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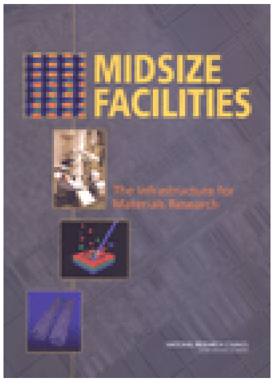

Midsize Facilities: Infrastructure for Materials Research

Committee on Smaller Facilities, Solid State Sciences Committee, National Research Council

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MIDSIZE FACILITIES

The Infrastructure for Materials Research

Committee on Smaller Facilities

Solid State Sciences Committee

Board on Physics and Astronomy

Division on Engineering and Physical Sciences

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Image of a silicon crystal obtained using a 300-kV VG microscope HB603U scanning transmission electron microscope equipped with a Nion aberration corrector, by M. Chisholm, with processing by A. Borisevich and A. Lupini and aberration correction by P. Nellist, N. Dellby, and O. Krivanek, Nion Company. Courtesy of Oak Ridge National Laboratory.

JEOL 4000EX 400-kV top-entry, high-resolution electron microscope equipped with an LaB6 filament. Courtesy of the Nanoscale Materials Characterization Facility, Department of Materials Science and Engineering, University of Virginia, http://www.virginia.edu/ms/electronfacility.html.

Two single-walled nanotubes (SWNT), the basis of many structures—and much research—in nanotechnology. Image courtesy of Accelrys, http://www.accelrys.com.

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Preface

As the role of midsize facilities in materials research has expanded over the past two decades, the need for a systematic and careful assessment has grown, especially in this fiscally constrained era. In response to these observations, the National Research Council (NRC) formed the Committee on Smaller Facilities in 2003, with support from the National Science Foundation (NSF) and the Department of Energy (DOE), to examine the broader issues of optimizing current and future investments in the facilities infrastructure of materials research. The committee was charged to examine the range of facilities between "small" and "large," to identify key features of performance, and to recommend strategies for successful operations, emphasizing revenue-neutral solutions (see Appendix A). It is worth noting that, although the study charge was to examine "smaller" facilities, after conducting its initial data gathering the committee decided that the term "midsize" was more appropriate.

The Committee on Smaller Facilities first met in May 2003 to hear presentations by senior personnel with experience in operating user facilities in both university and government laboratory settings (see Appendix B). The committee also heard from representatives of agencies currently providing extensive support for instrument acquisition and facility operation. At this first meeting, the committee also formulated a preliminary definition of "midsize facility," it established the study's general areas of investigation, and it articulated a plan for carrying out a series of facility site visits over the summer of 2003.

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During the summer of 2003, subgroups of the committee, generally consisting of two or three of its members and an NRC staff officer, visited various user facilities around the United States. The purpose of these visits was primarily to gather some firsthand experience relating to the planning, operation, and maintenance of typical midsize facilities. Another important function was to hear directly from users and to learn about the commonalities across and the differences between midsize and other types of facilities. To ensure maximum effectiveness, it was decided to target geographical areas that had clusters of materials research facilities and manifested different regional characteristics: that is, one region might contain a major science, technology, and population center, and another might contain more diffuse centers of activity. The number of sites to be visited was limited by the time and resources available, so it was not possible to cover the full breadth of the United States. The five separate site visit trips of the committee concentrated on the approximate geographical areas of the San Francisco Bay Area, upstate New York, Illinois, Boston, and the Pacific Northwest. A total of 47 facilities and other individuals were visited (see the end of Appendix D, the committee's interim report). To ensure that broadly similar information was obtained in each case, a checklist was developed and used as a common guide to facilitate discussion during these site visits (the checklist is presented at the end of Appendix D).

It is worth noting that the committee visited several facilities that did not conform to the working definition of midsize facility; for instance, an observatory and two commercial analytical service laboratories were included in the roster of visits. The committee felt strongly that the challenges facing midsize facilities in materials research were not unique; by learning about facilities in other fields, the committee gained a broader perspective and exposure to other types of solutions.

The full committee convened again in October 2003 to share the experiences and impressions gained by its various subgroups. Several presentations were made relating to the operation and organization of midsize facilities and the need for staff training. Extensive discussions followed, relating to the development of a vision for the committee's study, the working definition of a midsize facility, the characteristics of successful facilities and their best practices, current and future issues relating to facility operation, and future committee activities. After its second meeting, the committee prepared an interim report that outlined its status and plans (see Appendix D).

Recognizing the need to engage facility managers as well as current and potential users of future midsize facilities, the committee developed questionnaires for facility managers and users (see Appendix C). The questionnaires were designed to gather general information to better inform the committee about the range in

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staff, usage, budget, and capital investment among the facilities being considered. The questionnaires were not intended to be statistical data-gathering instruments.

To obtain a standard set of data, the questionnaires were circulated to the midsize facilities that had been visited over the summer of 2003 by committee members. They were also distributed by committee members to their colleagues and by NRC staff to targeted sets of midsize facilities such as the NSF-supported materials research science and engineering centers. In addition to questionnaires sent electronically to members of the American Physical Society's Division of Materials Physics and Division of Condensed Matter Physics, another 277 questionnaires were distributed to specific facilities that had been identified by committee members and staff. A total of 75 responses were eventually received (as summarized in Appendix C) from facilities ranging in size from the very small to the very large; 56 of the responses fit the committee's definition of a midsize materials research facility.

In addition to disseminating its interim report in the spring of 2004, the committee conducted two town hall meetings, coinciding with the March meeting of the American Physical Society and the spring meeting of the Materials Research Society. The primary purpose of these open meetings was to broaden awareness of the study and to disseminate the committee's questionnaires. Feedback on the committee's interim report was generally positive, and thoughtful suggestions were incorporated into the committee's deliberations at its next meeting.

Responses to the facility questionnaire were received by e-mail, postal mail, and fax and entered into a small database for organization. Because of possible biases that might be introduced by the self-selected population that actually responded to the questionnaire, the committee did not consider these results to be statistically significant, but rather believed that they provided a useful, representative overview.

The committee then reconvened as a whole in May 2004 to discuss responses to the interim report and the questionnaires. Considerable time was spent digesting the results of the surveys and evaluating how they should be summarized in the report. The committee then focused on formulation of its recommendations and preparation of the final report.

The committee was expected to consider a diverse range of midsize facilities. However, it is unlikely that a single set of recommendations will be applicable to all facilities or funding agencies that support them. The smallest of these facilities are mostly located within universities and funded primarily by NSF, the National Institutes of Health (NIH), and the National Aeronautics and Space Administration (NASA), with annual operating budgets in the range \$100,000 to \$1 million. Midsize facilities with somewhat larger budgets are still mostly sited at universities

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and also funded by NSF, NIH, and NASA ($1 million to $5 million). The largest facilities (>$5 million) are primarily located with national laboratories and funded primarily by DOE. Consequently, "one size fits all" recommendations are not appropriate. There are different sets of needs that depend on the size of the facility (annual operating budgets), location (university, national laboratory, commercial organization), and the nature of its activities (research, collaboration, education, service).

The large national user facilities, such as the national synchrotron light sources, are outside the scope of this study; they have been considered in detail in earlier reports.[1] However, the committee did consider the factors that affect operation of these national user facilities as being complementary to the considerations that are driving the needs of midsize facilities. A notable example within DOE's Office of Basic Energy Sciences is the construction of five new nanoscience facilities within the laboratory campuses of the Oak Ridge, Argonne, Sandia, Lawrence Berkeley, and Brookhaven National Laboratories. These construction and instrumentation awards are in the $50 million to $100 million range, and the centers are expected to have annual operating budgets in the $15 million to $20 million range.

The facilities created to maintain, operate, and support today's advanced instrumentation need to be recognized as a class of investment, across programs and across agencies. Furthermore, they need to be recognized collectively as a system, with plans for growth, operations, and sustainability: they need stewardship. The support for the infrastructure of midsize facilities needs to be given high priority. Realizing the economies of networking and consolidation can help identify these resources; other agency resources can be reallocated. As midsize facilities become more important, professional staff will become even more pivotal; their career path will need to be respected and cultivated.

The committee engaged this project with a firm grasp of current realities and optimism about the future. It is with conviction and a large degree of enthusiasm that the committee urges both agencies and researchers to read this report and to act on its findings and recommendations.

Robert Sinclair, *Chair*
Committee on Smaller Facilities

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[1] See, for example, National Research Council, *Cooperative Stewardship: Managing the Nation's Multidisciplinary User Facilities for Research with Synchrotron Radiation, Neutrons, and High Magnetic Fields*, Washington, D.C.: National Academy Press, 1999.

Acknowledgments

The members of the Committee on Smaller Facilities (COSF) wish to thank the nonmembers who made formal presentations at COSF meetings. (The presenters' names appear in Appendix B.) Their presentations and the ensuing discussions were extremely informative—and had a major impact on the committee's deliberations.

COSF also expresses its deep appreciation to the hosts and facilitators of its site visits (listed in Appendix D) during the summer of 2003; the hospitality was impeccable and the conversations candid, enlightening, and invaluable. There are clearly large numbers of scientists and engineers dedicated to providing a wide range of facilities and expertise to their communities.

The committee also thanks those who sent in letters and e-mail messages in response to COSF's public request for input from the very large community of scientists who use midsize facilities for materials research. Finally, the committee extends its gratitude to the American Physical Society and the Materials Research Society for their assistance in engaging the broader community through town meetings at their annual conferences.

It would be impossible for the members of a National Research Council (NRC) committee to produce a useful report without the help of NRC staff, and the committee thanks the staff for its excellent support, both on and behind the scenes. The committee especially recognizes the contributions of Dr. Timothy I. Meyer, who coordinated tirelessly, expertly, and enthusiastically, all of its efforts.

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Acknowledgment of Reviewers

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 Research Council's 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 deliberative process. We wish to thank the following individuals for their review of this report:

Ulrich Dahmen, National Center for Electron Microscopy, Lawrence Berkeley National Laboratory,
James P. Eisenstein, California Institute of Technology,
Patrick Gallagher, Center for Neutron Research, National Institute of Standards and Technology,
J. Murray Gibson, Advanced Photon Source, Argonne National Laboratory,
Christopher Grovenor, University of Oxford,
William Harrington, Evans East Corporation,
Julia M. Phillips, Sandia National Laboratories,
Ramamoorthy Ramesh, University of California at Berkeley, and
Michael Rubner, Massachusetts Institute of Technology.

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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 W.F. Brinkman, Princeton University. Appointed by the National Research Council, he was 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.

We also wish to thank the following individuals for their review of the committee's interim letter report (reprinted in Appendix D of this volume):

Nitash P. Balsara, University of California at Berkeley,
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Sol Gruner, Cornell University (Report Review Coordinator),
Frances Hellman, University of California at San Diego,
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Thomas Theis, IBM T.J. Watson Research Center, and
Robert Tycko, National Institutes of Health.

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APPENDIXES

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Executive Summary

Over the past four decades, methods for creating new materials and examining their detailed nature have become more subtle, sensitive, and precise. Scanning transmission electron microscopes can now identify the locations of individual atoms in a silicon wafer, focused-ion beams can create features with dimensions less than 10 nanometers (nm), and secondary ion mass spectrometers can simultaneously measure chemical concentrations and spatial locations, providing better than 35 nm resolution in one configuration and sub-parts-per-million (ppm) detection limits for high-resolution depth profiling of semiconductor devices in another. In no small way, the advent of these capabilities brought about the enthusiasm and excitement of nanoscience and nanotechnology. However, these developments come at a price—literally: today's sophisticated tools for materials research have become so expensive and complex that individual investigators often cannot own or adequately operate or maintain them.

Once dominated by tabletop instruments, materials research has blossomed into an endeavor whose threshold for individual investment has risen substantially over the past decades. Instruments critical to materials research are becoming so expensive that resources must be pooled to manage them in small to midsize, multiuser facilities. By centralizing resources (in terms of equipment, staff, and expertise), midsize facilities provide much-needed centers of instrumentation, innovation, and creativity for research, education, and training. Midsize facilities often offer commercial collaborators access to advanced research and development environments; the resulting partnerships can invigorate local industry and

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even spawn new ventures. Thus, midsize facilities play a critical role in the materials research enterprise.

The ubiquity of these facilities is one of their greatest strengths: as research needs are identified and as researchers coordinate their activities, it is possible to initiate such a facility, although doing so is becoming more difficult. That is, midsize facilities represent sufficiently small levels of investment that they can be (and have been) spread widely around the country. Most importantly, this characteristic allows smaller and nonelite research institutions to participate and contribute effectively.

As the role of midsize facilities has expanded, the need for a systematic and careful assessment of best principles for successful operation has grown, especially in a fiscally constrained era. In response to this need, the National Research Council formed the Committee on Smaller Facilities in 2003, with support from the National Science Foundation and the Department of Energy, to examine the broader issues of optimizing current and future investments in the facility infrastructure of materials research. The committee was charged to examine facilities in the range between "small" and "large," to identify the key features of success, and to recommend strategies for effective operation and utilization.

In its analysis, the committee defined "midsize facility" as follows: A midsize facility maintains and operates one or more pieces of equipment at a university or national laboratory and has the following characteristics:

- Facilitates scientific and/or technological research for multiple users;
- Provides services on local, regional, or national scales;
- Is open to all qualified users subject to generally agreed-upon rules of access;
- Has a resident staff to assist, train, and/or serve users; and
- Has a replacement capitalization cost of between approximately $1 million and $50 million and an annual operating budget (including staff salaries, overhead, supplies, routine maintenance and upgrades, and so on) in the range from about $100,000 up to several million (2004) dollars.

Federal program managers, university administrators, and the media have blurred the distinction between a "center" and a "facility." The committee distinguishes these entities in the following manner:

- A center is a collection of investigators with a particular research focus.
- A facility is a collection of instrumentation, equipment, or physical resources that enables investigators to conduct certain appropriate activities.

Facilities provide sets of tools that expand the capabilities of groups of researchers. Throughout this report, however, the committee argues that a successful midsize

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facility must be more than just a collection of equipment: staff, users, operating funds, specialized environments, and a management plan are some of the essential additional ingredients for successful operations.

Midsize facilities are distinct from small facilities in being large enough to require a dedicated and explicit infrastructure for their sustained success. They are distinct from large facilities in being small enough to be flexible and responsive to the needs of a relatively local user community and in possessing equipment the scale and cost of which allow duplication, when demand merits, in different regions of the nation.

The committee has identified real challenges facing the future viability of midsize facilities. Prominent among these are providing and sustaining long-term infrastructure, networking with other facilities, balancing competing purposes while maintaining a clear mission, and cooperating with commercial interests in compliance with federal guidelines for noncompetition. These facilities are sufficiently sophisticated in structure and content that careful stewardship is necessary: a complex support network (both individually and collectively) is required to maximize their effectiveness.

The committee estimates that there are about 500 midsize facilities nationwide that provide essential instrumentation support for materials research. The aggregated annual operating budget of this collection of facilities is estimated by the committee to be on the order of several hundred million dollars; the replacement cost for the equipment now in place at these facilities is estimated to be several billion dollars.

The committee summarizes its analysis with several conclusions:

- *Importance and uniqueness.* Shared experimental facilities in the form of midsize multiuser facilities are a key component in maintaining the nation at the leading edge of materials research, education, and training. Midsize facilities are everywhere in the materials research landscape, and they offer unique capabilities and benefits, especially when compared with current small-scale and large-scale facilities.
- *Need for long-term planning and commitment.* A continuing and fundamental challenge facing a majority of small to midsize facilities is planning, securing, and maintaining the long-term infrastructure necessary for productivity and success.
- *Need for systematic program planning.* The network of midsize facilities can no longer be treated as atomized and as a set of noninteracting units. There is a substantial opportunity for improved efficiency and effectiveness of the existing network, with increased cooperation, coordination, and consolidation among the individual facilities.

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- *A network ripe for optimization.* As a special category within the U.S. materials research enterprise, the class of midsize facilities described herein could contribute even more to national, regional, and local research priorities; it could serve even larger numbers of investigators; and it is ripe for optimization as a system. Certain facilities are closer than others are to optimal operations already: midsize facilities with clear stewards for ongoing operations and maintenance, facilities wholly embedded in the fabric of a larger laboratory infrastructure, and facilities well coordinated with other resources in their respective regions are operating effectively.

Clearly, there is a disconnect between what researchers at midsize facilities perceive to be needed for their success and the level of resources currently available. As directed by its charge to consider revenue-neutral options in these fiscally constrained times, the committee identifies reallocation of existing resources in materials research as an option for addressing the needs of midsize facilities. Preferential support should be provided to midsize facilities that are regionally based; that have the attributes of good management, organization, and potential for sustainability; and that are large enough to offer professional staff training and career prospects.

