private foundations, state government, institutional funds, and direct Congressional or Administration allocation.

Source/program	Funding obtained (Y/N)?	Amount obtained?

g) Date fundraising completed (Month/Year)? ____________________
h) Degree of challenge in fundraising, from 1 (easy) – 5 (difficult) ____________________
i) How was this instrument designed and built or obtained? ____________________

j) How is this instrument used? What areas of research? Is it used by industry? For education? ____________

k) How is this instrument supported and maintained? ____________

l) What opportunities and challenges does your institution face with regards to this instrument? ____________

m) Is this instrument shared? If so, is it within department (D), within institution (WI), and/or shared externally (E). If (E), please list sharing institutions. ____________

n) Hourly rate (if any) for use? ____________

o) Person responsible for instrument? Name/phone/e-mail ____________

p) On a nationwide basis, what is your assessment of the availability of and need for this type of instrument? ____________

q) Would an interagency program for this type of instrument be useful (Y/N)? If so, what should be the components of such a program? ____________

r) What federal policies could be put in place to enhance the design, building, funding, sharing, operations, and maintenance of this type of instrument? ____________

s) Additional comments?

____

LIST OF RESPONDING INSTITUTIONS

Arkansas, Little Rock, University of
Arkansas, University of
Auburn University
Boston College
Boston University
Brandeis University
Brown University
California, Berkeley, University of
California, Irvine, University of
California, Los Angeles, University of
California, Riverside, University of
Carnegie Institution of Washington

Cincinnati, University of
Colorado, Boulder, University of
Dartmouth University
Idaho State University
Illinois, Chicago, University of
Iowa State
Kansas Center for Research, University of
Kansas University Medical Center
Lehigh University
Loma Linda University
Maine, University of
Marquette University
Maryland, Baltimore County, University of
Maryland, College Park, University of
Massachussetts, Boston, University of
Massachussetts Institute of Technology
Michigan State University
Minnesota, University of
Nevada, Las Vegas, University of
New Mexico State University
New York, State University of
North Carolina, Greensboro, University of
Northern Illinois University
Oakland University
Ohio State University
Penn State University
Princeton University
Purdue University
Rice University
Rutgers University
San Diego State University
Syracuse University
Tennessee, University of
Texas A&M Health Science Center
Texas, Austin, University of
Washington State University
Washington University, St. Louis
Wayne State University
Wisconsin-Madison, University of

D

Summary of Researcher Survey Results

CONTENTS

OVERVIEW

In addition to the types of advanced research instrumentation and facilities (ARIF) at universities and the concerns of university administrators, the committee wanted a better idea of the concerns and issues, if any, for individual investigators. To find out, the committee released a survey for researchers, included at the end of this appendix, asking for their thoughts on ARIF and their assessment of the availability of and need for ARIF in their research fields.

In total, 37 researchers responded to the committee's questions regarding ARIF. This appendix summarizes their concerns about ARIF and the types of ARIF that were mentioned to be of particular need in the researchers' fields.

Several interesting and unique points were made concerning the nature of instrumentation that are not reflected in this summary. Montgomery Pettit, of the

University of Houston, for example, noted that without continued infrastructure support . . . we will see many young investigators changing the nature of the projects and science they do to areas that have less impact but assure better chances of success. The lack of instruments or the ability to upgrade aging local facilities simply dictates the science done in the future.

RESEARCHER CONCERNS REGARDING ARIF

In response to the first question asking for thoughts regarding ARIF, many researchers responded with particular concerns concerning policies, costs, and kinds of particular need. Figure D-1 shows the distribution of concerns of researchers regarding ARIF. Many researchers made comments in more than one category.

Below are excerpts of individual responses, grouped by the categories of concern shown in Figure D-1.

Geographic Distribution

"Such instrumentation is more often necessary for the launching of a new field than for the survival of the field. The proper distribution of such instrumentation requires careful planning.

I would hope that federal funding agencies would look at such facilities as regional resources that would meet national needs and fund them accordingly.

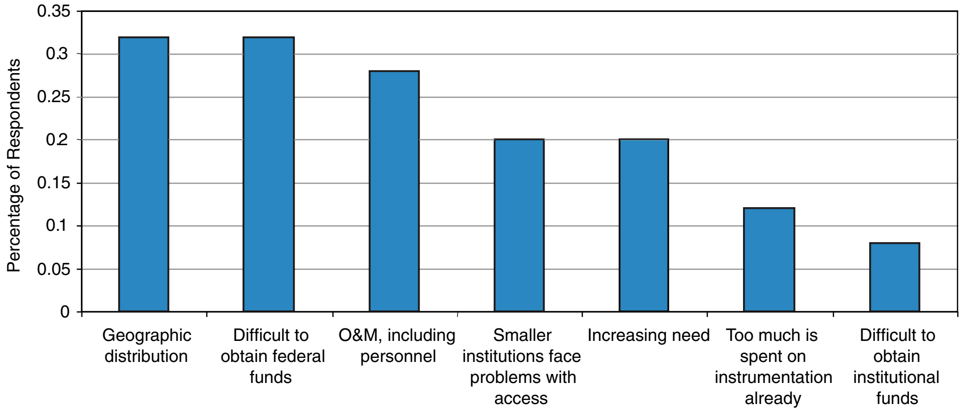

FIGURE D-1 Researcher concerns regarding ARIF.

"The nature of advanced transmission electron microscopy (TEM) is such that a successful experiment involves a very skilled operator and a very good sample, and travel to a remote 'user' facility with a sample of unknown characteristics is simply a nonstarter. Successful academic TEM researchers cannot operate without a state-of-the art facility in their own university. However, the cost of such instruments, say $5 to $10 million, makes their acquisition by the small number of groups (say fewer than 10 in the United States) who need and could usefully exploit such instruments very difficult.

Such instrumentation is essential for generation of new knowledge in some fields. Concentration of such instrumentation in only a few locations limits access. At the lower end of the specified range, this equipment may not require a large support infrastructure and I therefore believe it to be advantageous to distribute these resources as much as possible. At the high end of the specified range, this equipment probably requires an extensive support infrastructure dictating that it be located where such support can be found. In such cases, the equipment should become available as a remote resource to those who wish to use it but do not reside at that location. I am arguing for a balanced approach to distribution of the equipment that I believe best serves the community's interests.

This brings the issue to the second point, namely the availability of advanced research instrumentation: making instrumentation available to all will even out the race and allow innovation rather than access to resources to drive discovery. . . . Advanced research instrumentation provides a technological platform to answer the hardest, unanswered questions in science. An investment on the order of magnitude of 10 or 100 million dollars will pay off many times over if it opens up opportunities to discover new sources of energy, cures for diseases, etc. Beyond potential revenue-generating applications, having access to advanced research instrumentation also opens up avenues for fundamental discoveries, the implications of which may be currently unfathomable.

Many instruments that start out appearing to be expensive and esoteric rapidly become mainstream. The good side of this is that these instruments fuel impressive scientific results. The bad side is that scientists who do not have access to these instruments tend to fall behind in terms of their results and in what experiments they can propose in grant applications.

Additionally, advanced instrumentation generally supports a large consortium of researchers, who may or may not be geographically close to the equipment. It's not clear how use, training and scheduling can be formally addressed—currently, we essentially rely on informal arrangements.

In my experience, there are only several such instruments of a single type that should be needed by the entire national research community, in which case, such instruments should exist in regional centers that are available to investigators from out of town. There should be some way to coordinate the placement of such instruments that takes into account the locality of the most need and what makes sense in terms of spreading out across the country.

Hard to Get Federal Money

“At the present time there seems to be a tremendous amount of pressure for scarce resources. Base programs that can be directed at long-term research and development (R&D) to design future advanced research instrumentation seems to come from the same directorate and subdirectorate budgets as the large instrumentation projects in the specified cost range. This appears to make it very difficult on program officers to find the right balance between long-term and short-term goals, that is, realizing the opportunities that are timely from completed R&D while also allowing a path for the future to be established. . . . There is no question that the need is immediate and growing. Our field is a growing one, with many new junior faculty hires and a greater focus at some of the national laboratories (LBNL, SLAC, and Fermilab are all seeing some growth in the direction of astroparticle physics and cosmology). Yet, in the present budgetary climate, it seems that the program budgets are not able to grow in proportion to the demand. It is particularly difficult for younger researches trying to initiate programs rapidly burning through university startup funds while trying to help seed large projects, only to hear from program officers that they face very difficult choices on the horizon. . . . I’ve shared my perspective with the panel, but I fear that to address some of the challenges that I’ve stated will simply take a greater commitment of funds. Incumbent on all of us is to convince the administration and the congress, and the country at large, that we must commit to the scientific endeavor for the long haul. Through the development not only of advanced instrumentation but the development of the people (students, postdoctoral researchers, for example) who learn how to make these things, will we be able to meet areas of national need, including security, technology development and the economic growth it triggers. Admittedly, some tension and competition for funds is appropriate and desirable, but the current budgetary environment is much tighter than ideal.

Impossible for single researchers to commit the time to obtain.

I would urge the members of this committee to recommend most strongly that the Congress avoid the mistake of reducing the funds for scientific instrumentation of this sort, in spite of the current fiscal climate. Doing so would have severely adverse effects on US scientific research at a time when US government support is already weak and inadequate to keep pace with inflation, and would mortgage the future growth and competitiveness of both the US research and industrial communities.

"Successful academic TEM researchers cannot operate without a state-of-the art facility in their own university. However, the cost of such instruments, say $5 to 10 million, makes their acquisition by the small number of groups (say fewer than 10 in the United States) who need and could usefully exploit such instruments very difficult. There appears not to be a current program that addresses this need. An interagency program, probably administered by the NSF and focusing on physical rather than biological science applications, and for which academic researchers could compete for the sums involved, say to fund six $5-$10 million instruments, would be most welcome indeed.

It is difficult to get a major instrument funded now, and the trend is toward even more difficult times in the future.

From over 1 million to tens of millions of dollars the prospect of obtaining infrastructure for structural biology, biotechnology, or computational facilities is bleak. The current sources with the largest percentage for funding success are charitable foundations. Even here the percentages are very small. Building clean rooms and associated facilities for wet/dry projects, infrastructure for structural biology and computational facilities are critical for progress in a variety of areas, yet other than 'pork' no ongoing federal programs with reasonable funding percentages can support this range. When you make it through the sieve it is a one-time hit, whether foundation or government. The prospect of continued maintenance and upgrades is almost nil. . . Without continued infrastructure support in structural biology, biotechnology and computational science at the non-national-center level, we will see many young investigators changing the nature of the projects and science they do to areas that have less impact but assure better chances of success. The lack of instruments or the ability to upgrade aging local facilities simply dictates the science done in the future.

All I know is that it is extremely difficult now to get anything approaching the kind of support we need.

It is imperative that NIH continue to fund new instrumentation grants. In order for PIs and institutions to keep up with the changing trends in instrumentation, particularly as it relates to their ongoing NIH research, funds are needed to purchase such equipment. Unfortunately, public institutions have been seeing a downward trend in funding from the State, and the first place that is cut is funds for instrumentation. It would also be advantageous if NIH comes up with another instrumentation grant to cover bundled instruments (i.e., a number of lower-cost items, e.g., centrifuges, fluorescence spectroscopy, or microscopy). The higher-cost instrument grants program was also not activated this year, equipment over $750,000. This needs to be reinstated. In order for investigators to continue quality research they need access to state-of-the-art equipment. . . . We are a growing institution adding new faculty. New instrumentation is not only needed but essential to attract the best and most promising scientists. As stated above, we are a public institution experiencing a downward trend in state support. Access to funds to purchase new instrumentation is critical to our success. Advances in instrumentation for biology and applied life sciences have been extensive and we need to be able to take advantage of this new technology. Advanced instrumentation for research is important to the progress of science and medicine. We have faculty who are also developing new instrumentation for examining protein-protein interactions and utilizing more in depth methods of tracking proteins. These techniques and instrumentation are essential for understanding cell signaling and choices cells make in aging and dying. . . . Recommend that NIH consider another level of funding instrumentation for bundled or grouped instruments that cost under $100K but are difficult to purchase in the current economic status of public institutions.

Hard to Get Institutional Money

"There is absolutely no institutional support available. [refers particularly to O&M]

Acquisition of advanced research instrumentation with these capital costs must be part of a strategic plan that encompasses the academic, research, and economic development missions of the university. Acquisition with institutional funds of such large instruments is beyond the capability of this institution. Significant federal, state, and/or philanthropic funding would be required for the capital outlay.

Increasing Need

"My purview is all the sciences, so the needs are similarly broad. The only common thread is need for more expensive and sophisticated equipment that has shorter usable lifetimes and therefore needs replacing or upgrading more often. We need more equipment that is more expensive, and we need to replace it sooner. However, the federal programs for research equipment are shrinking so we are falling behind by all measures. The universities will never be able to handle the shortfall, so our science will be constrained. . . . At the same time that everyone asserts that science and engineering research is the key to our economic growth and competitiveness, the reality is we are funding less and less. This is very disheartening and frustrating. We are also facing stronger competition from the higher ed systems in other countries for the best faculty and students, so we have to have a competative edge. Our research facilities can be part of that edge. It's ironic that the entire budget of NSF is less than the cost of two of our most advanced planes.

There is an increasing need for advanced research instrumentation in many fields.

This is a very definite need for the community, especially at national (possibly regional) user facilities.

As Chair of the Chemistry Department, I believe that the need for high-end instrumentation will only increase in the next five years, as the sophistication of the research increases. The number of users is expected to increase in areas such as biology, chemical biology, nanoscience, supercomputing, etc.

The need for advanced instrumentation will only increase, as history clearly shows.

O&M, Including Personnel

"To obtain such instruments is way beyond the time single researchers can commit for the cause of common good. The maintenance fees will represent the second level of unforeseen difficulties. We do not have any means/mechanism to raise, in addition to the purchase and maintenance costs, running and operating budgets and resources to provide for well-trained personnel to run such instruments and provide service to multiple investigators. There is absolutely no institutional support available.

To be effective, an 'Advanced Instrumentation' program for transmission electron microscopy should not only address the costs for the actual instrumentation. Is equally important to ascertain that researchers are thoroughly trained on these sophisticated instruments. As the complexity of transmission electron microscopes increases significantly with the addition of advanced electron-optical components and specimen manipulators, the availability of highly trained operators will be increasingly important for the productivity of the instrument. Maintaining sufficient availability of well-trained operators may generate additional costs for appropriate personnel and/or regular user training—perhaps by the manufacturer. . . . Moreover, a good technical condition of a transmission electron microscope with the field-emission gun, corrector for spherical aberration, electron monochromator, and an advanced specimens stage will be very difficult to maintain without intense support from the manufacturer. Therefore, a program for "Advanced Instrumentation" in the field of transmission electron microscopy can only be effective if it also addresses the (often very high) costs that will necessarily arise from service contracts with the instrument manufacturer over the lifetime of the instrument.

Perhaps more problematic is support for the operation of such equipment. We would need to develop a business plan that rendered the operation selfsupporting after a defined period. Even so, support for the startup period would be a problem.

This is a very definite need for the community, especially at national (possibly regional) user facilities, which also must be funded for support personnel, local administration, supplies, and (ideally) travel and housing for US users. In the latter respect, the policies of ESRF and ILL for users from the European Community are significantly better than those at US facilities.

When you make it through the sieve it is a one-time hit, whether foundation or government. The prospect of continued maintenance and upgrades is almost nil.

Funding should include infrastructure support such as technical personnel and service contracts. Institutions should be required to contribute to such support. Otherwise, long-term usability of the equipment would be compromised. A recharge plan for users should be included in each application, as well as a plan how to deal with future upgrades. . . . The initial cost of the equipment is only a portion of the total cost associated with the equipment—significant funds are required for maintenance, support, consumable supplies, and the like. It's not clear how these costs are addressed in the current grant environment.

Smaller Institutions Face Problems with Access

"Inaccessible to most small universities, except in collaborations.

There are many instances of this sort of need, however, I feel that too large of a percentage of funds are routed to the same institutions without any attempt to nurture smaller institutions into participating in such large projects. This prevents students at the smaller schools from gaining research experience.

Now it seems that those institutions with large research facilities typically are the ones that obtain grants for major additions to their facilities.

The need now, and in the future, is incompletely satisfied. To say nothing is available is as wrong as saying that everyone can access everything they need. Although this may be interpreted as self-serving, I believe that distribution of, access to, advanced instrumentation at institutions other than the few 'leaders in the field' limits the preparation of tomorrow's investigators as well as limiting today's advancement of knowledge. I therefore think more opportunities need to be made available to the 'middle'; institutions with a research mission and are still in the process of building their programs as opposed to the recent emphasis on large grants to large entities. . . . Many advances come from the big places. Many advances come from the smaller places. Many of tomorrow's contributions come from both places. Don't forget the 'middle' and the 'little' when resources are being made available to serve the public good.

Such instrumentation needs to become more generally available than it currently is. Particularly, I am concerned that facilities like that which I have described be located at places like NIST and the National Labs, and that dormitories with eating facilities be set up for long-term visits (up to six months) by graduate students and postdocs who wish to work there. Grant funds to support such visits should be included in the facility budgets. . . . I would be strongly opposed to setting up such facilities at academic institutions, because they will create “super” universities that will operate to the detriment of all other institutions, including our outstanding four-year liberal arts colleges.

Too Much Is Spent on Instrumentation Already

“Between the national laboratories and other centers of excellence established e.g., at universities, there does not appear to be a lack of access to major instrumentation in my field (materials science). However, looking at instrumentation in general, much of the major instrumentation is highly specialized to specific disciplines (e.g., high-energy physics), which decreases its utility for broad use, especially for interdisciplinary research, e.g., at the interface between the biological and physical sciences. . . . In the physical sciences and engineering, I am concerned that too much federal funding is already dedicated to instrumentation, and not enough on our human resources (undergraduate students, graduate students, postdoctoral researchers, and faculty). After all, what is the value of instrumentation without a large pool of researchers to use it? This is especially a concern when the federal budget for medical research is several times greater than that for all other nonmedical fields combined. . . . I feel that ‘advanced research instrumentation’ as defined in this forum is a less pressing priority than a national recommitment to the physical sciences and to human resources in science and engineering. If an initiative for new instrumentation is pursued, it should give priority to flexibility of application by researchers from a variety of disciplines, perhaps envisioning new concepts of instrumentation that do not yet exist. Such efforts would call for a commitment of funds from several agencies. . . . It is paradoxical and perverse that it is often easier to get funding for million-dollar pieces of equipment than hundred-thousand-dollar projects to support graduate students. It is also not evident that major instrumentation is what is needed to address the world’s most pressing problems: hunger, poverty, energy technology, and wise use of resources. ‘Instrumentation with capital costs between $2M and $100M’ sounds to me like science at the service of scientists, not science at the service of humanity.