In order for the United States to develop and sustain a leadership role in materials research, the committee makes the recommendations presented below. The responsibilities should be shared between the research agencies and the community (as proposers, reviewers, managers, host institutions, and users). The first two recommendations identify pathways for realizing additional economies and for enhancing the effectiveness of the network of midsize facilities. The second pair of recommendations identifies means for strengthening individual facilities by recognizing the long-term commitments necessary for successful operations. The final recommendation recognizes the importance of follow-up and follow-through via periodic reviews of the investments made in midsize facilities.

REALIZING ECONOMIES

Recommendation 1: COLLECTIVE STEWARDSHIP
For the United States to maintain national capabilities to perform world-class, forefront scientific research in materials, the Department of Energy, the National Science Foundation, and other federal agencies should foster cooperative, responsible planning among all stakeholders to provide collective stewardship for midsize facilities. That is, midsize facilities require explicit programmatic planning for their support and oversight. Existing successful facilities should continue, and new opportunities should be created through the reallocation of resources.

Recommendation 2: REGIONAL NETWORKING
To improve the effectiveness of the current national investment in midsize facilities, agencies should realize the economies of networking. That is, midsize facilities participating in a regional network should be given priority for expansions of capability and capacity.

- *Teaming among and consolidation of neighboring facilities to form regional resources should be strongly encouraged by the agencies.*
- *Midsize facilities that are successful in this regard should be provided with adequate long-term infrastructure support.*
- *Proposals for new midsize facilities—or for significant changes to existing midsize facilities—should be viewed within the context of the particular region involved; such proposals should develop a strong business case based on measured need within the region and should outline expected relationships with existing resources in the region.*
- *To facilitate networking, midsize facilities should develop an online inventory of resources that would enable users to optimally identify facilities for their use and to allow managers to make referrals.*

Midsize facilities in materials research depend on many different programs, agencies, and organizations to gather enough funds to make investments in capital costs and to finance operating expenses. There is no single program agency that oversees their long-term viability. In contrast, the large national user facilities have explicit program agency stewards that oversee their long-term viability. Such coordinated stewardship is lacking for midsize facilities, and they suffer individually and collectively as a result. Typically, host institutions (usually universities) do not monitor the effectiveness of the facility, federal agency funds provided for the acquisition or construction of new instrumentation are not reviewed for impact, and user communities are not sufficiently informed to take advantage of alternatives. Explicit, programmatic planning at the level of the federal agencies should help coordinate and connect midsize facilities with mechanisms for their long-term viability. With support for long-term infrastructure, facilities would be able to focus on the important challenges of training and educating the materials scientists and technologists of the future, developing the next generation of instrumentation and analytical techniques, and providing an even larger community of researchers with access to enhanced capabilities for research.

Stewardship should also take into account the regional context. The development of a network of regional user facilities would facilitate effective use of instrumentation at institutions with less than a full-time need for it, encourage rapid sharing of new methods for use of instrumentation, and facilitate user access to related technologies of increasing importance for interdisciplinary projects. Reliable support for long-term infrastructure would provide incentives for facilities to develop such regional networks. The committee offers the hub-and-spoke model as one example of an effective regional network. In the current fiscal climate, these networks are essential to ensuring that researchers have access to the instrumentation they need, since the nation cannot afford to place midsize materials research facilities and instruments at every possible location. Further, before facilities are approved or significant enhancements to capabilities are awarded, proposals should be evaluated in a regional context by the federal agencies. Likewise, consideration should be given to a more regionally or nationally minded approach to planning for and purchasing instruments, rather than the approach of engaging in many individual negotiations.

The committee has observed that most high-quality facilities require some degree of additional support in order to provide stability, to improve the instrumentation, and to fulfill the facilities' educational responsibilities. It is anticipated that a portion of such facilities' operations and maintenance costs will be met by user fees. Thus, the importance of such fees as a line item in funded grants should be recognized by the agencies. Given that these high-quality regional facilities will be expected to address the needs of neighboring institutions, some of the operations and maintenance costs should be provided directly by the research agencies. Similarly, these facilities should be encouraged to develop new techniques and/or instrumentation. Thus, midsize facilities should be planned and operated in a manner that is intermediate between the smallest service centers with single, commercially purchased instruments and large national laboratories such as synchrotron radiation or neutron-scattering facilities.

IMPROVING EFFECTIVENESS

> *Recommendation 3: LONG-TERM INFRASTRUCTURE*
> *Host institutions and supporting agencies should give high priority to maintaining the long-term viability of midsize facilities, including long-term infrastructure such as resident staff, normal operating costs including maintenance contracts, user training and support, education and outreach, and in-house development of instrumentation and techniques. Midsize facilities that are successful in the context of teaming should be provided with improved support.*

The nation is currently making investments in sophisticated instrumentation without considering the commensurate long-term requirements of operations and maintenance. Facilities organized to provide access and support for sophisticated

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instrumentation are struggling to identify the necessary resources to provide the dividends on the initial capital investment. The committee recommends that agencies supporting materials research explicitly recognize the needs of midsize facilities programmatically, thereby allowing midsize facilities to be judged fairly against one another on common grounds in competitive peer review. Stewardship mechanisms should reflect the specific needs of midsize facilities; for example, funding should be long term, and oversight should also be longer term and should be better matched to the activities of facilities. In a revenue-neutral environment, support for long-term infrastructure of successful facilities should be carefully judged within a region against awards for new facilities or significant enhancements to existing capabilities.

> *Recommendation 4: PROFESSIONAL STAFFING*
> *Midsize facilities require extraordinarily talented and experienced staff. The career paths of these individuals should be respected and cultivated. A midsize facility should include technical and Ph.D.-level professional staff members who are offered opportunities for career development and/or participation in ongoing facility research. Operating plans for midsize facilities should explicitly address this issue.*

Since midsize facilities serve users from different institutions who have a broad range of experience in using instrumentation and techniques, it is vital that the facilities have resident staff to provide user education and support. Professional staff members are also necessary to develop and improve a facility in order to address specialized needs and to take advantage of emerging scientific opportunities.

At the heart of fulfilling their mission is the reliance of midsize facilities on their experienced staff to engage users, operate and maintain instruments, and enhance instrumentation. Accordingly, the committee recommends that the educational efforts of midsize facilities should also emphasize programs that explicitly provide ongoing training and career development for facility support staff.

FOLLOW-UP

> *Recommendation 5: PERIODIC REVIEW*
> *Successful performance should be identified and rewarded. Consistent with their long-term responsibilities, sponsors should periodically review midsize facilities to ensure that the facilities' primary objectives are continuing to be met, potential improvements to operations and instrumentation are identified, and continued*

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funding is appropriate. The depth of the reviews should be commensurate with the funding levels.

The operation of a regional facility that effectively meets researchers'—and the nation's—needs requires commitment, thoughtfulness, and effort considerably beyond what is required to maintain instruments for a single investigator or a small number of researchers. Periodic reviews provide opportunities to identify potential improvements to the facility's operations and instrumentation, as well as to assess the adequacy of funding. Finally, situations in which facility operation is no longer appropriate can be identified. Review panels should be composed of experts from both the scientific and the midsize project management domains. Criteria to be considered in such reviews should include the following:

- Instrument maintenance and upkeep;
- Accessibility and openness to users, including mechanisms for new user education, support, and training;
- The quality of educational programs, including professional training and development of staff;
- The development of new techniques or instrumentation;
- Effectiveness in meeting regional needs, including strong links to other facilities (small, midsize, or large) offering similar or complementary capabilities;
- Mechanisms for incorporating suggestions for improvements from the facility's network of users;
- Evidence of sound management plans and practices; and
- A record of cooperation and noncompetition with commercial interests in compliance with federal guidelines and regulations.

The committee recommends that periodic reviews of midsize facilities be used as one of the primary criteria in evaluating whether support for a facility's operations should be continued. One possible outcome of such a review might be an increase in funding for a facility's operations or improvements to its instrumentation. Another could be the transfer of the instrumentation to some other host institution. Consequently, the federal government should retain title to the instrumentation at a regional user facility for at least one major review cycle.

* * * * *

In closing, the committee emphasizes again the pivotal and invigorating role that midsize facilities have played in materials research. By providing access to

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shared tools, training, and resources, these facilities have been a cornerstone of research for a broad cross section of the community. Since the days of the first interdisciplinary research laboratories in the 1960s, materials research has blazed a trail in recognizing and responding to the needs of its investigators. It is now time to acknowledge the need for the next phase of transition, from a system of loosely connected independent facilities to a networked effort of coordinated facilities. By leveraging such opportunities, the materials research enterprise will continue to offer a transformative and effective path to the future.

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1

The Nature and Importance of Midsize Facilities

Midsize multiuser facilities play a major role in materials research. They give a broad range of users access to equipment and expertise for fabricating, characterizing, and measuring the properties of materials. The capabilities offered by midsize facilities are generally more wide ranging and much more expensive than are those encountered in a single investigator's laboratory. The sharing of resources has therefore become a necessity, at the same time presenting increasing opportunities for enhancing interdisciplinary research, contributing to the development of cutting-edge instrumentation, and educating the next generation of researchers.

According to the recent National Science Board report *Science and Engineering Infrastructure for the 21st Century*,

> An increasing amount of the equipment and systems that enable the advancement of research are large-scale, complex, and costly. "Facility" is frequently used to describe such equipment because typically the equipment requires special sites or buildings to house it and a dedicated staff to effectively maintain the equipment.[1]

Today, scientific advances require access to sophisticated facilities and instrumentation. The role of such facilities in materials synthesis, fabrication, character-

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[1] National Science Board, *Science and Engineering Infrastructure for the 21st Century: The Role of the National Science Foundation*, NSB 02-190, Arlington, Va.: National Science Foundation, 2003, p. 8.

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ization, and measurement is steadily increasing. In fact, these facilities are essential to the scientific infrastructure of the nation (see Box 1.1, "Growth in the Trend Toward Collaboration and Centralized Facilities"). There are significant opportunities for accelerating scientific advances in materials and nanotechnology research by invigorating such facilities and allocating their resources to best effect. Accordingly, the committee reemphasizes the importance of midsize facilities.

THE MANY ROLES OF MIDSIZE FACILITIES

Facilities to fabricate, test, and characterize novel materials are increasingly essential to the development of advanced materials and technology. These facilities are required by users with diverse backgrounds and interests, ranging from the

BOX 1.1
Growth in the Trend Toward Collaboration and Centralized Facilities

In addition to possessing intrinsic intellectual excitement, science and technology have been viewed historically as the key to growth in the national economy. The federal government has strongly supported research at universities and at national laboratories, while many corporations have established their own major research laboratories. University-based materials research originally consisted of individual investigators pursuing their own areas of interest and obtaining the necessary research tools by collaborating with other researchers or by grant funding. This approach has led to the proliferation of instruments with much duplication and, in some cases undoubtedly, inefficiency. The national laboratories have focused on the acquisition of analytical instruments and the establishment of central facilities to serve different research groups.

Corporate research has evolved in two directions, one consisting of efforts by individual investigators to enrich the pool of scientific knowledge that underpins the corporation, the other focusing on research and development that are directly relevant to the corporation's products or new growth markets. The establishment of such central facilities within industrial corporations enhanced both of these routes, although some individual investigators had their own instruments.

Major advances in materials research have been achieved by all of the approaches referred to above. Nonetheless, leaders within the materials community began to believe that the problems and needs of the science and technology base were not being as efficiently addressed by the individual-investigator approach as might be achieved by collaboration.[a] The first major effort to gain productivity "greater than the sum of the parts" was made by the Advanced Research Projects Agency in 1960, with the establishment of the Materials Research Laboratories at a handful of research universities (as part of the Department of Defense Interdisciplinary Laboratory program). These laboratories were designed to bring together individuals from different disciplines to foster the exchange of ideas and to address major materials problems needing the collaborative efforts of groups of scientists and engineers.

basic physics of matter to the manufacture of working devices. They are situated in research universities, in national laboratories, and within private enterprises. Major industrial companies such as IBM, Intel, and GE have their own facilities that are restricted largely to in-house research and development. Future technological developments are critically dependent on sound, long-term facility infrastructure.

The recent surge of activity in nanotechnology and the increasing miniaturization of devices have led to a central role for materials research in this technological endeavor. For instance, as the dimensions of transistors—the essential elements of microelectronic circuits and computer microprocessors—go below 90 nanometers (nm), the traditional silicon oxide polysilicon structures must be replaced by higher-performance materials (see Figure 1.1). The discovery of carbon nanotubes (either conducting or semiconducting) by high-resolution electron microscopy

This new approach to university research included the establishment of central facilities for a variety of functions, ranging from cryogenics research to materials synthesis and characterization. These facilities were equipped with state-of-the-art instruments and had professional and technical staff to serve the researchers' needs. The investigators were free to focus on the research without having to develop, fund, and operate the infrastructure necessary for their research. This new paradigm had considerable merit, and many funding agencies began to support the establishment of centralized facilities to serve the needs of multiple investigators. Today, centralized facilities are the rule rather than the exception.

The scale of research and development activities in the production, characterization, and optimization of new and advanced materials has grown significantly in recent years. This growth has been accelerated by the international excitement about and investment in nanoscience and nanotechnology.

The breadth of activities in these areas requires collaborative approaches and the use of a wide variety of highly sophisticated instrumentation and equipment. Such scientific instruments are expensive, and skilled technical staff are required to maintain the equipment and to train and guide users (often students and postdoctoral associates) to obtain the best results. The instruments play an important role not only in advancing the science and engineering of materials but also in training students to use and understand the capabilities and limitations of particular techniques.

Finally, materials characterization is often not a routine exercise. Instead, it is an investigative tool without which it is impossible to reach the basic understanding that leads to materials optimization and the invention of new applications, devices, and even materials systems.

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[a] See, for instance, Attachment 2, "International Benchmarking of US Materials Science and Engineering Research," in National Academy of Sciences, National Academy of Engineering, Institute of Medicine, *Experiments in International Benchmarking of US Research Fields*, Committee on Science, Engineering, and Public Policy, Washington, D.C.: National Academy Press, 2000.

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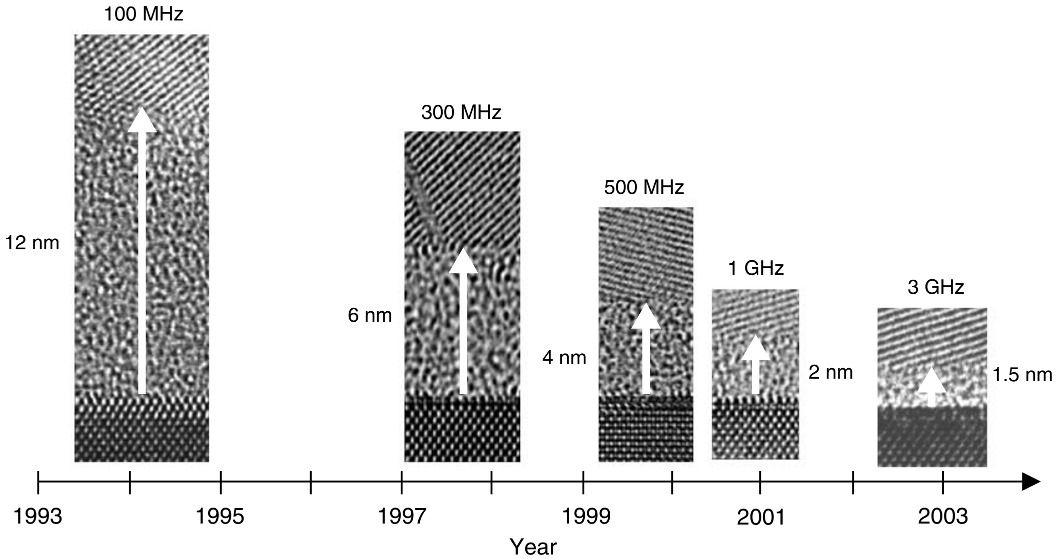

FIGURE 1.1 The decreasing gate oxide thickness of transistors used in modern personal computers. Courtesy of Lucent Technologies Bell Labs.

and the fabrication of semiconductor nanowires on the 1 to 10 nm scale could possibly bring about the design of completely different electronic devices.

In another area, the promise of organic light-emitting diodes and photovoltaic thin films is likely to transform displays and solar energy panels, and ceramic fuel cell technologies operating at lower temperatures could greatly enhance energy-creating efficiency. Likewise, the combination of biological and inorganic processes for self-replication could transform capabilities for manufacturing large-area nanoscale products.

Basic research into new materials and methods of synthesis is thus becoming highly interdisciplinary and increasingly dependent on the availability of centralized tools. Its importance to the competitiveness of U.S. industry is paramount. The question then arises as to how this research can be performed efficiently and well.

Enabling Research

Nanoscience and nanotechnology represent strong examples of research dependent on midsize facilities (see Figures 1.2 and 1.3). The equipment required to

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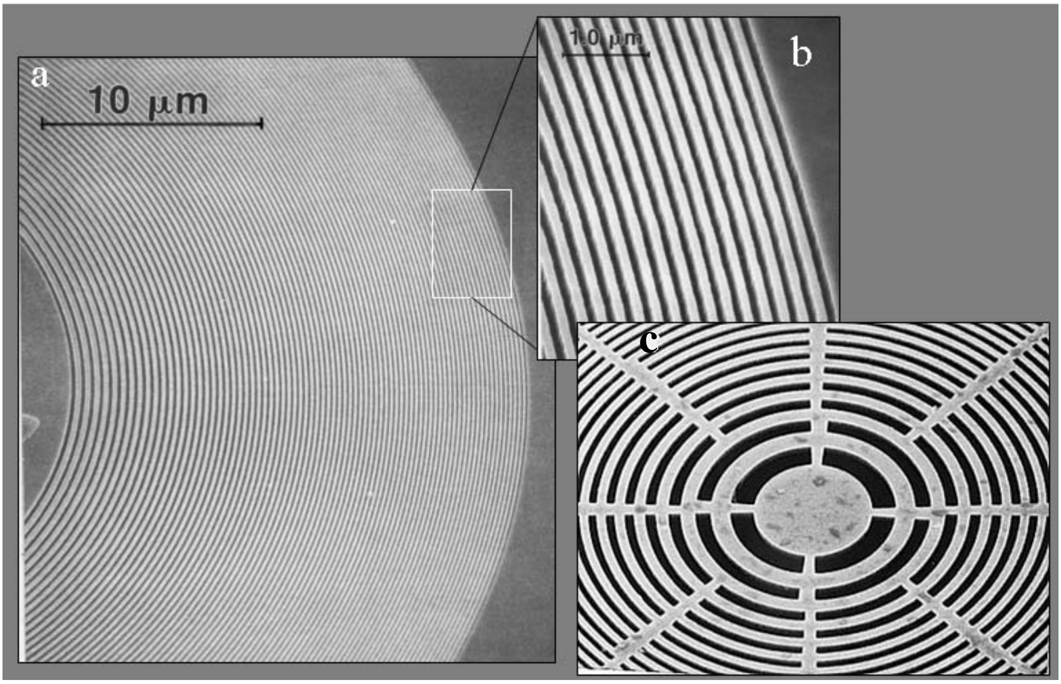

FIGURE 1.2 Diffractive optics such as these Fresnel zone plates have enabled major advances in soft x-ray microscopy for biological applications, spatially resolved hard x-ray microdiffraction for materials characterization, and even neutral atom optics that require freestanding structures. A germanium-phase zone plate is shown in (a) and (b) and a freestanding silicon zone plate is shown in (c). These structures are formed by electron-beam lithography and reactive ion etching, key tools for nanofabrication facilities. Courtesy of Lucent Technologies Bell Labs.

fabricate nanodevices is typically too expensive for a single investigator, or sometimes even for a single institution, and requires a combination of specialized skills that are not normally found in the laboratory of one investigator or academic department. As a consequence, several nanofabrication facilities have been established at universities and national laboratories. For example, the development of the instrument that uses focused-ion beams has played an important role in providing new capabilities for the fabrication of micro- and nanostructures. These facilities have enabled new research in biological and chemical sensors, gene chips, nanofluidics, molecular electronics, self-assembled monolayers, and integrated sensors.

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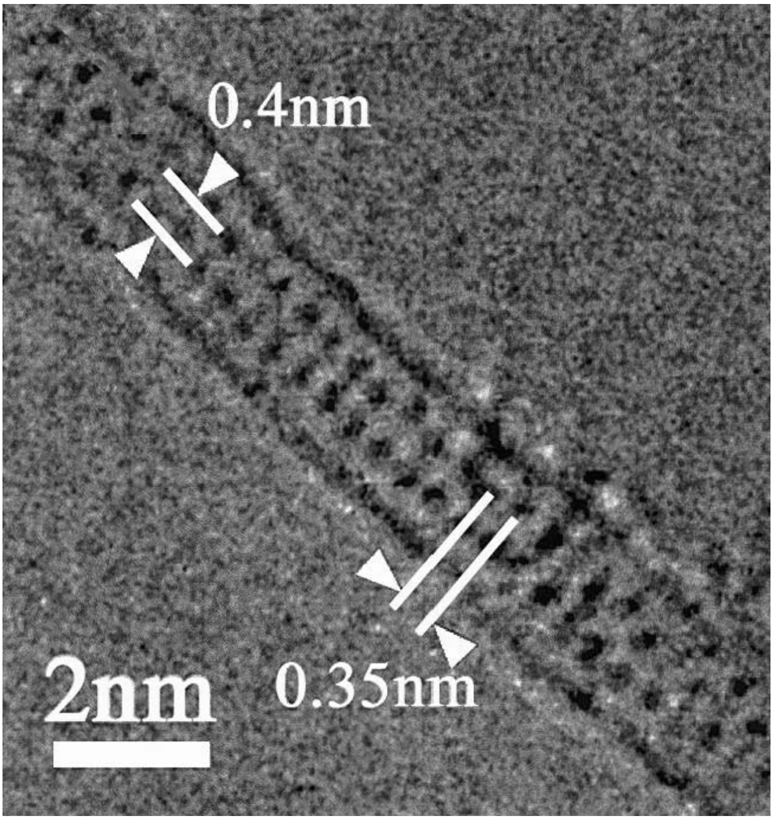

FIGURE 1.3 High-resolution transmission electron micrograph of crystals grown within a single-walled carbon nanotube. The synthesis and characterization of one-dimensional crystals with a well-specified chemistry, size, and crystal structure present a formidable challenge for materials chemistry and analysis. In this image, two layers of coordinated potassium iodide crystals grown within the single-walled carbon nanotubes are shown, as indicated by the arrows. An enhanced image-restoration technique developed by A. Kirkland and O. Saxton at Cambridge University makes possible an atom-by-atom reconstruction of these crystals, the first time that crystallography has been attempted on such a scale. Courtesy of J. Sloan and J. Hutchison, Oxford University.

Another aspect of the important role played by midsize facilities in advancing materials science is illustrated in the area of nanocharacterization. Nanocharacterization facilities are inevitably coupled with nanofabrication facilities—researchers always need to examine closely what they have created! (See Figure 1.4 for an example.) The collection of instruments required is again too expensive and

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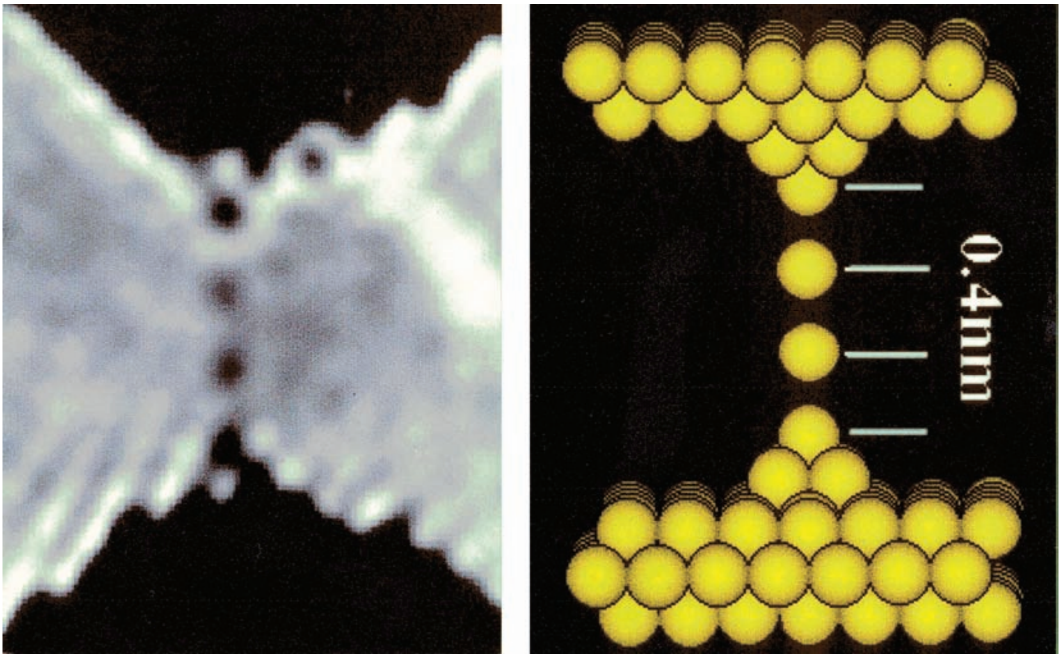

FIGURE 1.4 A single strand of gold atoms: (left) the structure as imaged with a transmission electron microscope (TEM) where the gold atoms appear in dark contrast, and (right) a diagram of what is being observed where the gold atoms appear in yellow. A single strand of gold atoms was first observed to exist suspended in free space between electrodes with an atomic spacing of 0.40 nm on average, extremely long compared with the nearest-neighbor distance, 0.29 nm, in crystalline gold. Quantum point contacts are structures (generally metallic) in which a “neck” of atoms just a few atomic diameters wide (that is, comparable to the conduction electrons’ Fermi wavelength) bridges two electrical contacts. They can be prepared by contacting a metal surface with a scanning tunneling microscope and by other methods. Courtesy of K. Takayanagi, Tokyo Institute of Technology, and Y. Kondo, JEOL, Ltd.

too specialized to be established in the laboratories of individual investigators or departments. High-resolution transmission electron microscopes (TEMs), scanning electron microscopes, multimode scanning probe microscopes, and focused-ion beams are examples of the equipment found in a modern nanocharacterization facility.

The operating techniques and some of the specialized accessories for such facilities must often be developed by experienced staff using the infrastructure that the facilities provide. From time to time, a commercial instrument requires signifi-

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cant alteration or enhancement before it can be employed successfully to address an important scientific or technological problem. These types of instrument enhancements or extensions often lead to major new capabilities that extend far beyond the original application and open up new research areas. Midsize facilities provide the natural environment for this work: an individual investigator does not have the resources to pursue it, and the (often-oversubscribed) largest facilities cannot afford the time and energy to customize or specialize an apparatus for each user's needs.

Instrument Development

Many facilities contribute directly to the development of the fundamental instrumentation around which these facilities are built, and thereby advance the field markedly. The experience that researchers gain by having access to the most advanced instrumentation, plus the experience gained by facilities in meeting—or in not having the instrumentation to meet—users' needs can spur the development of the next generation of instruments (see Box 1.2, "Increasing Sophistication of Instrumentation and Associated Trends"). With a healthy combination of technical staff, existing tools and equipment, and financial resources, midsize facilities are often more able than are single investigators or large national facilities to tackle the instrumentation challenges brought to them by users. Examples include developments in electron microscopy for "wet" and "cold" sample stages, piezoelectric drivers for in situ sample testing, and, more recently, demonstration by researchers at Northwestern University of a new technique that is capable of actively monitoring and controlling crystallization as it proceeds in real time.

Cross-Disciplinary Science

The development of biosensors and gene chips illustrates another important research thrust occurring at such facilities. It is becoming increasingly evident that many important scientific and technological opportunities lie at the intersection of traditional disciplines. Facilities with advanced instrumentation and skilled support staff enhance the effectiveness of interdisciplinary groups and make it possible for people with limited previous training to utilize techniques developed outside their fields. In facilitating interactions among people from different disciplines and encouraging cooperation, facilities act as meeting grounds and provide exposure to research endeavors that emphasize joint effort, planning, and cooperation.

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BOX 1.2
Increasing Sophistication of Instrumentation and Associated Trends

The increasing sophistication of instrumentation can be exemplified by the following descriptions of transmission electron microscopy, x-ray crystallography, scanning probe microscopy, the focused-ion beam, and electron-beam writers.

Transmission Electron Microscopy

In the decades from the 1960s to the 1980s, transmission electron microscopes (TEMs) were used mostly to examine the microstructure of alloys and ceramics, with diffraction contrast as the imaging mechanism. The addition of x-ray energy dispersive spectroscopy and the improvement of resolution allowed chemical analysis on the 10 nm scale, enabling the first routine, direct images of the atomic structure of materials. By the 1990s, electron energy loss spectroscopy and energy-filtered imaging brought about the possibility of chemical mapping at the 1 nm level and the determination of chemical ionization and bonding states.

Now, aberration correction and monochromators are extending all of these capabilities—within one compact machine that fits into a normal-size room—to the subangstrom (0.1 nm) scale! (See Figure 1.2.1 for a diagram of the evolution described here.) Aberration-corrected microscopy provides a direct image with fewer opportunities for “artifacts,” or incorrect image information. Uncorrected microscopy can achieve subangstrom resolution by combining a collection of many micrographs to achieve an image, but it also increases the introduction of artifacts. Concomitant with these developments, the approximate cost of these instruments has increased by a factor of 50, from about $0.1 million to $5 million or more for a fully aberration-corrected TEM.

In fact, in September 2004, Oak Ridge National Laboratory (ORNL) researchers, using a state-of-the-art aberration-corrected microscope and new computerized imaging technology, pushed back the barrier with respect to the size of what can be seen.[a] Led by ORNL researcher Stephen Pennycook, the team examined a silicon crystal and imaged atoms that are only 0.78 angstrom apart, demonstrating reliable subangstrom resolution with electron microscopy (see Figure 1.2.2).

X-ray Crystallography

It is well known that many invaluable achievements in x-ray crystallography have been realized at the very successful (large-scale) synchrotron facilities. Recently, it was announced that technological innovations are likely to bring about a new generation of small-scale synchrotron sources far exceeding the capabilities of rotating anode x-ray generators. These small-scale synchrotron sources would likewise be able to fit into a normal-size laboratory—an advance that would then make them easily available for use by many universities and institutions. This advance—while likely to enable significant new opportunities—will add to the strain on the midscale instrumentation budget (see Box 1.3, “Desktop-Size Synchrotron Radiation Sources,” for more details).

continued

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BOX 1.2 Continued

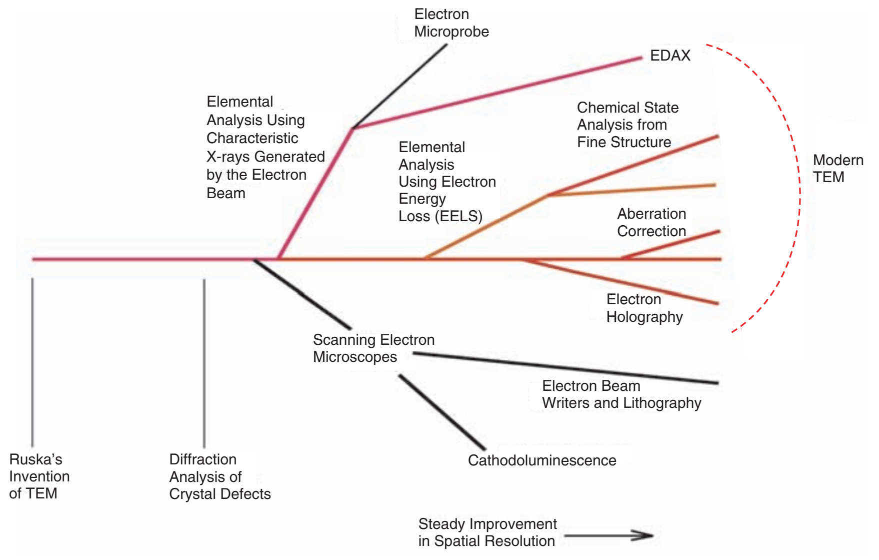

FIGURE 1.2.1 Evolution of electron microscopy, 1930 to the present, organized by improvements in spatial resolution. A modern TEM often has all the capabilities shown in red.

Scanning Probe Microscopy

Scanning probe microscopy (SPM) covers several related technologies for imaging and measuring surfaces on a fine scale, down to the level of molecules and groups of atoms. At the other end of the scale, a scan may cover a distance of over 100 micrometers in the *x* and *y* directions (horizontal plane), or the plane of the surface being imaged, and 4 micrometers in the *z* direction (vertical plane), or the height of the surface. This range is enormous. SPM technologies share the concept of scanning an extremely sharp tip (3 to 50 nm radius of curvature) across the object surface. The tip is mounted on a flexible cantilever, allowing the tip to follow the surface profile. SPM can now manipulate and probe the electronic structure of individual atoms. It can truly be said that the development of this technology is a major achievement, for it is having profound effects on many areas of science and engineering.