There are a number of specific, interesting problems that naturally require instrumentation of large scale. In most the cases I am aware of, either casually or in some detail, these projects yield good science, but not of the caliber that justifies their cost. The other complaint I have is that when project goes over budget, the usual move is to allow for overruns, to justify the money already spent. This is a dangerous cycle. With strict limits on budgets, and well-justified science goals, I have no fundamental problem with large programs; unfortunately, I do not often see that these simple criteria are met. . . . I see little calling in AMO for large-scale, advanced research instrumentation projects. Small-scale projects deliver the bulk of the cutting-edge research in my field.

In my field I think the instrumentation is better invested in individual investigator grants. The NSF budget for individual investigator grants and instrumentation is woefully inadequate. Major new instrumentation facilities should have a considerably lower priority than individual investigator grants.

Waste of money to support only a few in that range. In our field, we'll never need instrumentation (computers) that costs more than $2M at a time. So, provide programs that'd fund different varieties of worthy proposals, not just those either very 'large' (astronomy) or very 'small' (cells) areas.

EXAMPLES OF ARIF AND FIELDS REQUIRING ARIF

Figure D-2 outlines the types of ARIF or fields requiring ARIF that were mentioned in survey responses. Excerpts from the survey responses related to individual research fields or instruments follow.

Particle Physics

"Advanced research instrumentation is becoming ever more important to the US scientific community as science becomes increasingly specialized, and as new

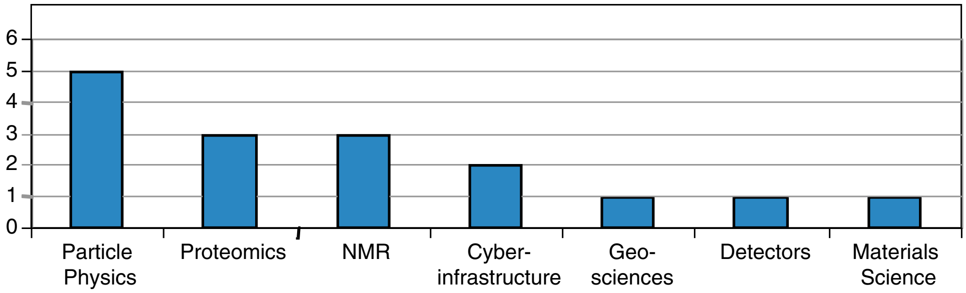

FIGURE D-2 Examples of ARIF or fields requiring ARIF mentioned in the researcher survey.

advances are being made on all fronts of science, particularly in nanotechnology, biology, and engineering. As US industry evolves into a new paradigm in which basic R&D is outsourced, its reliance on advanced research instrumentation for materials characterization will increase. The same is true for the individual university researcher for whom access to advanced instrumentation located at neutron or synchrotron-based research facilities, once considered off-limits to all save for a few experts, is now viewed as an essential component of any research program, as is evident by the dramatic growth in the numbers of university users at such facilities over the past five years. For example, the utility of neutron imaging techniques are only now being realized by industry in their efforts to develop useful hydrogen fuel cells, as neutrons can image the water by-product of the cell directly and in real time as it operates. Similarly, neutron scattering methods such as neutron reflectometry and small-angle scattering are now being extensively applied to characterize model biological systems such as cell membranes, for example the process of membrane fusion, which occurs whenever a virus attacks a cell, or when cells secrete packages of hormones. . . . There is not nearly enough neutron scattering instrumentation to satisfy current needs. A 2002 report from the Office of Science and Technology Policy (OSTP) on neutron facilities concluded that there was no chance of satisfying demand for neutron measurement capability in the United States, even with all US neutron research facilities fully instrumented and fully operated—including both the NCNR and the soon-to-be-constructed Spallation Neutron Source. The OSTP report found that Western Europe, a region with a research community similar in size to that of the United States, has over five times the neutron measurement capability of the United States, and that all of that capacity is heavily over-subscribed. Five years from now the SNS will have ramped up its operations. Yet rather than helping to satisfy US researcher demand, experience actually shows that the emergence of the SNS will most likely have the opposite effect, i.e., the SNS will attract and educate new researchers in the use of neutron techniques, and they will be drawn to the complementary capability at the NCNR. Thus demand for neutron instrumentation will most likely go up. This can easily be understood when one realizes that there is an enormous latent demand for neutron scattering and other types of neutron-based research, which will only get bigger as the US research community is given greater access and becomes better educated in the area of neutron science.

State-of-the-art beamlines at the APS (and other beamlines at the ALS, SSRL, and NSLS) are marginally underfunded which has prevented completion and limited operations. However, floor space is running out. Within 5 years, the United States may need to begin construction of two new third-generation synchrotrons and plan for developing new beamlines because real estate at existing facilities will have been filled and be fully used for excellent science. A particular need at the APS is for undulator upgrades (funded directly through the APS), each of which will be in the advanced research instrumentation category, and support for upgrading the beamline optics owned by the CATs (which also can be in the advanced research instrumentation category). . . . As much as hardware, significant instrumentation development is needed in software in some areas. A particular need is for collecting and processing diffraction data from micron- and nanosize crystals that cannot be handled by conventional four-circle techniques. Coordinated development involving many beamlines where such experiments can now be run will benefit several user communities without unnecessarily duplicating efforts. . . . Development of SNS including beamlines seems to be progressing well. The currently funded beamlines will have a major impact within 5 years. Further development of that facility will greatly improve the US scientific capabilities at that time and further out. . . . Many universities will want and can make good use of advanced computational facilities for data-intensive simulations. Whether these will fall within the advanced research instrumentation category is not clear to me. They will not be national user centers.

This is a good way for the United States to catch up with Japan and Germany on positron beams. There is a Nobel prize or two for the AMOP community in a number of antimatter projects. These include the antimatter-gravity experiment, a 511 keV laser, BEC of Ps at LN2 temperature, the creation and characterization of the dipositronium (Ps2) a diatomic molecule that is half koino-matter and half antimatter, nano-imaging, pathways to new compounds by selective annihilation, creation and characterization of mixed electron-positron systems, deep space propulsion, etc. . . . A small academic/government lab group now exists that is striving to get resources to construct a positron beam using a new idea for the moderation of MeV positrons created by pair-production of Bremstrahlung radiation induced by a LINAC. We need $5M, with which we could create a national users' facility for positron studies at Argonne National Laboratory. Our plan includes several generations of enhancements that will give us a positron source that is orders of magnitude more intense than any now existing.

Proteomics

"In molecular biology we have little need for individual equipment in this price range. However, we do have needs for systems whose aggregate cost can be in this range, such as instrumentation for proteomics analysis (advanced mass spectrometers coupled to gel handling systems).

Instrumentation of this type is essential for confronting the challenges in science that lie ahead. Particularly, I am concerned with the development of new high-resolution laser and ESI mass spectrometer systems that will be needed to

(a) 'decode' the human (and other) genomes, determining the structures of the component parts, how they are linked together, and which links are the key to function, and (b) learn how to manipulate such structures with light, to form new secondary, tertiary, and quaternary structures that mimic biological function, including translation, transcription, and replication. All computer modeling of such phenomena will rely on the availability of 'gas-phase' data of this type.

We are a growing institution adding new faculty. New instrumentation in not only needed but essential to attract the best and most promising scientists. As stated above, we are a public institution experiencing a downward trend in state support. Access to funds to purchase new instrumentation is critical to our success. Advances in instrumentation for biology and applied life sciences have been extensive and we need to be able to take advantage of this new technology. Advanced instrumentation for research is important to the progress of science and medicine. We have faculty who are also developing new instrumentation for examining protein-protein interactions and utilizing more in-depth methods of tracking proteins. These techniques and instrumentation are essential for understanding cell signaling and choices cells make in aging and dying.

NMR

"In my field (structural biology primarily using NMR), the need for advanced research instrumentation is very great currently, and will probably continue to be great 5 years from now. Five or six years ago, few labs had access to very high field spectrometers (750 MHz or above), but now the field has been pushed ahead to where many (most?) projects require such instrumentation. A significant number of researchers have access to these machines, but many either don't have access or must drive/fly long distances to obtain access. While on paper it sounds fine to ask a researcher to travel to a high field spectrometer, in practice this is very cumbersome and does not lead to cutting-edge results. For any particular NMR project, a dozen or more different NMR experiments must be carried out on a sample (and sometimes on several samples with slightly different conditions). Traveling back and forth to a 'richer' or better endowed university is not conducive to getting results. This is in contrast to x-ray crystallography where indeed one or two trips to the Advanced Photon Source could give a researcher enough data to finish a project.

The main gap is between \$2M and \$10M. This gap includes advanced NMR, fMRI, x-ray, laser, and electronic microscopy equipment. Much of this equipment is needed for biology and biosciences and should be included as part of core instrumentation facilities of major research universities.

In chemistry, there are limited types of instrumentation that fit this category. In my particular discipline within chemistry, only really high field NMR spectrometers and very fancy and powerful mass spectrometers would come close to the minimum $2M level you are talking about. It is unlikely that individual institutions can afford to purchase such instruments for local use only. The needs for such equipment are usually very specialized, but when needed, such instruments are indispensable. The obvious answer is that there is a need now and that it will grow in the future, in part because discoveries will lead to the invention of instruments that are more powerful and expensive than we have now. For example, a 900-MHz NMR now costs about $1M. I would guess that in the future there will be spectrometers that cost $2M.

Cyberinfrastructure/Geosciences

“To date, our vision has been defined by the NSF MRI competition, so we have considered ‘major’ equipment to be in the $2 million max area. However, we have just decided institutionally that we will have to renew our supercomputer every 3-4 years at a cost to us this time of $2 million, but likely more next round, and we are planning to do this with institutional funds. So, equipment we used to think of as being attainable only through grants we are now thinking about funding ourselves. We have not heretofore ventured into the next level, the $3-$100 million domain. There is a gap between the size of equipment we pay for ourselves or via grants, and the size of major national facilities like the DOE labs, so we don’t routinely think of or do science that needs equipment in this middle range, which means we are missing some valuable science that could be done in this range. However, at OU we are now a partner in building the National Weather Radar Testbed, an approximately $25 million phased-array radar. It took immense time and effort to pull together the coalition to do this, but it will be the basis of research leading to the next generation of weather radar. My point is we should have these ambitions and programs in other discipline areas, but our vision is curtailed and we don’t think that big.

Detectors

“We are underinvesting in AMO instrumentation at a time that this branch of science is undergoing a major revolution. One area that is particularly in need of resources is detectors. We are losing out to the Europeans and the Japanese in detectors with temporal and/or spatial resolution, such as streak cameras and fast CCDs. . . . The area of terahertz science needs much more support and attention. Coherent synchrotron radiation in this range of the electomagnetic spectrum is ripe for major breakthroughs.

Materials Science

"In Materials Science and Engineering, the major type of research instrumentation that falls into the plus $2,000,000 category are aberration-corrected subatomic-level-resolution transmission electron microscopes (TEMs). There is a BES/DOE program involving the major national labs (Oak Ridge, Lawrence Berkeley, and Argonne) to acquire one or more such instruments as 'user facilities.' The BES program at DOE has been funding acquisition of TEMs for at least two decades, and possibly longer, arguing that an advanced TEM can be compared to a synchrotron source, and that 'if you build them, they will come.' The truth is otherwise. As user facilities, their usage by rank and file academic electron microscopists is in most cases minimal; instead, the users are researchers who have no skills in advanced TEM (arguably the most difficult skill to acquire) and establish a collaboration with staff at one or the other National labs (it is actually a stretch for DOE to show 'success' of these TEM-based user facilities). There is nothing wrong with such an arrangement but it doesn't satisfy the needs of academic materials science electron microscopists, as will be discussed in question 13."

POLICY RECOMMENDATIONS

Policy recommendations made by researchers included the following:

- "ARI development budgets come from the same directorate and division budgets as large projects. It is necessary (though difficult) to find the right balance between long-term and short-term goals.
- There should be a recommitment to the physical sciences and to human resources in science and engineering, more so than to more support for instrumentation. If a new instrumentation initiative is put into effect, it should give priority to flexibility of application, perhaps looking into new categories of instrumentation that do not yet exist.
- Agencies should treat ARI facilities as regional resources that meet national needs.
- An interagency program supported by the NSF focusing on TEM for physical, not biological applications, which would fund six $5-$10M instruments. (Heuer)
- An NIH instrumentation grant to support bundled instruments under $100K—an ensemble of low-cost items. NIH should also reactivate the 'high cost instrument grants program.'

- 'Funding should include infrastructure support such as technical personnel and service contracts. Institutions should be required to contribute to such support. A recharge plan for users should be included in each application, as well as a plan how to deal with future upgrades.'
- Facilities should be centralized at placed like NIST and the National Labs, with the inclusion of housing for long-term visitors."

RESEARCHER SURVEY ON ADVANCED RESEARCH INSTRUMENTATION

Today, instrumentation plays a critical role in scientific and engineering research and exploration. We would like to get your help in gaining a better understanding of the issues related to instrumentation in your field and your thoughts on federal policies. This survey is part of a study being conducted by the National Academies Committee on Advanced Research Instrumentation in response to Section 13(b) of the NSF Authorization Act of 2002. The Instrumentation Committee is under the aegis of the Committee on Science, Engineering, and Public Policy (COSEPUP). COSEPUP, chaired by Dr. Maxine Singer, is the only joint committee of the three honorific academies: the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. Its overall charge is to address cross-cutting issues in science and technology policy that affect the health of the national research enterprise.

The study is examining federal programs and policies related to advanced research instrumentation used for interdisciplinary, multidisciplinary, and disciplinary research. If needed, the committee will propose policies to make the most effective use of federal agency resources to fund such instruments. Advanced research instrumentation, for the purposes of this survey, is defined as instrumentation that is not categorized by NSF as Major Research Instrumentation ($100,000 to $2 million in capital cost) or as Major Research Equipment (more than several tens of millions of dollars), but instead falls in between these two designations.

To respond to its charge from Congress and NSF, the Committee is interested hearing your thoughts on instrumentation in your field, as well as your opinions concerning current and possible future federal programs and policies for advanced research instrumentation.

We hope you will be willing to participate in this important information-gathering effort. *We recognize that answering all the questions in this survey may be challenging. We only ask that you do the best you can in providing the information requested.* If another person at your institution is better suited to answer this survey, please forward it to them, but please let us know to whom you sent it. We also encourage you to send this survey to any researchers at your institution who may have additional thoughts. Their comments may be sent either to you for compilation or directly to *instrumentation@nas.edu.*

We would appreciate receiving your response by Friday, April 1, 2005. Please return the completed survey via e-mail as an attachment to *instrumentation@nas.edu* or by fax to 202-334-1667. If you have any questions, please contact the study director, Dr. Deborah Stine, at *dstine@nas.edu* or 202-334-3239.

Thank you for your time and participation. For more information on the study, please visit our website at http://www7.nationalacademies.org/instrumentation/."

National Academies Committee on Advanced Research Instrumentation

MARTHA KREBS (Chair), President, Science Strategies
DAVID BISHOP, VP Nanotechnology Research, President, NJNC, Bell Labs
MARVIN CASSMAN, Independent Consultant
ULRICH DAHMAN, Director, National Center for Electron Microscopy, Lawrence Berkeley National Laboratory
THOM H. DUNNING, Jr., Director, National Center for Supercomputing Applications, University of Illinois, Urbana-Champaign
FRANK FERNANDEZ, Distinguished Instititute Technical Advisor, Stevens Institute of Technology
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WARREN S. WARREN, Professor of Chemistry, Director, NJ Center for Ultrafast Laser Applications, Princeton University
DANIEL WEILL, Professor (by courtesy), University of Oregon, Department of Geological Sciences

National Academies Committee on Advanced Research Instrumentation Researcher Survey of Instrumentation Funding and Support

Please answer the following general questions:

1. Name:
2. Title:
3. Institution Name:
4. Daytime Phone:
5. E-mail:
6. Research Field(s)?
7. Type of Institution (Public, Private, Independent Research Institute, etc….):
8. Do you hold or have you held any administrative positions that involve instrumentation decision-making (Y/N)?
9. If so, what?

Unless permission is otherwise given, the responses provided in this survey will only be used in an aggregated fashion in the Committee report.

10. May we use the comments you have provided verbatim in the report (Y/N)?
11. May we attribute these comments to you (Y/N)?

Please share your perspective on instrumentation:

12. What are you thoughts on advanced research instrumentation (instrumentation with capital costs between \$2M and \$100M)?

13. In your discipline, what is your assessment of the availability of and need for advanced research instrumentation, now and five years in the future?

14. Do you have any additional comments?

LIST OF RESPONDING RESEARCHERS

Akerib, Daniel
Bland, Paul
Cipolla, Sam
Csiszar, Katalin
DeGraffenreid, William
DeGuire, Mark
Duerk, Jeffrey
Ernst, Frank
Esembeson, Bweh
Fertig, Chad
Field, Robert
Fujita, Hilzu
Gallagher, Patrick
Habicht, Gail
Heuer, Arthur
Hochstein, John
Holmes, Richard
Kirz, Janos
Knothe Tate, Melissa
LiWang, Patricia
Miner, Steve
Nicol, Malcolm

Paule, Marv
Pettitt, Montgomery
Pratt, Daniel
Reinhardt, William
Reisler, Hanna
Resnick, Andrew
Rybicki, Edmund
Sayre, Lawrence
Schrader, David
Storey, Dan
Stwalley, William
Sun, Jiayang
Surko, Clifford
William, Lee
Yorio, Thomas

E

Summary of Disciplinary Society Survey Results

CONTENTS

OVERVIEW

In addition to the perspectives of institutions and researchers, the committee was interested in the broad views of advanced research instrumentation and facilities (ARIF) from different scientific, engineering, and medical fields. To obtain more information, committee staff drafted a survey of disciplinary societies that was distributed to roughly 150 executive officers and directors and federations of such societies.