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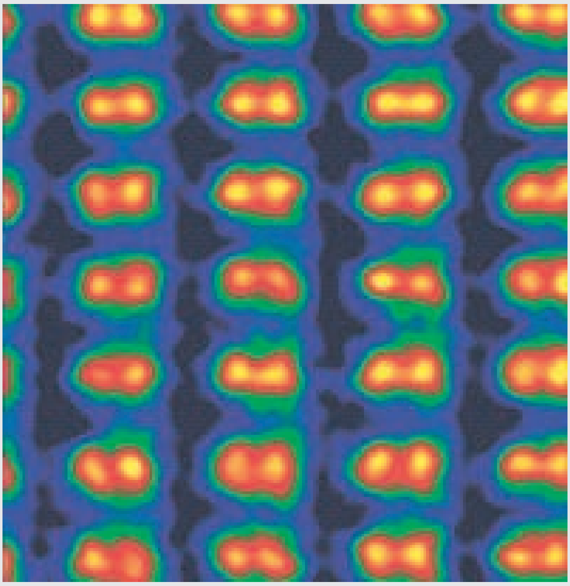

FIGURE 1.2.2 Looking straight down on a silicon crystal in the direction of the <112> crystal plane, the atoms line up in closely spaced pairs of columns with just 0.78 angstrom between each column in a pair. The dumbbell shape shows that the microscope has achieved better than 0.78 angstrom resolution. With a smaller beam, the rows would be seen as two clearly separated features, but with a larger beam, the pair would blur into one oval-shaped feature. Analysis of the power spectrum shows the presence of information down to a record 0.6 angstrom. The image was obtained using a 300 kV VG Microscope HB603U scanning transmission electron microscope equipped with a Nion aberration corrector, by M. Chisholm, with processing by A. Borisevich and A. Lupini and aberration correction by P. Nellist, N. Dellby, and O. Krivanek, Nion Company. Courtesy of Oak Ridge National Laboratory.

Focused-Ion Beam

The focused-ion beam (FIB) has become an invaluable research tool within the past 10 years. This versatile instrument allows the focusing and rastering of a less than 10 nm ion beam onto a material, with the possibility of directing a scanning electron beam at precisely the same location. Thus, either ion-induced or electron-induced images are possible. The strength of the FIB lies in the ability to use the ion beam to etch away or section through a device to examine its subsurface structure. Moreover, the ion (or electron) beam can locally decompose an organometallic or other complex gas that is bled into the specimen chamber to deposit metals or dielectrics onto the material, thereby building up a nanoscale structure.

continued

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BOX 1.2 Continued

In industry, a major application is in the repair of defects in masks that are used in photolithographic delineation. The FIB tool has also enabled semiconductor manufacturers to identify defective circuits and quickly make a TEM cross section of the device at the defect location to identify the cause, all within a few hours. This capability is now rapidly spreading in TEM laboratories in the United States for the preparation of TEM samples from materials that are notoriously difficult to prepare by more conventional methods. The FIB can actually be used to make device repairs with a process known as circuit edit—that is, by cutting an interconnect that is incorrectly joining two features and building a new interconnect with the use of organometallic gases. Now the FIB is even being used to cut into biological materials (for instance, blood cells), and in conjunction with cold-stage electron microscopy reveals the cytostructure directly. An even more revolutionary capability is to fabricate nanostructures directly with the FIB.

Electron-Beam Writers

In the field of fabrication, electron-beam writers have progressed from 200 nm definition in the 1970s to the current level of 10 nm (see Figure 1.2.3). Similarly, the availability of

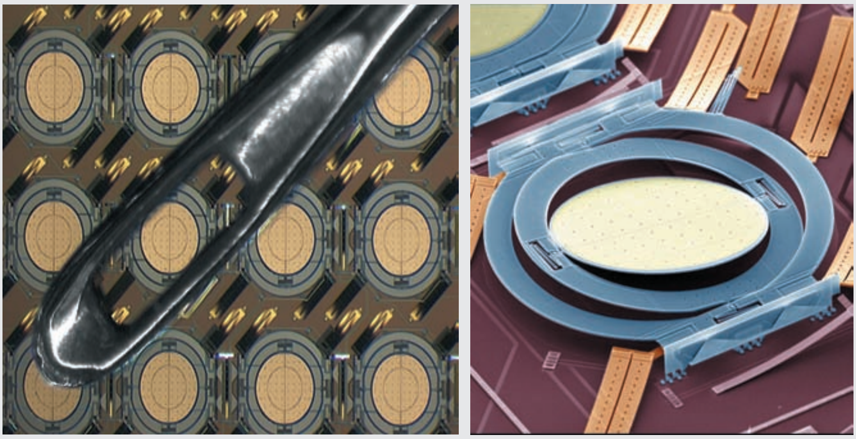

FIGURE 1.2.3 Microelectromechanical system mirror arrays such as the optical cross connect (left; single mirror shown right) fabricated at Lucent Technologies have proven to have application to many different technology industries. The ability to tailor the mirror sizes, array dimensions, frequency performance, range of motion, and so on has stimulated research applications in telecommunications, high-definition displays, gene chips manufacture, and even semiconductor circuit production. Fabrication of such components and subsystems requires clean environments and a heavy investment in the tools similar to those found in semiconductor circuit fabrication facilities. Courtesy of Lucent Technologies Bell Labs.

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electron-beam lithography has facilitated the investigation of quantum-size effects by enabling the fabrication of specific device structures. These examples illustrate the emerging trend of using instrumentation to define structures of materials that can then be characterized directly. This trend will quickly become an essential part of experimental sciences at the nanoscale, as the tools themselves are used to fabricate and characterize materials, bringing an enhanced level of understanding to the long-term paradigm in materials research of microstructure-property correlations.

Staffing Trends

The increase in the capabilities and sophistication of instrumentation is placing new demands on the technical and professional staff required to support the instrumentation. For instance, it is not uncommon that a master's or a Ph.D. degree is a minimum requirement for independently operating secondary ion mass spectrometry or TEM instrumentation in service-oriented companies. Such advanced training is also required in any facility offering analytical services. Such positions might previously have been staffed with personnel having associate degrees or bachelor's degrees. Industrial companies also require Ph.D.-caliber staff for their own in-house analytical staff, and the demand for skilled, highly trained instrumentation specialists is increasing while the number of domestic Ph.D. students in the physical sciences is steadily decreasing.

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[a] P.D. Nellist, M.F. Chisholm, N. Dellby, O.L. Krivanek, M.F. Murfitt, Z.S. Szilagyi, A.R. Lupini, A. Borisevich, W.H. Sides, Jr., and S.J. Pennycook, "Direct Sub-Angstrom Imaging of a Crystal Lattice," *Science* **305**, 1741 (2004).

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Education and Outreach

Midsize facilities are central not only to advancing materials research but also to training the next generations of scientists and engineers in materials disciplines at the B.S., M.S., and Ph.D. levels. Maintenance and staffing of facilities are central to the functioning of these facilities in both their research and their training roles. The committee cannot overemphasize the importance of the role that midsize facilities play in the professional training of scientists, technicians, and cross-disciplinary researchers.

Midsize facilities carry out three important roles in the development of undergraduate students, graduate students, and postdoctoral associates:

BOX 1.3
Desktop-Size Synchrotron Radiation Sources

Synchrotron radiation has already revolutionized x-ray science as a consequence of its extremely bright beams and its continuous spectrum. The disciplines taking advantage of this structural analysis tool include structural molecular biology, physics, geology, materials science, semiconductor processing, and molecular environmental science. A disadvantage of synchrotron radiation, however, is that it is primarily available only at a small number of large electron accelerators.

Recently, Lyncean Technologies, Inc., was formed to produce a desktop-size synchrotron source called the Compact Light Source (CLS), which is expected to produce 1 angstrom (Å) and longer wavelength radiation. Existing synchrotron light sources employ multi-gigaelectron-volt electron beams that are stored in large rings of magnets to generate intense, bright, 1 Å wavelength radiation. The CLS couples an electron beam with a laser beam to accomplish the same effect. The shift from periodic magnets used in a typical synchrotron light source to the laser beam used in the CLS allows a reduction of energy and scale by a factor of more than 200.

Although not as bright as the beam provided by large accelerator-based sources, the radiation that the CLS would provide is considerably more intense than that of the x-ray generators used throughout the world in academic and industrial laboratories. Its wavelength would be tunable, allowing the performance of experiments that cannot be conducted with conventional x-ray generators. A great deal of the research now done at the accelerator-based synchrotron radiation facilities could be performed locally, as the CLS is expected to provide an x-ray beam that can drive up to three end stations at a cost of perhaps less than $5 million. Such local (midsize) facilities would provide experience that would allow more effective use of the larger facilities. Consequently, they would complement the large accelerator-based synchrotron radiation sources. However, demands for this capability will put additional pressure on sources of funding for midscale instrumentation.

These devices will undoubtedly require additional research and development before commercialization. And, while estimates of pricing are in the few-million-dollar range, they do not include the necessary instrumentation to exploit the radiation (e.g., beamlines).

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1. Providing access to instruments and techniques that are not available within their advisers' or their departments' laboratories;
2. Introducing techniques outside the scope of their advisers' expertise; and
3. Facilitating the introduction of these young scientists to users from different disciplines and/or scientific or technological sectors (e.g., industrial or national laboratories).

Midsize facilities provide a unique educational and training ground for students as well as for senior investigators. Learning new techniques from a practical perspective is a valuable complement to classroom exposure to technology. A

The need for local synchrotron radiation facilities was discussed in the *Report of the Basic Energy Sciences Advisory Committee Panel on Department of Energy Synchrotron Radiation Sources and Science*. The report stated:

> A final, significant note about beamline utilization is that users apparently place great value upon nearby access to synchrotron radiation facilities. In the early years when only SSRL [Stanford Synchrotron Radiation Laboratory] was available, users came from all parts of the country. Increasingly, however, all facilities have become regional facilities, with most of the users from the local region. Even the APS [Advanced Photon Source] has nearly half of its CAT [Collaborative Access Team] members from the state of Illinois. Although several interpretations of this trend are possible, the simplest is to accept that regional facilities, be they 2nd or 3rd generation, appear to be going a long way towards serving the needs of the local user communities. When combined with the increase in demand at all the sources, one is forced into the conclusion that there is great latent demand for regional storage ring facilities in all parts of the country.[a]

Although the values cited for the Advanced Photon Source user community are quite old (circa 1997; in fact, today less than 25 percent of the users come from Illinois),[b] the value placed on nearby access to facilities remains the same. The desktop sources discussed here could meet part of that latent demand.

Finally, it is breakthroughs in instrumentation development such as this one that can spur the progress of research—but only if the new tools are distributed, operated, and maintained with care and forethought.

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[a] Basic Energy Sciences Advisory Committee, *Report of the Basic Energy Sciences Advisory Committee Panel on Department of Energy Synchrotron Radiation Sources and Science*, Washington, D.C.: Department of Energy, November 1997, p. 89. Available online at http://www.sc.doe.gov/bes/BESAC/syncpanel.pdf; last accessed June 1, 2005.

[b] Private communication with M. Gibson, Director, Advanced Photon Source, May 2005.

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common situation is for a facility manager or experienced staff scientist to provide training to individuals or to a small group, teaching the uses of instrumentation or the implementation of a new method of using the instruments. The training is usually conducted with samples of research interest to the investigators. Multidisciplinary or cross-sector collaborations[2] result from these interactions, broadening the perspectives of the students and increasing the scientific output. As a consequence, they become more valuable additions to the U.S. science and technology workforce.

A common experience at a facility is that a graduate student becomes quite skilled in an advanced technique. The student comes into contact with scientists from other fields—or sectors—who are also experimenting at the facility. The other scientists recognize the value of collaborating with the student. The student recognizes the opportunity to learn about a new problem or field. A collaboration arises that markedly broadens the student's perspective. The student becomes more confident in his or her skills and better able to adapt to new problems and environments. This type of interaction can happen only if the student obtains hands-on experience and is present at the facility.

Facilities also often fill an important role in promoting public understanding of science. The array of scientific accomplishments, the scale and talent mix of staff members involved, and the remarkable capabilities of modern machines make it both practical and exciting to share effective presentations with the general public, especially with precollege students.

Commercial Activities

By serving as testbeds, expert resources, or simply research and development work space, midsize facilities help invigorate ongoing commercial ventures or even spawn new ones. Industrial collaborators pay fair market prices to use midsize facilities on short-term or even on recurring bases, because they recognize the economy of outsourcing the operations, maintenance, and professional staff overhead that such facilities require.

Finally, one type of facility that warrants specific mention is the commercial analytical service laboratory. These facilities are unlike those at universities and national laboratories, which generally receive their funding directly or indirectly from the federal government, and are unlike those at private corporations, which

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[2] For the purposes of this report, the committee defines multidisciplinary and cross-sector collaborations as follows: *Multidisciplinary collaborations* bring together experts trained in different academic areas to work on a common problem. *Cross-sector collaborations* bring together researchers from universities, government, and industry.

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are internally funded. Commercial analytical laboratories are generally formed by individuals who contribute personal funds, borrow from a lending institution, or raise equity by selling ownership to others. With these initial capital funds, they purchase equipment, hire personnel, and establish a laboratory to provide characterization services to all who can afford the fees that are needed to cover the true expense of sustaining the facility. All costs such as building rent, personnel budgets, capital equipment purchases, and some profit must be collected as revenue if the commercial laboratory is to operate successfully. Therefore, charges for commercial analytical laboratory services are typically much higher than are those for services from a university or national laboratory facility. A private corporation will also calculate the full cost of its internal facility to determine the cost-effectiveness of these internal facilities. Thus, a corporation may also “outsource” to a commercial laboratory those services not efficiently performed in-house. The long and successful history of the leading commercial analytical laboratories is testimony both to the demand for their services and to their ability to recoup sufficient operating costs so as to be sustainable and profitable.

DEFINITION OF A MIDSIZE FACILITY

Midsize facilities are distinct from small facilities in being large enough to require a dedicated and explicit infrastructure for their sustained success. They are distinct from large facilities in being small enough to be flexible and responsive to the needs of a relatively local user community and in possessing equipment the scale and cost of which allow duplication, when demand merits, in different regions of the nation.

In many ways, midsize facilities fulfill a role complementary to that of the large facilities such as the synchrotron and neutron facilities. While both midsize and large facilities are important to the national scientific endeavor, there are distinct differences in their modes of operation (in addition to the very large differences in their operating budgets). The large facilities provide intensive user time at limited periods during the year. They generally require a proposal and its approval for access requiring advance planning. In contrast, midsize facilities generally provide frequent access to their instrumentation and generally (but not always) do not require a proposal process. Thus, synchrotron users may have access to synchrotron beams three to four times per year or less, while midsize facility users often use the instruments on a weekly or more frequent basis. At many of the midsize facilities, the researchers make use of multiple techniques for their studies—indeed, this is essential in addressing complex materials problems. The very nature of synchrotrons and neutron scattering facilities requires that they serve a large regional or national clientele. In contrast, the midsize facilities serve more local communities, although

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in many cases they have unique instruments and capabilities that attract users nationally or internationally.

As developed by the committee and used in this report, the following definition of the term "midsize facility" informs the discussion throughout and is reflected in this study's recommendations:

> A midsize facility maintains and operates one or more pieces of equipment at a university or national laboratory and has the following characteristics:
>
> - Facilitates scientific and/or technological research for multiple users;
> - Provides services on local, regional, or national scales;
> - Is open to all qualified users subject to generally agreed-upon rules of access;
> - Has a resident staff to assist, train, and/or serve users; and
> - Has a replacement capitalization cost of between approximately \$1 million and \$50 million and an annual operating budget (including staff salaries, overhead, supplies, routine maintenance and upgrades, and so on) in the range from about \$100,000 up to several million (2004) dollars.

The committee recognizes that not all midsize facilities meet all elements of this definition.[3] It also believes that midsize facilities often distinguish themselves in other ways. A midsize facility frequently meets one or more of the following additional criteria:

- Provides a unique or special service that is not generally available in an individual investigator's laboratory;
- Fulfills a particular scientific or niche need in the research enterprise;
- Has a clear mission that addresses a well-defined or emerging need of a well-defined community;
- Plays a leading role in education, workforce training, and workforce development;
- Facilitates instrument and technology development and/or training;
- Promotes synergy and communication among its users and with others;
- Fosters cross-disciplinary and cross-sector interactions, including scientific, medical, and engineering endeavors; and
- Represents a means for coordinating scientific activities among other facilities or institutions with complementary capabilities.

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[3] Indeed, over the summer of 2003 the committee visited a number of facilities that would not qualify as midsize facilities for materials research, and yet they provided valuable information that was relevant to the committee's charge.