The survey asked for an overview of the types of ARIF that were used in the fields represented by the societies and an assessment of the availability of and need for the instruments. It also asked the society what new types of instrumentation would interest researchers in the societies in the near future. Respondents were asked to assess current federal agency policies with regard to ARIF and to express the primary federal policy issue faced by their field.

In total, the committee received seven responses. All the respondents wrote generously about their fields and their needs. Because of the number of responses and desire for confidentiality, some responses are not included in this summary.

EXAMPLES OF ARIF

This section provides the responses from professional societies regarding current ARIF examples in their field:

Chemical Physics

"Experimental instrumentation in this price range currently reside primarily at the national laboratories (LANL, LLNL, LBL, ORNL, PNNL, BNL, FNL, ANL, INEL, SNL, etc.) and include what might be termed 'big science,' that is, instrumental approaches that are not possible at independent research institutions. Critical instrumentation in this price range for chemical physics research include (but are not limited to):

- Neutron scattering techniques/spectrometers—neutron diffraction, small angle neutron scattering, quasielastic neutron scattering, neutron reflectometry.
- Synchrotron radiation techniques/spectrometers—EUV/x-ray spectroscopy, x-ray diffraction, time-resolved high-energy experiments.
- High-field NMR spectrometers—pulsed field gradient, two-dimensional.
- Tunneling electron microscopes—in situ capabilities with aberration correction to follow the dynamics of nanoscale systems in real time.
- Elaborate state-of-the-art laser systems including facilities for studies of attosecond pulses.

The utility of these resources is becoming more apparent to the research community, and the need for access to them is growing. For example, synchrotron radiation sources are now oversubscribed by users [see, e.g., B. Crasemann, Synchrotron radiation in atomic physics, Can J. Phys. 76:251-272 (1998)]. High-performance computing architectures also play a major role in chemical physics research, and the availability of this type of computation resources is always very limited. At the lower end of this price range, cluster computers also play an important role. Currently, the options are either large computer systems at national supercomputing facilities or relatively small private clusters. The number of national facilities is currently too low as researchers vie for access to these facilities and the need for these resources is constantly growing.

Division of Chemical Physics
American Chemical Society

Plant Biology

"There is a need for more use of high-frequency nuclear magnetic resonance (NMR) spectrometers for doing whole cell/whole plant functional metabolomic studies. The cost is $5-$7 million for a high-field, 900-MHz instrument not including housing and related costs. NMR spectroscopy is a diagnostic tool that operates on the same principle as magnetic resonance imaging (MRI). However, instead of looking at structures at the anatomical level, scientists use NMR spectroscopy to study structures at the atomic level. Through NMR, scientists get atomic-level pictures of biologically important molecules including proteins, nucleic acids, and carbohydrates. This contributes to an understanding of how molecules function. For example, NMR helps researchers understand how proteins recognize and interact with carbohydrates on the surfaces of cells.

There needs to be a recognition that plant growth facilities such as greenhouses that provide critical control of lighting, temperature, watering, and humidity are instruments. There is a tremendous need for support in this area. Often greenhouse facilities are viewed as building projects by universities and government agencies and are therefore very difficult to fund. However, modern greenhouses are in fact sophisticated instruments necessary for controlled experimentation with plants. Modern greenhouse facilities cost several million dollars.

American Society of Plant Biologists

Political Science

"Major instrumentation requirements in political science largely rest in the operation of major longitudinal data series and the maintenance of the institutional support for them, with the peak example being the National Election Survey sustained by the National Science Foundation and currently managed by the University of Michigan. This operates in the $7-$8 million range. The discipline has a strong need for additional capacity for such longitudinal data collection—both to apply new methodologies (such as ability to capture implicit attitudes as well as explicit) and to address other areas of politics, and in particular, electoral and other political behavior in comparative political settings.

While it's of course difficult to put boundaries on such capacity, I would estimate that the discipline could currently benefit from and take active advantage currently from half a dozen additional such major longitudinal surveys: tracking other dimensions of domestic political behavior, measuring political behavior in new ways, exploring emergence of new democracies, archiving patterns of political communication, and extending all work to comparative settings, including the study of comparative electoral systems.

A second emerging area is the development of laboratory capacity for political science. Individual labs, such as the one newly supported by the NSF at Indiana University, cost about half a million dollars; the discipline over the next few years needs such laboratories in a dozen major US institutions. These labs are used for computerized research into the behavior of human subjects in simulated 'political' situations.

A third area involves archiving, particularly of political communication materials, and the construction of meta-data. These efforts involve both the coding of political communication data, such as the News Laboratory at the University of Wisconsin-Madison, and the merger of text, audio, and video files with a coding overlay. One can imagine such archive laboratories in each of the 50 states. Virtual data center projects are also emerging, where marginal costs of use are free but development costs are very expensive.

The discipline shares with other disciplines in the humanities a need for preservation and digitization of primary materials—newspapers, and so forth. This includes a major project under way now at the National Endowment for the Humanities that calls for significant investment in the National Digital Newspaper. It is currently an $18 million annual effort at NEH. While political science is by no means the sole beneficiary of this infrastructure investment, it is central to our work and a small piece of what eventually needs to be accomplished.

Michael Brintnall
Executive Director
American Political Science Association
(Individual response)

Particle Physics

"One often thinks of an 'Instrument' as a facility for making measurements, such as a scanning electron microscope or CAT imager, where a user may come in and make measurements on a sample of interest. The closest analogy in high-energy physics is the combination of an accelerator which produces beams of particles and a detector which measures the products of the particle interactions. The high costs of accelerators put them well beyond the cost regime being studied by the present panel so we concentrate on detectors. Typical detectors may be a combination of specialized instruments such as precision devices for localizing particle tracks, magnetic spectrometers for measuring particle momenta, and calorimeters for measuring particle energies.

Experimental detectors in high-energy physics tend to fall into two major categories: Large general purpose detectors at accelerators (typical costs are several hundred million dollars, hence not the subject of this study) and smaller detectors designed to address a very specific physics question. The latter falls squarely in the cost range of interest to this study. Examples of such detectors include the MiniBoone neutrino detector designed to confirm or rule out a surprising previous result on neutrino oscillation, the CDMSII detector to search for dark matter, and several experiments around the world to detect neutrino-less double beta decay. It is worth mentioning that an excellent experiment called CKM to measure rare charged kaon decays at Fermilab was recently cancelled for lack of funding.

The number of medium-size projects in the field is quite low at present, however there is no question that the need for medium-scale experiments to address specific questions in high-energy physics will continue or grow. Funding in this category has always been tight, due especially to competition with the very large experiments. This is unfortunate, because the small- and medium-size experiments provide excellent training for students and postdocs and provide good science value for the money. In addition, it is important for the overall health of the field to be able to take a chance with a few small innovative experiments that have the potential to surprise us with unexpected results.

There is a second category of instrumentation research in the \$2-\$100M range which needs support and that is developing novel techniques to the technical readiness level where they could be considered for medium- or large-scale detectors. Suppose someone has an idea for a completely new type of calorimeter or particle-tracking device. How can they show that this idea has merit? The first step probably involves making a table-top scale prototype and carrying out a series of feasibility studies. These might cost a few 100 K\$ and come from laboratory discretionary funds. If the idea passes these initial tests, the next step might be the construction of a full-scale subsystem and testing in an accelerator beam. Since these tests may require specialized readout electronics, data acquisition systems, and a small team of people, the costs could easily fall in the \$2-\$10M range. It has been extremely difficult to find this type of funding since the agencies expect it to come from existing operations budgets while laboratories and universities find these operations budgets barely adequate (often inadequate) to support the on-going programs.

Division of Particles and Fields
American Physical Society

EXAMPLES OF FUTURE ARIF NEEDS

Descriptions of various research communities anticipated needs for ARIF, as described by disciplinary societies, are excerpted below:

Chemical Physics

"As research instrumentation grows more complex and more expensive, we envision many individual research labs encroaching on the lower end of this instrumentation limit. For example, in the next few years, ultrashort extended UV and x-ray sources, various UHV surface analysis tools, and ultra-high-field NMR spectrometers should become available commercially and individual investigators will want to have such costly equipment in their labs. There is also the need for tunable free-electron lasers and linear accelerators applicable to QED research.

At the same time, there are various types of equipment that can only exist in shared facilities, such as equipment with a >$10M pricetag. As the SNS goes online at Oak Ridge, there are many instruments associated with this source that should be built. The SNS has the potential to be the premier neutron diffraction facility in the world with its predicted high neutron fluxes. This is one piece of instrumentation that should be a VERY high priority because it would be unique and would bolster the US presence in this internationally dominated field.

Computing architectures will continue to be in high demand in the future. We can anticipate new architectures becoming available (e.g., vector processors rather than massively parallel scalar processors). Another important component for the usability of these high-end computer systems is the availability of software for specific applications. There is the need for significant investment in the software as well as the hardware for high-performance computing systems. Limited funding drives the need for development of shared software (community codes) as well as shared hardware.

Division of Chemical Physics
American Chemical Society

Plant Biology

"One would be a cyclotron-based mass spectrometer, which would be very useful for high-throughput, high-accuracy proteomics. Another would be a computer cluster of appropriate size. It is possible that instrumentation starting in this price range will drop in cost as the market develops. These two items would be very useful in the future of genomics and its attendant -omic disciplines. There will be a continued demand for high-end electron microscope and nuclear magnetic resonance spectrometers.

As plant research moves more towards understanding the functions and interactions of all plant genes in crop plants, it will become increasingly important to use highly controlled growth conditions. The technologies needed to provide controlled lighting, temperature, water, and humidity control depend on elaborate and expensive equipment. We will see in the next 5 years that researchers in our society will become increasingly interested in having sophisticated plant growth facilities.

American Society of Plant Biologists

Mass Spectrometry

"Primarily high-field (≥15 tesla) Fourier transform ion cyclotron resonance mass spectrometry, although some integrated proteomics instruments (robotic sample manipulation and introduction, automated data reduction) will hit that range soon. Also, there is some use of free-electron lasers combined with mass spectrometry, and the FEL component can be in the $15M range.

Note that as the cost of the instrument increases, the need for operating it at a national user facility increases. Remote operation (cyberinfrastructure) will also become more prevalent.

American Society for Mass Spectrometry

Political Science

"This is difficult to assess beyond recognizing the continued evolution of the themes mentioned above—especially increasing need for infrastructure for longitudinal data sets and enhanced capacity for political science laboratory work.

Two areas however deserve note. One is the promise of significant investment in the interface between academic scholarship in political science and administrative systems. An example that would warrant significant instrumentation investment is the formulation of a network of exit polling to validate election outcomes. The exit polling system in the United States has not worked effectively based on the commercial-new media model we have followed, and significant investment is needed to fix it. Another is the global necessity to link political-administrative information systems with physical science systems to translate natural disaster warnings into effective systems for sharing life-saving information and implementing public safety plans. Arden Bement of the NSF has pointed out, for instance, that in the recent south Asia tsunami, we detected the physical threat but were unprepared for the administrative follow-through. We need to link the science from physical, social, and political systems.

A second emerging area is the incipient collaboration between political scientists and other scientists in brain imaging and genomics. Already very preliminary work is appearing using fMRI measurements in assessment of motivation for political and civic action. Likely political science will purchase 'time' on equipment in other sciences for this work rather than make major instrumentation investments ourselves, but the demand nevertheless is likely to grow rapidly in the future.

Michael Brintnall
Executive Director
American Political Science Association
(Individual response)

Particle Physics

"Medium-scale detectors will continue to be crucial. A few illustrative examples are:

a) reactor-based neutrino detectors to measure the crucial parameter for accessing CP-violation in the neutrino sector.

b) fixed target experiments to search for rare decays.

c) accelerator-based neutrino detectors to measure neutrino scattering processes and constrain backgrounds for future detection of CP violation in the neutrino sector.

d) dark matter detectors employing 500-1,000 kilograms of sensitive material. The dark matter issue could become particularly interesting if early results from the LHC show evidence for a dark matter candidate.

e) neutrinoless double beta decay detectors.

f) advanced bolometer arrays for measuring the polarization of the cosmic microwave background.

e) new instruments on ground-based telescopes to improve our knowledge of cosmology.

f) In addition, we will need to develop new detector technologies for the proposed International Linear Collider.

Division of Particles and Fields
American Physical Society

COMMENTS ON FEDERAL POLICIES

In addition to the comments excepted below, several disciplinary societies commented on the difficulty of finding a balance between the need for new instrumentation and the need for support of operating costs for existing facilities. Others commented that individual investigator grants are already challenging to fund and funding these proposal is more important then funding instrumentation.

Mass Spectrometry

"There is currently very limited support for technique development. The next generation of major instruments (commercial or academic) requires manpower that is currently produced only in a very few research groups. The reason is that most federal support is 'hypothesis-driven,' and that's not a good model for building new instruments, for which performance and applications are not necessarily predictable. Moreover, the best justification for next-generation instruments (e.g., NMR, mass spec) is NOT new world record performance for a few narrowly chosen examples (as emphasized in grant proposals), but rather that experiments formerly possible only with heroic difficulty become routine with the higher-level instrument. Finally, support for instrumentation typically does NOT include manpower, and that makes it difficult to train grad students and postdocs in that area.

The primary problem for mass spectrometry is that the instruments typically fall in a range ($150-$800K) not supported by federal funding. For example, mass spectrometry is the fastest-growing of all segments of the spectroscopy market and is a larger market than NMR, but receives only a fraction of the federal funding allocated to NMR. A big reason is the NMRs cost the right amount of money—e.g., major equipment at ~$1M (with a limit of 1-2 awards per institution) goes disproportionately to NMR, because it matches the category most closely.

American Society for Mass Spectrometry

Plant Biology

"Biological instrumentation is frequently vested in a technician-run core facility, and it is often overtly stated as a requirement for federal funding that shared use instrumentation be placed in such a facility. This attitude is old-fashioned and has the effect that the instruments and their applications are run only at the education level of the technician. Cutting-edge activities are automatically discouraged. A policy shift is needed to fully integrate technology and instrument development and operation, with biological questions and research directions. This can only be done through faculty-led development and operation of the instruments, and the development of collaborative programs that emphasize the synergy of instrument development and use and the uncovering of new biological knowledge.

American Society of Plant Biologists

Particle Physics

“There is a second category of instrumentation research in the \$2-\$100M range which needs support and that is developing novel techniques to the technical readiness level where they could be considered for medium- or large-scale detectors. Suppose someone has an idea for a completely new type of calorimeter or particle-tracking device. How can they show that this idea has merit? The first step probably involves making a table-top scale prototype and carrying out a series of feasibility studies. These might cost a few 100 K\$ and come from laboratory discretionary funds. If the idea passes these initial tests, the next step might be the construction of a full-scale subsystem and testing in an accelerator beam. Since these tests may require specialized readout electronics, data acquisition systems, and a small team of people, the costs could easily fall in the \$2-\$10M range. It has been extremely difficult to find this type of funding since the agencies expect it to come from existing operations budgets while laboratories and universities find these operations budgets barely adequate (often inadequate) to support the on-going programs.

Funding in HEP comes from a mixture of DOE and NSF. As cosmology becomes an increasingly important component of HEP, NASA is also involved. Each agency approaches projects in a different way, and it is difficult to get projects started that straddle agency boundaries. For example, NSF has so far been unwilling to consider funding experiments based at DOE laboratories. The field of high-energy physics is truly international and the federal agencies are still struggling with assessing priorities and negotiating cost-sharing on the international scale. While this is particularly crucial for very large projects, it impacts medium-scale projects and detector technology development as well.

Division of Particles and Fields
American Physical Society

Chemical Physics

"One of the biggest issues is the balance between funding for very expensive research instrumentation and funding for research programs that will use the instruments. The perception is that it is easier politically to secure funding for new instrumentation, so that funding for new facilities seems to rise faster than funding for research programs in the basic sciences. There is also need for more emphasis on basic research and to encourage graduate students and post-docs to remain in the field, ease their career opportunities.

Dedicated 750 NMR or instrumentation at an even higher cost level requires maintenance. That is a big problem, especially in the world of academic institutions, since nobody (except NIH in certain cases) will pay for it.

Division of Chemical Physics
American Chemical Society

DISCIPLINARY SOCIETY SURVEY ON ADVANCED RESEARCH INSTRUMENTATION

Today, instrumentation plays a critical role in scientific and engineering research and exploration. We would like to get your help in gaining a better understanding of the issues related to instrumentation and your thoughts on federal policies. This survey is part of a study being conducted by the National Academies Committee on Advanced Research Instrumentation in response to Section 13(b) of the National Science Foundation (NSF) Authorization Act of 2002. The Instrumentation Committee is under the aegis of the Committee on Science, Engineering, and Public Policy (COSEPUP). COSEPUP, chaired by Dr. Maxine Singer, is the only joint committee of the three honorific academies: the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. Its overall charge is to address cross-cutting issues in science and technology policy that affect the health of the national research enterprise.

The study is examining federal programs and policies related to advanced research instrumentation used for interdisciplinary, multidisciplinary, and disciplinary research. If needed, the Committee will propose policies to make the most effective use of federal agency resources to fund such instruments. Advanced research instrumentation, for the purposes of this survey, is defined as instrumentation that is not categorized by NSF as Major Research Instrumentation ($100,000 to $2 million in capital cost) or as Major Research Equipment (more than several tens of millions of dollars), but instead falls in between these two designations. The scope of this study includes cyberinfrastructure.

To respond to its charge from Congress and NSF, the Committee is interested hearing your thoughts on issues related to instrumentation in the fields represented by your society as well as your opinions concerning current and possible future federal programs and policies for advanced research instrumentation.

We hope you will be willing to participate in this important information-gathering effort. *We recognize that answering all the questions in this survey may be challenging. We only ask that you do the best you can in providing the information requested.* If another person at your society is better suited to answer this survey, please forward it to them, but please let us know to whom you sent it. We also encourage you to send the attached researcher survey to any members of your society who may have additional thoughts. Their comments may be sent either to you for compilation or directly to *instrumentation@nas.edu*.