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The committee makes three final important observations:

1. The committee has clarified its nomenclature since the release of its interim report (Appendix D), in which it used the term "smaller facility" to describe the type of facility that it now calls a midsize facility. The change in terminology is intended to reduce confusion. In conversations with the community, the committee found that the term "smaller facility" was often misinterpreted as describing "small" facilities, such as those maintained and used by only one investigator in his or her private laboratory space. The committee believes that the term "midsize facility" is clearer.
2. Federal program managers, university administrators, and the media have blurred the distinction between a "center" and a "facility."[4] The committee distinguishes these entities in the following manner:

    - A center is a collection of investigators with a particular research focus.
    - A facility is a collection of instrumentation, equipment, or physical resources that enables investigators to conduct certain activities.

3. It is also important to distinguish between the instrumentation itself and the facility that supports the instrumentation: that is, a discussion of facilities should not be focused on instrument procurement alone.[5] Instruments are sophisticated tools employed by researchers to extend their capabilities. Facilities may contain certain instruments or suites of instruments, but facilities include mechanisms for supporting, operating, and accessing the instrumentation so that research can be performed. Facilities provide the interface between researchers and the sophisticated instrumentation.

Facilities provide sets of tools that expand the capabilities of groups of researchers (examples of the variety of instruments used in materials research are given in Box 1.4). Throughout this report, however, the committee argues that a successful midsize facility must be more than just a collection of equipment: staff, users, operating funds, specialized environments, and a management plan are some of the essential additional ingredients for successful operations.

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[4] For instance, the popular Materials Research Science and Engineering Center program of the National Science Foundation supports centers that often contain a "shared experimental facility" element.

[5] A forthcoming report by the National Research Council's Committee on Advanced Research Instrumentation is expected to address these issues in more detail and in a broader context, including interdisciplinary and interagency perspectives.

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BOX 1.4
The Array of Instruments for Materials Research

Modern scientific instrumentation is rich with acronyms, abbreviations, and complex nomenclature. The field of materials research is no exception. In part because of the breadth of the research enterprise, the suite of tools available to synthesize, fabricate, characterize, measure, and analyze a sample is enormous and can be overwhelming. However, each type of instrument has a specific purpose with special capabilities and special limitations.[a] Learning to use these tools is as much about actually operating them as it is about learning which tools should be used to achieve which desired outcomes.

Many people are familiar with the optical microscope, but in the modern era, this method of imaging is only one of many, many possibilities. An optical microscope combines two distinct systems: an imaging component that directs photons of visible light at the sample, and a magnification element that allows the user to resolve the finer details of the interactions of the light with the sample. The optical microscope simply provides information about how particles of a certain type (visible light) interact with the sample. Because the human eye is also sensitive to visible light, we usually think of an optical microscope as merely a sophisticated magnifying glass. The key to understanding characterization and measurement instrumentation is to understand how an instrument interacts with the sample and to what types of features it is responsive, that is, what differences in the sample's properties cause a variation in instrument response.

Almost all characterization and measurement tools involve a process that scatters incident particles (or a beam of particles) off a sample; the result of the particle-sample interaction is analyzed for clues about the sample. For electron microscopes, the incident particle beam is a collimated beam of electrons that can scan across the sample, tunnel through it, or be transmitted. For secondary ion mass spectrometry, particles incident upon a sample eject secondary ions that are analyzed for composition. In various types of x-ray experiments, x-ray photons form the beam of incident "particles."

As materials research has evolved as a science and engineering discipline, more sophisticated measurements of sample properties have become necessary. Similarly, more sophisticated synthesis, fabrication, and preparation methods have emerged. As shown in Figure 1.4.1, specialized techniques have been developed that concentrate on different features: some techniques focus on imaging alone and offer different resolutions, while others measure concentrations of atoms in bulk and offer different detection sensitivities. As shown in Figure 1.4.2, the different techniques also access different depths of the sample under study.

Following is a list of definitions of the acronyms used in Figures 1.4.1 and 1.4.2:

- AES Auger electron spectroscopy
- AFM atomic force microscopy
- EDS x-ray energy dispersive spectroscopy
- ESCA electron spectroscopy for chemical analysis
- μESCA microspot electron spectroscopy for chemical analysis
- FE-AES field-emission Auger electron spectroscopy
- FE-SEM field-emission scanning electron microscopy
- FTIR Fourier transform infrared spectroscopy
- GC/MS gas chromatography mass spectrometry
- GDMS glow discharge mass spectrometry
- RBS Rutherford backscattering
- SEM scanning electron microscopy

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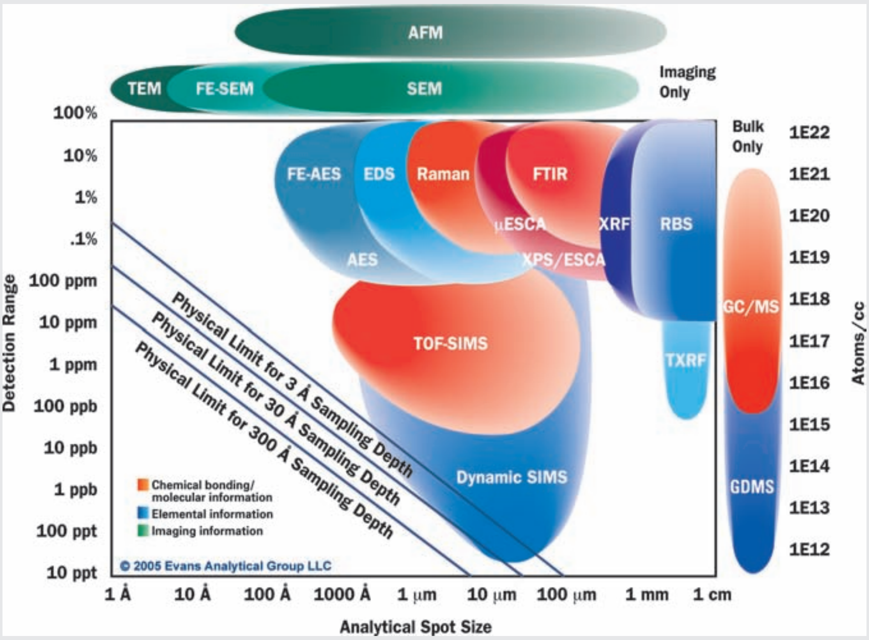

FIGURE 1.4.1 Analytical resolution versus detection limit for a variety of standard characterization techniques in materials research. Courtesy of Evans Analytical Group.

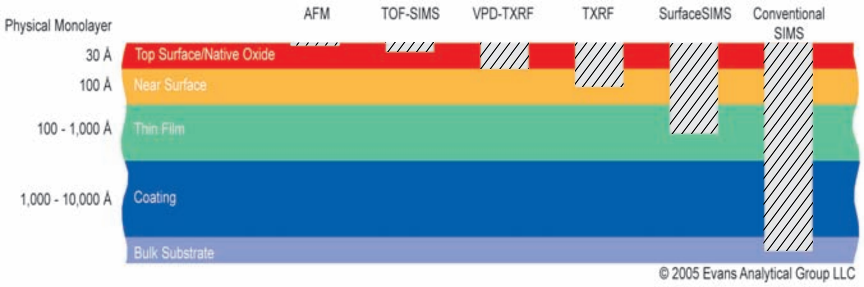

FIGURE 1.4.2 Depiction of the depth of sample material that can be analyzed with different materials characterization techniques. Courtesy of Evans Analytical Group.

continued

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BOX 1.4 Continued

- SIMS secondary ion mass spectrometry
- TEM transmission electron microscopy
- TOF-SIMS time-of-flight secondary ion mass spectrometry
- TXRF transmission x-ray fluorescence
- XPS x-ray photoelectron spectroscopy
- XRF x-ray fluorescence

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[a] For more information, the interested reader is referred to the excellent volume C.R. Brundle, C.A. Evans, Jr., and S. Wilson, *Encyclopedia of Materials Characterization: Surfaces, Interfaces, and Thin Films,* Stoneham, Mass.: Elsevier, 1992.

SCOPE OF THIS STUDY

This study was undertaken to assess the effectiveness of the network of midsize facilities that the federal government supports—fully, or in large part—to enable materials research within the United States, to establish the level of accessibility of the facilities to the broadest possible research community, and to determine how the network could be modified to have maximum impact in a financially constrained era. The formal charge to the committee is provided in Appendix A.

The primary concerns driving this study are the significant opportunities over a wide cross section of scientific disciplines that might be missed because the resources of midsize user facilities are not fully exploited. The capabilities of instruments such as secondary ion mass spectrometers or electron microscopes are rapidly increasing, yet the cost of acquisition and maintenance is escalating to the point that the smaller facilities, typical of individual institutions, can no longer afford their purchase and upkeep. Furthermore, the developments in instrumentation that often take place in midsize facilities underpin critical tools for industry, as, for instance, happened with the focused-ion beam. Likewise, these facilities fill an extremely important role in the education and training of future scientists and engineers by ensuring that students have familiarity with the latest instrumentation and techniques.

This report describes the findings of the NRC's Committee on Smaller Facilities, which was established by the Solid State Sciences Committee of the Board on Physics and Astronomy. The basic challenge addressed by the committee is framed by the following observations:

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1. Instruments critical to materials research are becoming sufficiently expensive that the individual investigator cannot afford them; resources must be pooled to manage these instruments in midsize multiuser facilities.
2. Midsize facilities are sufficiently sophisticated in structure and content that a complex support network is required to maximize their effectiveness.

ORGANIZATION OF THE REPORT

Chapter 1 defines midsize facilities, outlining the activities carried out at them, and argues that they are more than just collections of instruments—they pool talent, leverage resources, seed cross-disciplinary interactions, and provide research, training, and education services to a broad community.

Chapter 2 describes general features of midsize facilities, characterizes their operations, and illustrates with some examples.

In Chapter 3, the committee reports on its findings concerning the most significant challenges facing midsize facilities. The common thread in these challenges is the struggle to ensure long-term viability—be it in securing stable infrastructure, working within the larger context of other facilities in the region, maintaining a clear mission relevant to users, or cooperating with commercial interests. Because midsize facilities are designed to last longer than one researcher's short-lived project, their operations require mechanisms to ensure economic stability, qualified staff, regular maintenance, student education, revitalization, and training support that transcend the single-research-project life cycle. Likewise, since these facilities serve more than one research group's needs, they are additionally challenged to balance the competing demands of many different users.

Chapter 4 characterizes the current investments in midsize facilities and refers to the international context. The absence of a thematic home for the long-term commitments essential to midsize facilities is identified as one area ripe for improvement. The potential advantages (and challenges) of several forms of regional facility networks are also discussed.

Throughout this report, the committee argues that a successful midsize facility must be treated as something more than just a collection of equipment: trained staff, users, long-term infrastructure, and a management plan are some of the essential additional ingredients for successful stewardship. Chapter 5 presents the committee's findings and observations, conclusions, and recommendations.

At the end of the report are appendixes containing the following: the committee's statement of task (Appendix A); the agendas for the committee meetings (Appendix B); facsimilies of the two questionnaires, the distribution list, a compilation of the data received, and their analysis (Appendix C); the committee's interim report of March 2004 to the funding agencies (Appendix D); a sample report

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from one of the site visits (Appendix E); a description and some statistics on federal programs that support midsize facilities (Appendix F); a summary of the National Science Foundation Workshop on Chemical Instrumentation held April 16-17, 1999 (Appendix G); a personal perspective from a midsize facility user (Appendix H); and the biographies of committee members and staff (Appendix I).

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2

Key Features and Capabilities of Midsize Facilities

GENERAL OBSERVATIONS

Based on the site visits of committee members to nearly 50 facilities and on information gleaned from the 75 responses to the questionnaires developed for this study, the committee's general overall finding regarding the characteristics of midsize facilities is that they have great diversity—in funding, business strategies, operations, staffing, and users.

By definition, midsize facilities provide instrumentation, support, and services to a user community. Within this grouping, however, the committee found substantial variation in facility missions, business plans, and expectations for the future, as exemplified below:

- *Origins.* The longest-lived facilities are typically connected to centers of the highest-caliber expertise: that is, facilities able to draw on the collective wisdom of an established group of world-class researchers have the longest histories. More modern facilities are typically initiated by collections of individual researchers at a university, often with the support of the department or dean of the school. According to the questionnaire responses, more than 70 percent of midsize facilities are located at universities.
- *Operating modes.* To remain viable, all midsize facilities make an effort to systematically recoup their operating expenses. Importantly, none includes amortized or depreciated capital expenditures as one of the expenses recovered annually, because the recovery of the cost of depreciation for government-

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funded capital investments at universities is not allowed. A variety of techniques are employed to cover operations. Some facilities attempt to subsist primarily on user fees, operating as so-called recharge facilities. Another model, principally in the Department of Energy (DOE) laboratories, relies heavily on institutional and/or federal support and has no user fees. Most facilities rely on a mix of funding sources. Among those that depend on user fees as a primary source of support, several make special allowances for graduate student and postdoctoral users. For example, the Microfabrication Laboratory at the University of California at Berkeley caps the maximum hourly charges that can be incurred by a single user in any one month so that a principal investigator's grant would not be drained by a burst of concentrated effort by a student. This type of policy cap on charges incurred by student users is common. Another interesting model for covering professional staff costs involves "backstopping," so that if a facility loses its primary source of funding, its technical staff will have alternative support over a short period of time (perhaps 1 to 3 years), allowing them to identify other opportunities. Harvard University supports such a policy for its Center for Imaging and Mesoscale Structures, for instance. Some facilities are designed primarily for service work, while others are focused more on carrying out cutting-edge research that is commonly done as a collaboration between users and facility staff.

- *Ease of access.* Larger facilities tend to have well-defined access rules and formal booking systems, while others, especially the smallest ones, have a less formal access structure.

Research Activities Supported

Materials research spans a broad program of exploration into the properties of materials—the substances of which everything is made. Generally speaking, experimental materials research can be grouped into different categories, although any one research project typically cuts across many activities. Borrowing nomenclature developed by the community, the committee believes that most small to midsize multiuser facilities support one or more of the following types of research:

- *Synthesis—a chemical or physical process used to prepare a material of specific chemical composition and/or spatial arrangement of the component atoms.* A very large number of synthetic processes and techniques have been or are being continuously developed to prepare known and novel materials. The first generation of ceramic high-temperature superconductors was discovered by materials synthesis.

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- *Fabrication—the process of creating a structure through direct assembly of the component materials, using layering or deposition techniques and selective removal techniques such as etching or trimming.* Many common semiconductor devices are built through a process of microfabrication; the first single-electron transistor was fabricated in 1987 at Bell Laboratories.
- *Characterization—the process of determining a material's nature, such as elemental composition, characteristic length scales, or electronic and crystalline structure.* The discovery of carbon nanotubes and the determination of their structure were first achieved by the high-resolution electron microscopy work of S. Iijima in 1991.
- *Measurement—the process of determining a material's physical or electronic attributes, often by a stimulus-response experiment under certain conditions.* As high-performance circuits are fabricated, measurement processes are often used to ensure the highest quality, greatest yield, and ultimate value.
- *Computation—the use of computing resources to extract or predict material property information from models or sets of measurements.* For instance, in 2004, DOE formed the Computational Science Center at Brookhaven National Laboratory to focus on computational biology; open to users, the center will help determine the structure and functions of proteins.

According to responses to the committee's survey, the predominant activities at midsize facilities are characterization and measurement, together representing more than 60 percent of the responses, followed by fabrication or processing. The least popular activity is materials synthesis (about 10 percent), a deficit in the materials research portfolio that has been noted elsewhere with some alarm.[1] While considerations of the detailed balance of the portfolio were judged to be outside the committee's purview, this observation merits further attention by the community.

Funding

Experience from the commercial analytical laboratory sector (in which a business must provide for "running in the black" to accord with the most realistic form of accounting) suggests that annual budgets should ideally be split evenly among labor charges, capital depreciation and amortization, and "operations" that include

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[1] See, for example, Basic Energy Sciences, *Design, Growth, and Discovery of New Materials: An Urgent U.S. Need*, Report of a DOE Workshop, October 10-12, 2003, Washington, D.C.: Department of Energy, 2003.

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utilities, space rental, maintenance, and supplies. Other costs include general and administrative expenses (including accounting and higher-level management).

Of the 56 midsize facilities that responded to the committee's survey, total operating budgets quoted range from $0 to $35 million (see Figure 2.1). Different methods of accounting for facility costs are clearly being used by the different facilities. Sources of funding include state, institutional, and federal monies, and user fees. In some cases, funding comes almost entirely from federal agencies, while support in a few special cases was reported to be derived entirely from user fees (in most of the latter cases, the user facility is housed within a larger center that provides infrastructure support). The 56 reporting facilities alone represent an operating budget of close to $70 million, of which university centers represent about 70 percent (in dollars). The distribution of funding sources for the 56 different midsize facilities is illustrated in Figure 2.2. The dominant sources of support overall are from federal research programs (35 percent) and from user fees (35 percent), closely followed by contributions from host institutions (27 percent). All facilities reported that identifying sources of annual operating funds was one of their most significant concerns.

Staff

The number of full-time-equivalent (FTE) staff supporting the operation of midsize facilities ranges from 0 to more than 25, peaking in the range 1 to 10, as

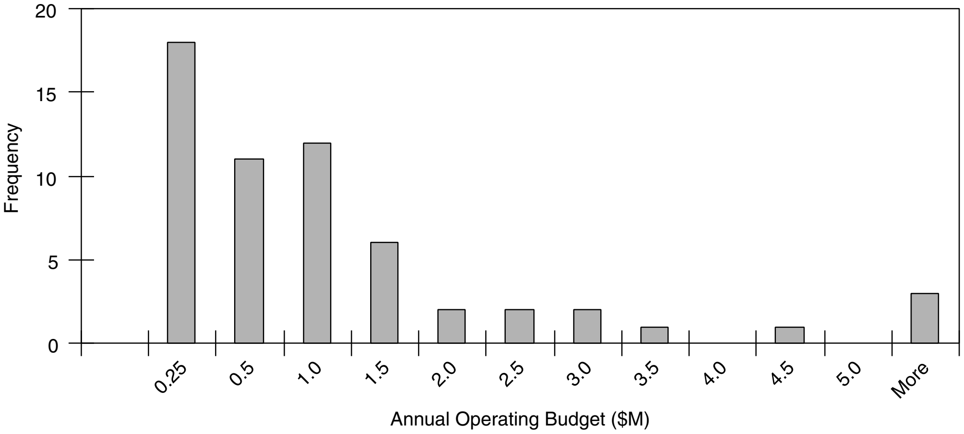

FIGURE 2.1 Distribution of midsize facility annual operating budgets. Data based on responses to the committee's survey (see Appendix C).

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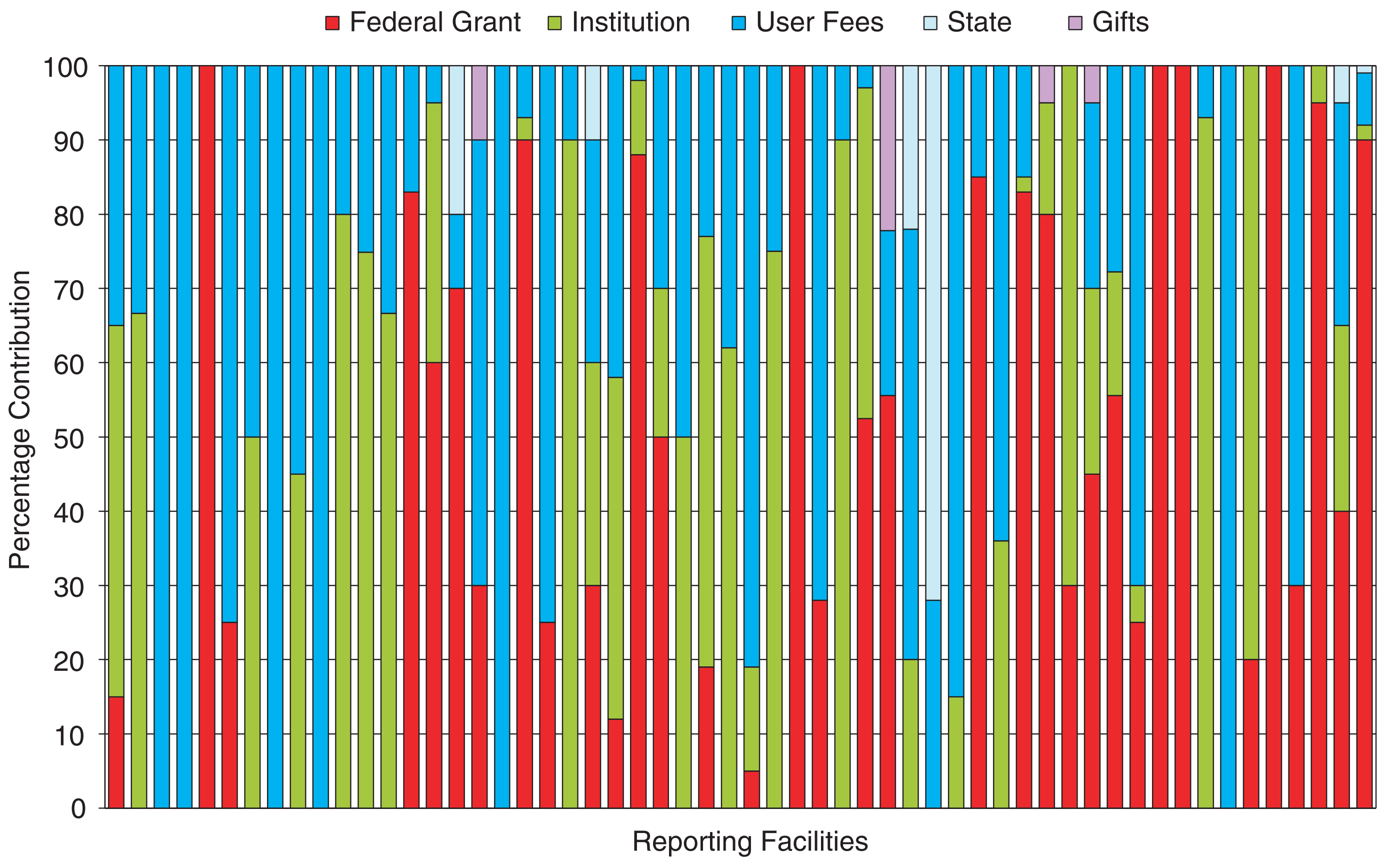

FIGURE 2.2 Comparison of sources of support for individual facilities' annual operating budgets; facilities not meeting the committee's definition are not included. The dominant sources of support overall are from federal research programs (35 percent) and user fees (35 percent), followed by contributions from the host institutions (27 percent). Data based on responses to the committee's survey (see Appendix C).

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reported in survey responses (see Figure 2.3). There appears to be no strong correlation between the number of FTEs and the annual operating budgets of the facilities, probably because different methods are being used by different facilities to account for their operating, staff, and student costs. Different facilities take different approaches to staffing. In some cases, one or more experienced technicians are available to operate and maintain equipment. Some midsize facilities necessarily manage by employing graduate students for this function. Finally, some facilities explained that in order to attract the most competent and qualified staff, the facility must offer competitive research opportunities for them.

Industrial Partnerships

In common with larger facilities, many midsize facilities have developed partnerships with industry. Nearly every facility that the committee visited in 2003 (the sites are listed in Appendix D) had industrial collaborators. That is, the facility infrastructure clearly benefited more than just the academic user community. Product development and prototyping exercises now have such an initial investment overhead that many companies cannot initiate a facility on their own. For

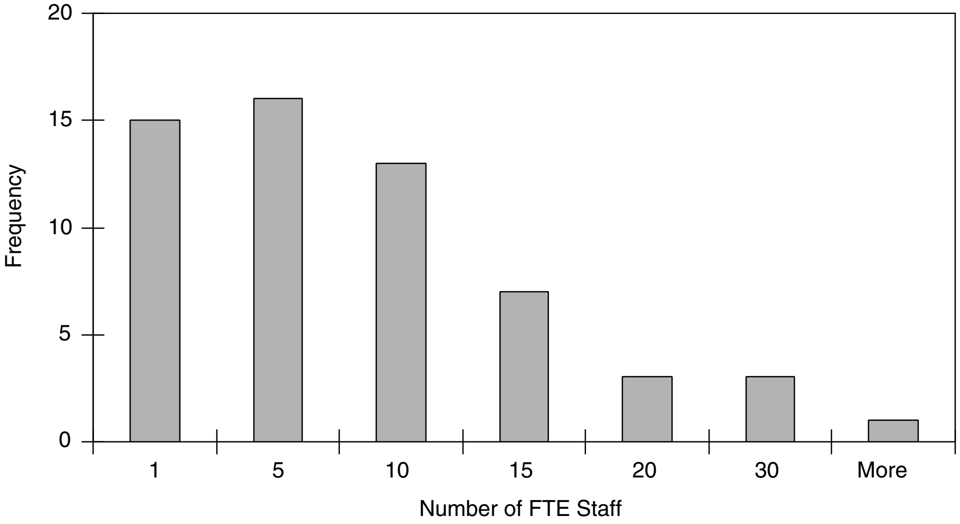

FIGURE 2.3 Distribution of the number of full-time-equivalent (FTE) staff supporting midsize facilities. Each bar represents the number of facilities that have the indicated number of FTE staff or fewer; for instance, the leftmost bar indicates that about 15 facilities have one staff member or fewer. Data based on responses to the committee's survey (see Appendix C).

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instance, the committee learned that having commercial property zoned for cleanroom space was increasingly difficult for investors; by contrast, many universities have developed permitting and regulatory relationships with local authorities that make this process much easier. See Figure 2.4 for one example of a collaborative endeavor between industry and a midsize facility.

The types of partnerships between midsize facilities and industry typically fall into three general classes:

- *Fee for service.* Small companies, usually in the particular facility's locale, bring or send samples or requests for service to the facility. Under this arrangement, the company pays access fees approximating what the host institution defines as full cost recovery to the facility for the transaction. This type of arrangement is generally used to provide one-time services such as fabrication or characterization.
- *Membership.* For a certain annual fee, member companies are granted special privileges, including access to both equipment and staff at the facility. However, to meet the requirements of federal accounting standards, the industrial partners still must often also pay hourly access rates to use the equipment. Facilities using this model of partnership with industry tend to rely on high industrial membership fees to help offset other costs of running the facility, such as supporting staff salaries. Several facilities reported that under their particular membership arrangements, company staff might spend significant time at a bench in the facility, sometimes developing a product or optimizing a process.
- *Collaboration.* Under this arrangement, research scientists from the collaborating industrial partner spend significant time at the facility, paying for equipment time and use and performing development research in association with the facility staff. Papers with coauthorship might even result. For instance, at the Frederick Seitz Materials Research Laboratory at the University of Illinois at Urbana-Champaign, committee members spoke with a scientist from Gillette Razor, Inc., who had just completed a long-term development effort in collaboration with facility staff. The representative commented that, in his case, the most important resource offered by the host institution was consultation with and advice from the resident staff.

Instruments

Midsize facilities provide materials research instruments that include characterization, measurement, fabrication, synthesis, and computing equipment, as indicated to the committee during its site visits and in survey responses. Typically

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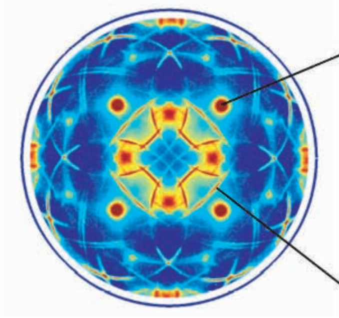
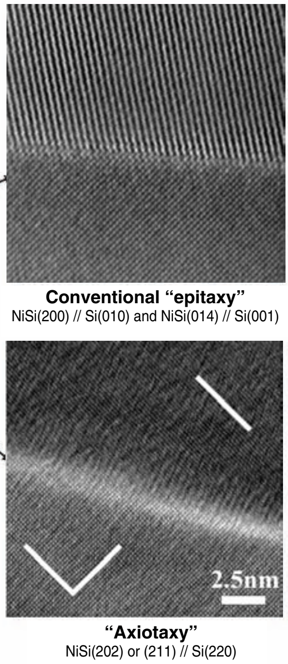
Nickel silicide (NiSi) is being investigated by IBM for use as a gate metal in advanced silicon-based electrical devices. When deposited, the individual grains of the film have a distribution of orientations (“texture”) with respect to the substrate. The texture affects the electrical and mechanical properties of the film.



X-ray diffraction pole figure obtained by IBM Watson researchers for a thin film of NiSi deposited on single crystal silicon. Pole figures are used to describe the distribution of crystal orientations in a film. The surprising observation here was the presence of arcs of intensity located at specific positions in the pole figure. This suggested that there might be an alignment of particular lattice planes between the film and substrate.



High resolution electron microscopy — performed using NCEM’s Atomic Resolution Microscope — allows direct visualization of the alignment of planes between the NiSi layers and the silicon substrate.

In conventional epitaxy, the alignment of all three crystallographic axes of the film is fixed with respect to the substrate. This is caused by the presence of identical spacings along two directions in the common plane between the film and substrate.

A new type of epitaxy — which has been coined axiotaxy — was found in this study. In this case, only one set of planes between the film and substrate share the same lattice parameter. This results in one-dimensional periodicity between the film and substrate.

This new epitaxy appears common in many candidate silicides for device applications.

FIGURE 2.4 A collaborative project between researchers at the IBM T.J. Watson Research Center and Eric Stach at the National Center for Electron Microscopy (NCEM) resulted in the discovery of a new type of thin-film texture. Coined “axiotaxy,” this texture is characterized by the sharing of only one set of lattice spacings between the film and its growth substrate. Conventionally, texture is determined through the use of large-area x-ray diffraction “pole figures” that depict the relative orientation of crystalline grains in a material. In this work, researchers at the IBM Watson Research Center utilized pole figures obtained at the National Synchrotron Light Source. Surprisingly, in addition to evidence of conventional epitaxial texture, complex arcs of intensity in specific locations were seen, indicative of an unusual fiber texture. High-resolution electron microscopy was required to confirm the existence of this new type of texture. These samples presented several particular microscopy challenges that required the use of a unique microscope at NCEM: the 800 kV Atomic Resolution Microscope. This microscope has sufficient point-to-point resolution (1.6 Å), sample tilting capabilities (±45° along two orthogonal axes), and high voltage (for increased sample penetration of the strongly scattering nickel silicide layers) to produce atomic resolution images of these samples. Extensive microscopy confirmed the presence of both conventional epitaxial grains and grains with the new axiotaxy texture. Courtesy of the National Center for Electron Microscopy and the IBM T.J. Watson Research Center.

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in response to the needs of users, facilities choose either to specialize narrowly or to offer a broad suite of tools. A discussion of the means of acquisition of instrumentation and the type of instrumentation sought at midsize facilities follows:

- *Acquisition.* Most facilities tend to rely heavily on their major users to help acquire new instrumentation through grants from federal agencies. For example, a facility would agree to provide floor space and staff from its operating budget in exchange for management of the tool. The capital investments would be obtained from individuals or small groups of individual investigators who would submit grant proposals to federal agencies for acquisition of the new instrument. Successful grantees would transfer responsibility for the instruments to the facility, effectively "outsourcing" the operations, maintenance, and support of the instrument to the facility. In turn, the facility's operating budget would only have to cover the cost of maintaining and operating the equipment. This type of model was indicated to be common for facilities that specialize in suites of instruments such as clean rooms. Some investigators reported that this type of operating model made their proposals more competitive.

  It should be noted that promises of the purchase of costly instrumentation are also being used by universities as a means of attracting new faculty with start-up packages; the funds for these efforts are usually levied from various sources such as endowments or donor gifts or from federal reimbursement of indirect research costs. Whether this practice can be a viable long-term strategy for university facilities when overall federal funding in materials research is relatively flat remains to be seen, but it illustrates the extent to which universities are struggling to assist in the purchase of advanced instrumentation.
- *Character of instruments.* Some facilities focus on novel ("racehorse") instrumentation (see Figures 2.5 and 2.6), whereas others offer more basic equipment and services ("workhorse" instrumentation). Although racehorse instruments are often required for the most discriminating analyses, workhorse instruments serve broader communities and can act as feed-and-filter stages for the sophisticated racehorse instruments. For instance, a workhorse instrument may be invaluable for preparing samples or techniques for a more specialized instrument in a so-called hub-and-spoke arrangement.

  Outside materials science, a good example of this hub-and-spoke model was observed during the committee's site visit to the Lick Observatory near San Jose, California. The light-gathering power of the telescope at the Keck Observatory on Mauna Kea in Hawaii is far greater than are the capabilities

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FIGURE 2.5 Nuclear microprobe at the Center for Accelerator Mass Spectrometry at the Lawrence Livermore National Laboratory. Courtesy of the Center for Accelerator Mass Spectrometry.