We would appreciate receiving your response by Monday, April 11, 2005. Please return the completed survey via e-mail as an attachment to *instrumentation@nas.edu* or by fax to 202-334-1667. If you have any questions, please contact the study director, Dr. Deborah Stine, at *dstine@nas.edu* or 202-334-3239.

Thank you for your time and participation. For more information on the study, please visit our website at http://www7.nationalacademies.org/instrumentation/. Copies of both this survey and the researcher survey are available on our website.

National Academies Committee on Advanced Research Instrumentation

MARTHA KREBS (Chair), President, Science Strategies
DAVID BISHOP, VP Nanotechnology Research, President, NJNC, Bell Labs
MARVIN CASSMAN, Independent Consultant
ULRICH DAHMAN, Director, National Center for Electron Microscopy, Lawrence Berkeley National Laboratory
THOM H. DUNNING, Jr., Director, National Center for Supercomputing Applications, University of Illinois, Urbana-Champaign
FRANK FERNANDEZ, Distinguished Instititute Technical Advisor, Stevens Institute of Technology
MARILYN L. FOGEL, Staff Member, Geophysical Laboratory, Carnegie Institution of Washington
LESLIE KOLODZIEJSKI, Professor, Electrical Engineering and Computer Science, Massachusetts Institute of Technology
ALVIN KWIRAM, Professor of Chemistry, University of Washington, Vice Provost for Research Emeritus
WARREN S. WARREN, Professor of Chemistry, Director, NJ Center for Ultrafast Laser Applications, Princeton University
DANIEL WEILL, Professor (by courtesy), University of Oregon, Department of Geological Sciences

National Academies Committee on Advanced Research Instrumentation Disciplinary Society Survey of Instrumentation Funding and Support

Please answer the following general questions:

Name:
Title:
Society:
Daytime phone:
E-mail:
Research field(s) represented by your society:

1. **Unless permission is otherwise given, the responses provided in this survey will only be used in an aggregated fashion in the Committee report. Your society will be listed as a respondent to the survey.**
    a. May we use the comments you have provided verbatim in the report (Y/N)?
    b. May we attribute these comments to your society (Y/N)?

Please share your perspective on instrumentation:

2. In the fields represented by your society, what types of advanced research instrumentation (instrumentation with capital costs between $2M and $100M) are used? What is your assessment of the availability of and additional need for these instruments?

3. What new kinds of instrumentation in the $2-$100M price range do you think researchers in your society will be interested in five years from now?

4. Besides additional federal funding, what is the primary federal agency policy issue your field faces and what is your assessment of current agency policies for advanced research instrumentation?

5. Do you have any additional thoughts regarding advanced research instrumentation that you would like to share with the Committee?

LIST OF RESPONDENTS

American Astronomical Society
American Chemical Society
American Physical Society
    Division of Condensed Matter Physics
    Division of Particles and Fields
American Political Science Association
American Society for Mass Spectrometry
American Society of Plant Biologists
Federation of Materials Societies

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Summary of National Laboratory Survey Results

CONTENTS

SUMMARY

In total, 10 federal laboratories or research centers responded to the committee's survey on instrumentation. Four reported instrumentation with capital costs between $2 million and $100 million. The list of respondents is included at the end of this appendix.

In the survey, the committee asked about the relationship between the laboratory and universities. Some laboratories offer use of their instruments free of charge to external users as long as the results are openly published. Some ARIF at federal intramural research centers are open for use, with fees charged for external use; others are not shared. Excerpts from some comments related to the laboratory-university relationship are excerpted later.

Oak Ridge National Laboratory (ORNL) provided an extensive response to the committee's survey with detailed information on six ARIF at the laboratory at large and 13 ARIF at the Spallation Neutron Source that were constructed or acquired in the preceding five years. A summary of ORNL's response is included in this appendix to provide a picture of ARIF at a national laboratory.

Like the universities, many of the respondents noted difficulty in finding sufficient support for operations, maintenance, and staff. The annual cost of operation for the ARIF reported ranged from $100,000 to several million dollars.

Several laboratories specifically commented on the importance of instrumentation, and ARIF in particular. With regard to the definition of ARIF, the Princeton Plasma Physics Laboratory noted that "research instrumentation should be broadened to include capacity computing. Simulation is becoming a third leg of the scientific enterprise along with theory and experiment."

RELATIONSHIP WITH UNIVERSITIES

A number of national laboratories described close relationship with university researchers, and several noted the importance of staff.

> The very nature of high-energy physics research requires close collaboration between the laboratory and our university partners. The effort involved in the design, construction, test, and commissioning of most of our detector systems (instruments) is shared among the participating universities and the laboratory. Most of our collaborations are now international in nature. Creating well-defined, clear and concise responsibilities (effort and funding) with participating institutions is always a challenge.
>
> Fermi National Accelerator Laboratory

> Close relationship with academic community to ensure that proposed instruments meet scientific needs. In some cases, academia had direct input into concepts.
>
> Anonymous
> Intramural research laboratory

> We carry out mainly academic research. We educate over 500 scientists a year in analytical techniques. This is a challenging task that put a lot of stress on the staff. These are excellent experts who give away their knowledge generously. Yet, this kind of scientists is often not appreciated enough.
>
> Ivan Petrov
> Principal Research Scientist, Adjunct Prof
> Center for Microanalysis of Materials
> The Frederick Seitz Materials Research Laboratory

One intramural research laboratory expressed difficulty in sharing advanced instrumentation with outside users:

> . . . it is difficult to balance our need to meet . . . core mission responsibilities with our desire to share access to advanced instrumentation with academia. Our . . . facilities rely on well-trained users, and so allowing use by temporary academic researchers and other outside users with unknown levels of training and experience is an important issue that we need to resolve before opening [them] to broader outside use.

OTHER COMMENTS

Instrumentation Needs

"We need extensive small- ($10K) to medium-scale ($100K) research collaborations addressing all aspects of living marine resource biology, ecology, and utilization. Our challenges are mainly geographic and cost of operations in Alaska and the Arctic oceans. No instrumentation with capital cost greater than $2 million is likely to be needed in the future."

Alaska Fisheries Science Center
Supporting Agency/Agencies: NOAA, National Marine Fisheries Service

"DOE/BES dedicated $1.1 million in FY 2004 to our program for equipment purchases. We are attempting to locate funding for an aberration-corrected STEM/TEM with a monochromator and in-colunm energy filter (capital cost $3 million) and a UHV aberration-corrected instrument with large space in the sample area for atomic resolution dynamic electron microscopy observations (capital cost $4.5-$5 million). Finding funding for these instrument is difficult.

We believe we are in a unique position to design and operate an atomic resolution TEM with for in situ science as an open facility. Three workshops in recent years have clearly demonstrated the scientific community needs such an instrument. DOE may sponsor such an instrument within a program on aberration-corrected microscopy in the time frame 2010-12. Yet the demand right now is great and the impact would be enormous. The cost is ~$5M and has proven an insurmountable barrier for now.

We participated in the first NSF program for Instrumentation for Materials Research—Major Instrumentation Projects for over $2M with, in my view, an excellent proposal. It was rejected rather hurriedly based on the whimsical comments from one of the reviewers.

In terms of future instrumentation needs, we think we would need a UHV aberration-corrected TEM dedicated to in situ science."

Ivan Petrov
Principal Research Scientist, Adjunct Prof
Center for Microanalysis of Materials
The Frederick Seitz Materials Research Laboratory

"Fermilab has the FNPL—Fermilab NICADD PhotoInjector Laboratory (capital cost $7 million), Fermilab Magnet Test Facility (capital cost to replace today would be $10 million), KTeV Detector (capital cost $30 million), and the MIPP Experiment FNAL-E907 (capital cost $4 million). It is currently attempting to get funding for the Superconducting Module and Test Facility (SMTF) (capital cost $97 million).

Fermilab has interest in acquiring new research instrumentation for our both our physics and accelerator R&D programs. A number of new experiment proposals are under development that would potentially fall with the $2M to $100M cost window. The laboratory is also involved in a number of R&D areas addressing the needs of future accelerators that will require instrumentation costing in access of $2M."

Fermi National Accelerator Laboratory

Policy Issues

"Creating collaborations between various agencies and even various divisions within a single agency can be difficult, frustrating, and results in increased project costs that could be avoided if better mechanisms were in place to deal with multi-agency spanning projects. An example would be working across interdivisional boundaries with a single agency, such as DOE/HEP and DOE/NS on a project that could exist in both divisions. A simple method of conducting business in this case could and would result in reduced project costs and reduced project time to completion. "

Fermi National Accelerator Laboratory

"Over the past several years the research infrastructure of NIH was improved significantly. Besides careful planning this required substantial financial resources. The challenge will be to maintain and further improve the technological base without much increase of the NIH budget.

Very often advanced research instruments have specific requirements regarding their operational environment. The multilayered structure of Federal Agencies, with shared responsibility for building design, construction, and maintenance, makes it cumbersome to ensure that those requirements are met and may add needlessly to the cost of construction and maintenance."