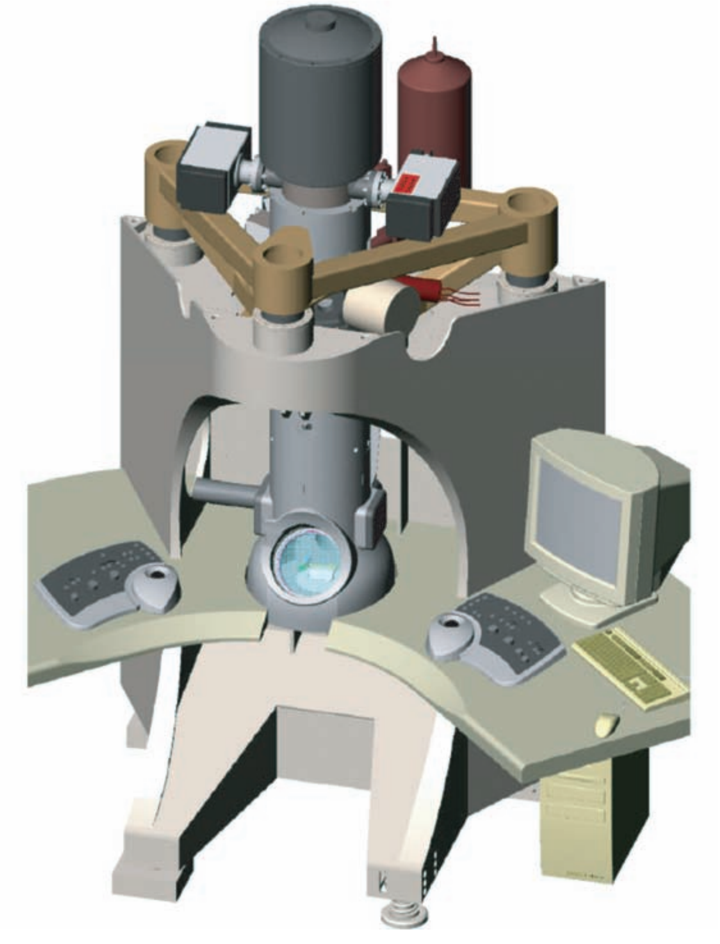

FIGURE 2.6 A generic "super scanning transmission electron microscope" from LEO Electron Microscope. Courtesy of Carl Zeiss SMT AG.

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of the telescope at Lick. To remain competitive, Lick management redirected the observatory's research to focus on two important activities: first, on providing sufficient observing time and support so that observers can test and tune their experiments at Lick before traveling to Keck for their final data gathering and, second, on providing longer observing time for measurements or discoveries first made at Keck. Lick Observatory has therefore become an important staging ground for observers taking advantage both of the Keck Observatory and of the Palomar Observatory. It has become an instrument development laboratory, as scientists can access the telescope more frequently and have greater freedom to develop new tools and techniques. Finally, Lick maintains a niche as a telescope that can provide extended access for measurements that integrate over many nights (for instance, monitoring the long-term evolution of a phenomenon discovered at Keck or Palomar).

Specialized Laboratory Environments and Services

In addition to investments in costly instruments, midsize facilities have also made significant investments in specialized laboratory environments and other enabling capabilities. Vibration-sensitive equipment such as lithography and imaging tools can require expensive remediation during laboratory construction in order to avoid problems such as mechanical vibration, stray magnetic fields, and electrical ground loops. Crystal growth chambers, thin-film deposition processes, and ion implantation systems often make use of materials that require chemical scrubbers, negative-pressure rooms, monitoring equipment, and industrial hygiene reviews and inspections and unique safety procedures. Many electronic device and materials studies require high-efficiency particulate air (HEPA)-filtered clean rooms and employ purified and deionized water in their preparation. Biological assay experiments can require ultrafiltration to reduce the total organic carbon and avoid interferences.

A laboratory renovation project for a single instrument with special environmental requirements such as those described above can cost several million dollars and involve significant zoning issues for universities. Clean-room construction, for example, exceeds $1,000 per square foot, and high-hazard clean space can approach $2,000 per square foot. This investment is often underappreciated, yet it is critical to achieving a required specialty environment or top performance from an instrument. Today's research tools cannot be treated as isolated, independent units.

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Maintenance and Upkeep

According to responses to the committee's questionnaire, some facilities, typically those having cutting-edge equipment and providing services to a broad user base, rely heavily on service contracts provided by equipment manufacturers. Other facilities reported that expert support staff are expected to perform routine service and maintenance. Some facilities reported that when their operating budgets become tight, maintenance or service contract arrangements with manufacturers are often identified as the first place to go to trim costs, which is clearly detrimental to the continued performance of the instruments. A few facilities identified the recruitment of expert technical staff from industry as a pivotal moment in their evolution—obtaining the ability to support their instruments independently was necessary for sustainable (and affordable) operation.

Users

Since it is by definition a multiuser operation, a midsize facility relies on its users as its core constituency. According to the facilities questionnaire responses, there is no specific correlation between the number of users of a facility and the operating budget beyond the generally positive one. Several different methods are employed to account for numbers of users and annual budgets, which could explain the lack of correlation.

Utilization of midsize facilities is generally dominated by local researchers (nearly 75 percent): that is, users come primarily from within the host organization (university, national laboratory, and so on) or from relatively nearby. The committee thus observed that midsize facilities appear to serve relatively small "regions."

One factor contributing to a lack of long-distance users is associated travel and accommodation costs; most facilities, even those that do not charge specific user fees for instrument usage, cannot provide support for travel. As a result, access to a facility by long-distance users is often limited by their ability to cover the travel expenses from their own research grants. Another factor, of course, is the time required to travel.

Details such as access, training, and operating hours that affect users and user numbers follow:

- *Access.* Most facilities open their doors to all qualified users. However, as competition for access has increased, facilities have developed more sophisticated screening procedures. The general screening criterion is "the highest-quality science." In extreme cases, users are required to submit proposals

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for peer review by a panel of experts; such procedures engendered delays of up to 6 months for access. Generally, however, users are required to employ online or on-site mechanisms to reserve tools in advance.

- *Training.* The degree of training necessary to use the equipment of a facility varies widely, depending on the level of sophistication and automation of the instruments. In simple cases, self-teaching is perceived as adequate. Most widespread is the model in which users are trained by resident staff and are then given access privileges. For the most complicated systems, complete operation by staff members is common, and often considered most desirable because of concerns about possible unintentional damage by an inexperienced operator.
- *Operating hours.* Some facilities emphasize 24-hour-a-day, 7-day-a-week operation and access. Other facilities have restricted access hours, often as determined by the host institution's assessment of safety and security. For facilities with 24-hour access, the users are usually required to complete a training sequence alongside facility staff in order to gain open access and operation privileges for the particular equipment of interest.

Education and Outreach

The midsize facilities that responded to the committee's questionnaire are estimated to impact a student population of greater than 7,000, with about 90 percent of this number using university-based facilities. These numbers clearly indicate that the overall impact of all midsize facilities on student education and training must be regarded as highly significant. Some facilities offer the formal instruction that is needed for the operation of their equipment and interpretation of results, while others offer individual, hands-on training at the instrument. Several sites offer opportunities for students and teachers participating in the Research Experience for Undergraduates and Research Experience for Teachers programs.

USER COMMENTS

Although the facility users' response rate to the committee's survey was modest, certain features bear mention. Users spent on average about 25 percent of their research time at midsize facilities, and over half used facilities sited primarily within their host institution. Respondents unanimously agreed that midsize facilities are critical enablers for their research. They cited reasons such as "better equipment than I have in my own laboratory," "allowed me to do measurements not otherwise possible," and "without this shared infrastructure and its maintenance and relevant training personnel, my research program simply couldn't function."

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All respondents were generally satisfied with their experiences at midsize facilities, although the leading concern was the age and upkeep of the instrumentation. Another point of widespread agreement was the belief that the capabilities of midsize facilities are not well known or advertised; the primary technique for finding out about midsize facilities was reportedly word-of-mouth at conferences from colleagues. Many respondents asked for a Web-based directory of services so that they could become more easily acquainted with resources in their own area.

Users' comments were varied with respect to the most important criterion determining their choice of which midsize facility to use. The comments ranged from "has the capabilities needed but without the operational costs, which are restrictive" to "proximity, provided the tools work" to "helpful staff willing to collaborate and train graduate students on state-of-the-art equipment." Most respondents cited technical capabilities and proximity to their home institution as important criteria determining their choice. Most users reported that while visiting facilities, they obtained assistance and research advice from the facility director or staff.

In response to the committee survey's question about "what level of cost would be prohibitive," respondents expressed the constraints that they felt in terms of costs to their research grants; a typical level of cost considered prohibitive is $100 per hour of use, so the desirable range is significantly less. Depending on the nature of the services required, the maximum lead time that researchers indicated they were willing to tolerate varies considerably, ranging from 6 months for nationally unique materials analysis studies to 1 to 3 days for access to certain microscopy facilities. In general, researchers preferred to travel to facilities that were close enough to keep the entire trip confined to 1 day. In fact, when seeking participants for its Materials Centers of Excellence program, the Army Research Laboratory used a geographical limitation of an approximately 400 mile radius to constrain the range of the institutions that could apply for funding as a team to form the center.[2]

In terms of budgeting for facility use, almost all users who responded to the survey reported that they had budgeted for user fees when developing funding requests, and all made specific mention of facility use as part of their research proposal. Most respondents indicated that they would ideally prefer about $10,000 per year to cover their facility usage. A simple calculation, assuming the $100 per hour usage cost (as an upper limit), suggests that the annual usage of facilities numbers in the hundreds of hours per year.

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[2] J.W. McCauley, K.T. Ramesh, and D.E. Neisz, "The ARL Materials Centers of Excellence: A New Model for Government-University Collaboration," presentation at 2004 International Nano Ceramics/Crystals Forum and International Symposium on Intermaterials, June 20-23, 2004.

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The most common suggestions from users are typified in comments such as, "It's hard to lump together midsize facilities . . . some exist to help users complete projects . . . others are more of a large group of scientists who collaborate together" and "[the provision of] ongoing support for small centers . . . [is needed] in order to provide staff to train users and keep instruments repaired" and "reinstate support for travel." One user enthusiastically suggested, "Strongly encourage universities to provide hard-money support for technical staff!"

SELECTED EXAMPLES

The committee presents the following examples mainly to illustrate the diversity in funding, funding sources, and level of operation of different midsize facilities.[3]

- The Center for Microanalysis of Materials at the Frederick Seitz Materials Research Laboratory at the University of Illinois at Urbana-Champaign is a large midsize facility, operating entirely without user fees, that is supported primarily by the host institution (70 percent)[4] and DOE (30 percent). With an annual operating budget of $1.5 million, it has 16 FTE staff members who provide support for materials fabrication, characterization, and measurement to roughly 600 users. The user demographics are graduate students (65 percent), government (20 percent), industry (10 percent), and undergraduate (5 percent). Users predominantly come from on campus (70 percent), but many of the remaining users travel significant distances. Clearly a relatively modest, consistent investment by DOE in a university-based facility has had significant positive impact. (See Box 2.1 for further discussion.)
- The Shared Experimental Facilities of the Center for Materials Research at Cornell University support research investigations of the NSF-funded Materials Research Science and Engineering Center (about 45 percent) and other, separately funded researchers on campus (about 45 percent) and off campus (about 10 percent). The facility has an annual budget of $1.2 million that comes primarily from user fees (70 percent) and federal sources (30 percent), a staff of 15 FTE, and roughly 450 users. The reported user demographics are graduate students (65 percent) and undergraduates (15 percent), with these users originating primarily on-site (90 percent).

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[3] Information presented in this section was collected through site visits, questionnaires, and private communication with facility directors, who reviewed the statements for accuracy.

[4] In this case, note that the host institution contribution is being indirectly provided in large part by the State of Illinois through the University of Illinois.

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BOX 2.1
Center for Microanalysis of Materials at the Frederick Seitz Materials Research Laboratory[a]

The Center for Microanalysis of Materials (CMM) is a user-oriented and user-friendly facility that provides the modern analytical capabilities essential to today's materials research efforts. Many researchers at the town hall meetings conducted by the Committee on Smaller Facilities in the spring of 2004 commented that the CMM is the leading analytical user facility in the country, also recognizing that the facility would be difficult to duplicate elsewhere. The CMM is one of four Department of Energy (DOE) Electron-Beam Microcharacterization Centers, and as a DOE Basic Energy Sciences user facility and collaborative research center, it is open to researchers from universities, government laboratories, and industry, nationwide as well as internationally.

The CMM is located in the Frederick Seitz Materials Research Laboratory (MRL) on the campus of the University of Illinois at Urbana-Champaign. The facility dates back to about 1965, when it was an Advanced Research Projects Agency (ARPA)-supported materials research laboratory. The facility was funded jointly by DOE and the National Science Foundation (NSF) for many years, but lost NSF core support altogether in about 1994. Overall NSF participation in the laboratory has since actually risen through the involvement of individual investigators.

The CMM emphasizes the microstructural and microchemical composition of materials, the chemistry and electronics of surfaces, crystal structures, phase transitions and defect structures of materials, and the relationship between the structure and the properties of solids. By using the center's services, materials researchers from academe and from industry can access 25 major instruments in the areas of electron microscopy, surface microanalysis, x-ray diffraction, and backscattering spectroscopies (see Figures 2.1.1 and 2.1.2). The breadth of instrumentation available through the center enables researchers to find the best instrumentation techniques for their specific needs.

The CMM's annual operating budget (in 2004) is about $1.5 million, about 33 percent of which is provided directly by DOE's Office of Basic Energy Sciences; the remainder is provided through the university by the state (the facility's director estimates that the operating budget is closer to $2.2 million when including fringe and other personnel benefits covered by the university). The university waives overheard charges on the federally contributed funds. The 2004 operating costs break down as follows: 70 percent for staff salaries, 5 percent for service contracts, and about 25 percent for maintenance and supplies. A separate capital equipment budget provides about $1.2 million each year, shared between DOE and the university.

The CMM provides an extensive suite of equipment, including secondary ion mass spectrometers (2); an Auger electron spectrometer (1); x-ray photoelectron spectrometers (3); transmission electron microscopes (TEMs) (6); scanning electron microscopes (3); x-ray diffractometers (5); a focused-ion beam (1); scanning probe microscopes (5); a low-energy electron microscope (1); and ion accelerator instruments (2). The total replacement cost is estimated to be more than $50 million.

The CMM staff consists of about 12 Ph.D.- and M.S.-level members and 4 highly trained technicians. In the words of the director, the "system would collapse without technical staff." The technicians do the majority of the maintenance work,[b] and so maintenance contracts with the manufacturers are generally not required. The center is staffed with experts in each technique who teach researchers so that they can operate the instruments to conduct their own measurements. Licensed users have 24-hour access to the instruments. CMM staff members also provide guidance, consultation, and collaboration in the microanalysis of materials.

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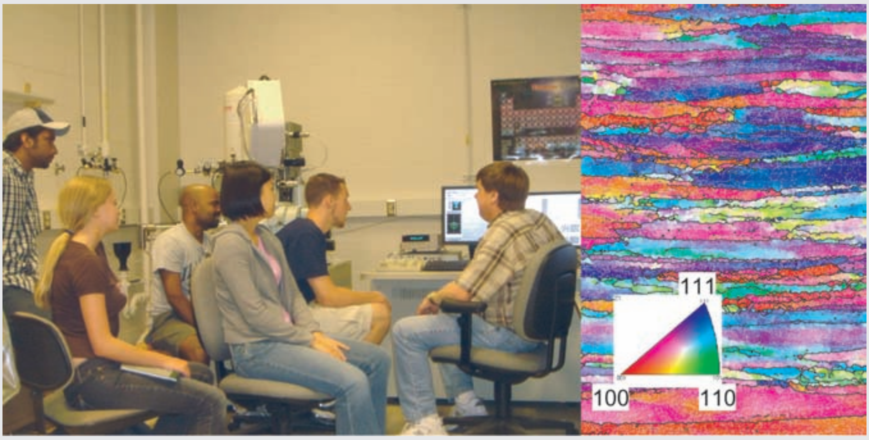

FIGURE 2.1.1 (Left) Dr. J. Mabon conducts a teaching session on an analytical scanning electron microscope at the Center for Microanalysis of Materials. (Right) An electron backscattered diffraction orientation map of an Al-Li alloy. Such texture maps are used to determine the critical orientation mismatch that results in the delamination of adjacent grains. The colors of the diffraction orientation map correspond to the crystal plane orientations of the alloy particles as indicated by the inset in the lower left corner. Results courtesy of R.J. McDonald, J.C. Mabon, A.J. Beaudoin, and P. Kurath. Photo courtesy of Center for Microanalysis of Materials, University of Illinois at Urbana-Champaign.