Klaus Gawrisch
Senior Investigator
Lab: Laboratory of Membrane Biochemistry & Biophysics (LMBB),
National Institute on Alcohol Abuse and Alcoholism (NIAAA),
National Institutes of Health (NIH)
Supporting Agency: Defense Advanced Research Project Agency (DARPA)

"Federal and Agency-level Policy on acquisition/development of Advanced Computational Instrumentation . . . is dynamic and can drive short-term changes in instrumentation acquisition direction."

Anonymous

"While competition is good for surfacing new, original ideas and research concepts, more directed funding is appropriate for maturing the technologies. Instruments such as lasers and lidars should be considered as national facilities. Directed funding for continuous improvement is needed, but difficult to secure."

Anonymous

"A small budget exists within the office of fusion energy sciences to develop novel diagnostics. this is an important effort and should be broadened to include the development of diagnostics for a buring plasma experiment."

Princeton Plasma Physics Laboratory

"Current agency policies for advanced research instrumentation are open and positive."

Southwest Fisheries Science Center
NOAA

General Thoughts

"Most 'advanced' instrumentation for high-quality and rigorous research is customized for the particular investigator/investigation and requires specialists' skill in the acquisition and interpretation of raw data, conversion to engineering units, and interpretation of results. The customization can be in detectors and sensors, specimen preparation, specimen environment, or data acquisition and control algorithms and software. The ability of the end user to interpret the results meaningfully is a key part of the 'instrumentation' and may not be readily transferable to other researchers. When the instrumentation's basic principles are well understood and the apparatus is made reliable and usable in the general laboratory, it will find a general audience of research users (in its field). At that point it will migrate to the "mainstream" to be provided by instrumentation equipment vendors and become less 'investigator unique.'"

Anonymous

"Research instrumentation should be broadened to include capacity computing. Simulation is becoming a third leg of the scientific enterprise along with theory and experiment. In addition to the very large supercomputers, smaller capacity computing centers are required to develop codes and run problems, which require fewer processors."

Princeton Plasma Physics Laboratory

CASE STUDY—OAK RIDGE NATIONAL LABORATORY

The ORNL performs research in neutron science, energy, high-performance computing, complex biologic systems, advanced materials, and national security. Most of the support for the laboratory comes from the Department of Energy, although it receives 20% of its support from other agencies. About 3% of the laboratory's FY 2004 funding was allocated for work associated with instrumentation. This internally allocated funding went to continuing costs, including operation and maintenance, and instrument development and modification. Most of the instrumentation at ORNL is shared with academic researchers through formal user programs and collaborative projects.

The laboratory reported a total of 19 ARIF that were constructed or acquired in the preceding 5 years. Thirteen are at the Spallation Neutron Source (SNS), including a number of spectrometers, diffractometers, and beamlines, all for use of neutron radiation. The design and engineering of those instruments are carried out either at SNS or in close collaboration with industry vendors or academic institutions or consortia. SNS instruments are general available to researchers from national laboratories, universities, and industry through a peer-reviewed proposal system.

ORNL also reported six other ARIF, primarily advanced microscopes. An aberration-corrected transmission electron microscope ($3.2 million in combined acquisition and upgrade costs) was reported; it required $5 million for construction of a new building to house it and $100,000 per year in operation costs. An instrument of that sort is used by a broad array of disciplines, including basic condensed matter, engineering, physics, chemical, biology, and environmental science.

NATIONAL LABORATORY SURVEY ON ADVANCED RESEARCH INSTRUMENTATION

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To respond to its charge from Congress and NSF, the Committee is interested in hearing your thoughts on instrumentation at your laboratory as well as your opinions concerning current and possible future federal programs and policies for advanced research instrumentation.

We hope you will be willing to participate in this important information-gathering effort. *We recognize that answering all the questions in this survey may be challenging. We only ask that you do the best you can in providing the information requested.* If another person at your laboratory is better suited to answer this survey, please forward it to them, but please let us know to whom you sent it. We also encourage you to send this survey to anyone, particularly laboratory or facility directors, who you believe may have additional thoughts. Their comments may be sent either to you for compilation or directly to *instrumentation@nas.edu.*

We would appreciate receiving your response by Monday, April 11, 2005. Please return the completed survey via e-mail as an attachment to *instrumentation@nas.edu* or by fax to 202-334-1667. If you have any questions, please contact the study director, Dr. Deborah Stine, at *dstine@nas.edu* or 202-334-3239.

Thank you for your time and participation. For more information on the study, please visit our website at http://www7.nationalacademies.org/instrumentation/.

National Academies Committee on Advanced Research Instrumentation

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THOM H. DUNNING, Jr., Director, National Center for Supercomputing Applications, University of Illinois, Urbana-Champaign
FRANK FERNANDEZ, Distinguished Instititute Technical Advisor, Stevens Institute of Technology
MARILYN L. FOGEL, Staff Member, Geophysical Laboratory, Carnegie Institution of Washington
LESLIE KOLODZIEJSKI, Professor, Electrical Engineering and Computer Science, Massachusetts Institute of Technology
ALVIN KWIRAM, Professor of Chemistry, University of Washington, Vice Provost for Research Emeritus
WARREN S. WARREN, Professor of Chemistry, Director, NJ Center for Ultrafast Laser Applications, Princeton University
DANIEL WEILL, Professor (by courtesy), University of Oregon, Department of Geological Sciences

National Academies Committee on Advanced Research Instrumentation National Laboratory Survey of Instrumentation Funding and Support

Please answer the following general questions:
Name:
Title:
Laboratory/Facility Name:
Supporting Agency/Agencies:
Daytime Phone:
E-mail:
Research Field(s) Supported:

Do you hold or have you held any administrative positions that involve instrumentation decision-making (Y/N)?
Is so, what?

1. **Unless permission is otherwise given, the responses provided in this survey will only be used in an aggregated fashion in the Committee report. Your laboratory or facility will be listed as a respondent to the survey.**
    a. May we use the comments you have provided verbatim in the report (Y/N)?
    b. May we attribute these comments to you (Y/N)?
2. Please list below the total amount of basic and applied (nonclinical) research funding received by your laboratory/facility from federal agencies:

Agency	FY2003	FY2004

3. Was any of this funding specifically allocated for instrumentation? If so, what was the nature of this funding (how much, what is it for, etc….)?
4. Does your laboratory/facility have any instruments whose capital cost at the time of purchase or construction was greater than $2M and less than $100M?
    a. If not, does your laboratory/facility hope to acquire any?
    b. Is so, in the tables that follow, please provide details regarding instruments in this range that were purchased, constructed, or proposed *in the last five years.* If additional tables are required, please duplicate as necessary.
5. What new kinds of advanced research instrumentation (instrumentation with capital costs between $2M and $100M) do you think your laboratory/facility will be interested in five years from now?
6. Other than the issue of increased funding, what is your assessment of current agency policies for advanced research instrumentation?
7. With regard to instruments, what is the nature of your laboratory or facility's relationship with academic research? What are the opportunities and challenges of this relationship?
8. Do you have any additional thoughts regarding advanced research instrumentation which you would like to share with the Committee?

Existing or Proposed Instrumentation: ________________________

a) Capital cost ________________
b) Siting cost (for remodeling existing facility) ________________
c) Annual cost of operation (estimated or known)? ________________
d) Total expected lifetime (years) and cost? ________________
d) Date need recognized (Month/Year)? ________________
e) Date fundraising began (Month/Year)? ________________
f) Funding sources solicited (list specific programs within sources if applicable). Funding sources may include industry, government agencies, private foundations, state government, institutional funds, and direct Congressional or Administration allocation.

Source/program	Funding obtained (Y/N)?	Amount obtained?

g) Date fundraising completed (Month/Year)? ________________
h) Degree of challenge in fundraising, from 1 (easy) – 5 (difficult) ________________
i) How was this instrument designed and built or obtained? ________________
j) How is this instrument used? What areas of research? Is it used by industry? For education? ________________
k) How is this instrument supported and maintained? ________________
l) What opportunities and challenges does your institution face with regards to this instrument? ________________
m) Is this instrument shared? If so, is it within department (D), within institution (WI), and/or shared externally (E). If (E), please list sharing institutions. ________________
n) Hourly rate (if any) for use? ________________
o) Person responsible for instrument? Name/phone/e-mail ________________
p) On a nationwide basis, what is your assessment of the availability of and need for this type of

instrument? ____________________

q) Would an interagency program for this type of instrument be useful (Y/N)? If so, what should be the components of such a program? ____________________

r) What federal policies could be put in place to enhance the design, building, funding, sharing, operations, and maintenance of this type of instrument? ____________________

s) Additional comments?

____

LIST OF RESPONDENTS

Ames Research Center, National Aeronautics and Space Administration
Center for Microanalysis of Materials, Frederick Seitz Materials Research Laboratory
Electronics and Electrical Engineering Laboratory, National Institute of Standards and Technology
Fermi National Accelerator Laboratory
Laboratory of Membrane Biochemistry and Biophysics, National Institute on Alcohol and Alcoholism, National Institutes of Health
National Marine Fisheries Service, National Oceanic and Atmospheric Administration
Oak Ridge National Laboratory
Princeton Plasma Physics Laboratory
Science Directorate, National Aeronautics and Space Administration
Southwest Fisheries Science Center, National Oceanic and Atmospheric Administration

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