The CMM does not charge user fees. Before 2000, user fees were in effect and ranged from $10 per hour for x-ray diffraction to about $100 per hour for TEM usage; such fees provided support for perhaps two-thirds of the CMM operations budget. When user fees were dropped, the gap in support was filled by direct funding from DOE and the university. It is worth emphasizing that instrument usage has since doubled in 2 years and tripled in 4 years. For the required recovery of costs from industrial users, fees range from $150 to $250 per hour.

The MRL carefully records the CMM's usage both in terms of individual users and hours of individual instrument usage. For fiscal year (FY) 2004, it reported more than 60,000 hours of use (in 16,000 sessions); 46 percent of this usage was by MRL-affiliated faculty and staff, 35 percent by other campus users, and 14 percent by other national laboratories and industrial researchers. The total number of individual users for FY 2004 was just over 600, 30 percent of whom came from outside the university; of those 30 percent, 1/5 are from national laboratories, 1/5 are from industry, 1/5 are international users, and 2/5 come from other universities. The remaining 70 percent or so of the users are from on campus but account for more than 80 percent of the usage. There is an increasing number of off-site users. More than 300 users

continued

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BOX 2.1 Continued

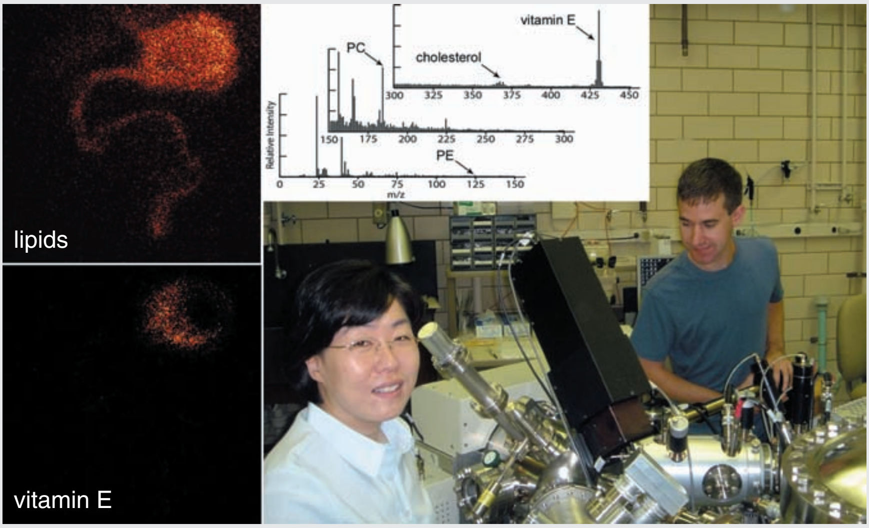

FIGURE 2.1.2 At the right, graduate student E. Monroe and staff scientist Dr. J. Lee (left) have identified the spectroscopic signature of vitamin E at the CMM and obtained the first images revealing the subcellular distribution of vitamin E (bottom left) in the neuronal lipid membrane (top left) by utilizing time-of-flight secondary ion mass spectrometry (TOF SIMS). The TOF SIMS mass spectrum of vitamin E is shown in the top center panel. Courtesy of E. Monroe, J. Lee, and the Center for Microanalysis of Materials.

were trained in 2004 alone. Thus, the CMM acts as the largest "supplier" of scientists and engineers educated in the use of advanced instrumentation for materials research.

MRL managers identify three key ingredients for a successful midsize facility: trained and competent staff, diverse and well-maintained equipment, and open and welcoming access policies. Their greatest concern is the stability of long-term funding.

For the future, the CMM sees its next major purchase as a Cs-corrected TEM with enough space in the objective lens to provide for versatile in situ experiments at very high resolution. The estimated cost is $4 million to $5 million and is expected to be funded as part of the DOE TEAM (Transmission Electron Aberration-corrected Microscope) project, or perhaps otherwise. In addition, a significantly increased proportion of biological and biomaterials use is envisaged. Clearly there are many insights into successful multiuser facilities from a study of this operation.

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[a] This box is based on material supplied by I. Petrov, director, Center for Microanalysis of Materials, May 2005.

[b] Some have speculated that the rural location of the university and its associated demographics have empowered such able-bodied and highly skilled staff.

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- The Shared Equipment Authority at Rice University is a larger midsize facility supported primarily by the host institution (62 percent) and user fees (38 percent). With an annual operating budget of $650,000, it has 6 FTE staff providing support to about 140 users. The user demographics are graduate students (90 percent) and industry (10 percent), and they originate on-site (89 percent), locally (10 percent), and regionally (1 percent). This campus-wide effort serves as an interesting model for connecting existing resources into a larger enterprise that is coordinated and centrally planned, not unlike a small-scale regional network of facilities. (See Box 2.2 for an extended discussion.)
- The W.R. Wiley Environmental Molecular Sciences Laboratory (EMSL) at the Pacific Northwest National Laboratory is a multipurpose laboratory that provides national computing, nuclear magnetic resonance (NMR), spectroscopic, and nanoscale characterization services. Users engaged in open research generally are not charged for using EMSL facilities or equipment. The facility serves more than 1,600 users per year, with an annual operating budget of about $40 million. EMSL serves both the adjacent DOE laboratory and users from around the country. As many of its facilities, such as those for high-field NMR, are unique, it attracts users from the entire country—serving as more than just a "regional" facility. Furthermore, because of its role within DOE, it aspires to having an international reputation for its research rather than simply serving the Northwest. (See Box 2.3 for more information.)
- The Keck Microfabrication Laboratory at Michigan State University is a small midsize facility supported by the host institution (80 percent) and user fees (20 percent). Its operating budget is about $100,000, and it has 1 FTE staff member who provides support for 20 users, of whom 90 percent are graduate students and 10 percent are undergraduates.

ESSENTIAL QUALITIES OF SUCCESSFUL MIDSIZE FACILITIES

Based on the site visits made for this study and on the committee members' own experiences, it has become clear that midsize facilities generally recognized as being successful share a number of the following key characteristics:

- Contain well-maintained equipment that facilitates both routine and state-of-the-art research;
- Incorporate a mix of permanent scientific and well-trained technical staff;
- Provide open and reasonable access with clear guidelines for the particular user community;

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BOX 2.2
Rice University's Shared Equipment Authority[a]

In 2001, the science and engineering faculty of Rice University collaborated on developing a proposal to the university administration for coherent, systematic, and unified support of their facility and instrumentation needs. The university accepted the proposal, and the Rice Shared Equipment Authority (SEA) was formed. The SEA is not a centralized facility per se; rather, it is a mechanism for the centralized management of distributed resources across the campus. It is managed through a faculty committee that sets user rates and policies through consensus-based governance.

The SEA Board consists of 19 faculty members, 5 technicians, and 2 administrative staff. The SEA has an annual operating budget of $650,000, of which 62 percent is derived from the host institution and 38 percent from user fees, and represents a replacement capital investment of more than $13 million. The host institution covers the salaries of the 6 FTE technical and administrative support staff. At present, more than 140 different users access the SEA per year, 90 percent of whom are affiliated with Rice directly. There are many useful insights to be gained by a careful review of the proposal prepared by the SEA.

The SEA provides service in sophisticated research equipment and facilities at an affordable cost to all members of the Rice University community. It also provides support and open instrumentation usage to outside companies, nanotechnology start-ups, and other universities based on availability. The creation of this service center infrastructure and management has enabled Rice and its faculty to become innovative leaders in the fields of photonics, bioinformatics, nanotechnology, and environmental systems.

Currently the Rice SEA supports more than 50 instruments—in x-ray diffraction, optical microscopy, electron microscopy, optical spectroscopy, nuclear magnetic resonance, mass spectrometry, thermal analysis, scanning probe microscopy, clean rooms of class 100/1000, and micro-/nanofabrication (see Figure 2.2.1). Under the SEA these instruments are maintained by full-time, professional technical staff, supported directly by the university. The professional staff scientists provide a variety of assistance in operating, training, maintenance, sample preparation, and safety procedures to all users.

A key component of the successful initiation of this university-wide transformation was a careful analysis by the SEA board of the issues at its institution and the preparation of a 5-year strategic plan, excerpts of which are reprinted below.[b] In a policy statement that accompanies

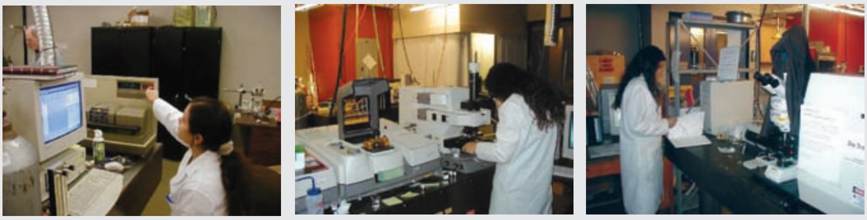

FIGURE 2.2.1 Several instruments included in the Rice SEA are (left to right) a thermogravimetric analyzer with infrared spectroscopy, a Fourier transform infrared microscope, and a Raman microscope. Courtesy of Rice University Shared Equipment Authority.

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the strategic plan, the SEA describes procedures for acquiring new instruments, setting user fees, managing equipment usage, and replacing underused or underperforming instrumentation.

Rice aims to be an international leader in the emerging interdisciplinary areas of nanotechnology, biotechnology, information technology, and environmental research and identified its infrastructure as a key component to success:

> To take full advantage of [its] investment in interdisciplinary research, Rice must develop its research infrastructure. Facilities that support electron microscopes, magnetic resonance spectrometers, and clean rooms, for example, are the necessary framework that supports any nano-bio-info-enviro research program. They are the bricks and mortar tools that will make it possible for Rice's faculty to become leaders in the new areas of photonics, bioinformatics, nanotechnology and environmental systems.

The expenses of shared equipment fall into three categories: maintenance, staff support, and equipment acquisition. The Rice SEA board broke its budget into these categories (see Table 2.2.1). An important observation, however, is that maintenance and staff alone represent nearly a quarter of the anticipated needs.

TABLE 2.2.1 Rice Shared Equipment Authority Budget, 2001-2006, by Category

Category	Total 5-Year Cost ($)	Fraction of Total
Maintenance	1,160,050	0.09
Staff	1,908,048	0.14
Equipment acquisition	10,193,572	0.77
Total	13,261,670	1.00

As presented below, the Rice SEA board factored its strategic plan into three areas—management, policy, and fund-raising:

> *Objective #1. Management: Create and nurture campus-wide faculty oversight of shared equipment planning and administration.*
>
> Current climate: Faculty that critically depend on shared equipment are very reluctant to share control over these instruments. Many feel that their research programs will suffer unless they have nearly complete authority over user policies, fees and administration. As a result, small faculty groups and departments will set up "fiefdoms" to operate instrumentation for their own particular interests; this results in an enormous duplication of space, staff and maintenance resources. For example, this university has invested over the past 5 years in the acquisition and maintenance of 8 x-ray diffractometers, two in the last three months alone; these machines are spread among four departments with varying levels of public access and faculty oversight. Similar duplications exist for scanning electron microscopes, nuclear magnetic resonance instruments and GC-MS systems. It is true that for many of these techniques, the specific user base (i.e. biologists as opposed to chemists for example) requires separate instruments with different capabilities. However, these distinctions are becoming less pronounced in the new interdisciplinary paradigm while the duplication of efforts continues to waste valuable resources.
>
> Future Goals
>
> - Establish and support an interdepartmental, interdivisional faculty oversight group charged with the management of shared experimental equipment resources. The deans of science

continued

BOX 2.2 Continued

and engineering in 2001 started the shared equipment authority to begin the process of developing faculty trust in institution-wide infrastructure management.

- Form smaller sub-groups out of SEA to handle detailed decision making on particular instruments, and include in these groups any interested faculty. SEA has begun this process by starting user groups for many shared instruments.
- Mandate the SEA to submit budget requests annually to the deans.
- Provide staff, administrative and financial support for SEA.

Recommended Policy Changes

- The management of shared experimental equipment should be split from that of shared computing equipment.
- Decisions to add existing instruments to the list managed by this group should be voluntary, and SEA should receive additional resources as its management efforts expand.

Objective #2. Policy: Revise institutional policy on cost centers to allow for more efficient management of shared research equipment.

Objective #3. Fundraising: Raise funds, through both federal and private sources of funding, for shared equipment acquisition and maintenance.

Here at Rice, user fee revenue has traditionally not offset the instrument costs in most cases. The reasons for this are twofold: first, Rice is a small campus with relatively few faculty compared to other private research institutions. Thus, the on-campus user base is small and most instruments while essential for conducting research are used at only 40-60% capacity. Second, for much of the shared equipment there has been no staff support for upkeep and training. Given the university culture, staff are awarded to departments to maintain internal instruments. Shared equipment has had no lobby for institutional support, and thus no staff. As a result, there is no mechanism for training users or keeping instruments well maintained. This has resulted in significant downtime on instruments (the TEM was down over 20% of the time one year) which inhibits the development of a stable user group. Limited staff support has also curtailed our ability to attract external users. Thus, we estimate slightly more than half of the instrument maintenance costs can be realistically gathered through user fees.

The SEA board convinced the university that it should fund hard-money staff positions to supervise the maintenance of shared equipment and user training. In return, the SEA ensured that the equipment would pay its own way and that the facilities would be of as broad use to the university community as is reasonably possible. The hard-money staff positions were important in enabling the SEA to hire some superb staff. On the university research scale of use, there was simply no way to recover professional staff salaries from user fees. The implementation of the SEA plan overcame the traditional territorial concerns of individual investigators once it was realized that the SEA would serve the common good. It has dramatically improved the operations of several instruments by providing for standardized training and maintenance; no one department or principal investigator is in charge; and the people who pay are the people who use the facilities, meaning that there is no arbitrary tax on nonusers to support the instruments, except in the most indirect sense through the university.

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[a] This box is based on material supplied by V. Colvin, director, Shared Equipment Authority, January 2005.

[b] Excerpts in this section are reprinted from the Rice Shared Equipment Authority's "5 Year Strategic Plan," publicly available online at http://www.ricesea.org/plan; last accessed June 1, 2005.

BOX 2.3
W.R. Wiley Environmental Molecular Sciences Laboratory[a]

The W.R. Wiley Environmental Molecular Sciences Laboratory (EMSL), operated by the Pacific Northwest National Laboratory for the U.S. Department of Energy and located in Richland, Washington, helps educate students and scientists to meet the demanding multidisciplinary challenges of the future.

Challenges to explore alternative energy products are leading to studies of new and innovative materials. Solid oxide fuel cells are just one possible "clean" energy source, and the specialized instruments at EMSL are being used to explore these types of designer materials.

With six topical facilities and more than 130 staff, EMSL capabilities include more than 12 nuclear magnetic resonance spectrometers, arrays of surface deposition and analysis tools, and mass spectrometers, as well as computational resources (Figure 2.3.1). The EMSL supercomputer is among the top 20 in the world, and the 900 MHz nuclear magnetic resonance spectrometer is one of the highest-field wide-bore instruments in operation worldwide (see Figure 2.3.2).

A multidisciplinary user facility, EMSL makes its instruments and staff expertise accessible worldwide through a peer-reviewed proposal process. Since operations began in 1997, EMSL has benefited more than 5,500 researchers on topics ranging from chemistry and nanocatalysis to proteomics and materials science. Many EMSL instruments are one-of-a-kind, developed

FIGURE 2.3.1 Shown (left to right) are Environmental Molecular Sciences Laboratory (EMSL) students T. Kaspar and A. Tuan and EMSL staff member S. Chambers, with the photoelectron spectrometer connected to EMSL's Molecular Beam Epitaxy (MBE) I system, which was based on the MBEII prototype and recognized by the 2002 Federal Laboratory Consortium Excellence in Technology Transfer Award with Motorola. Courtesy of the Environmental Molecular Sciences Laboratory.

continued

BOX 2.3 Continued

FIGURE 2.3.2 Many unique instruments developed at the Environmental Molecular Sciences Laboratory (EMSL) make technology more accessible to the scientific community. The flexible control system for ion trap mass spectrometers can be built at a fraction of the cost of commercial products. Here, EMSL researcher K. Swanson is shown with the Asymmetric Ion Trap Mass Spectrometer (patent pending), which was developed by EMSL and Pacific Northwest National Laboratory staff members S. Barlow and M. Alexander. Courtesy of the Environmental Molecular Sciences Laboratory.

through teamwork between researchers and the scientific and technical staff of EMSL to address ambitious scientific questions.

Researchers participate in activities individually or as members of large, multiuser teams. The synergy of these teams—composed of experts from diverse focus areas—enables solutions for scientific challenges previously considered insurmountable.

EMSL provides a problem-solving environment of advanced instrumentation and computational tools to scientists engaged in research on physical, chemical, and biological processes in pursuit of the nation's most difficult and critical scientific challenges. Individuals and teams of researchers around the world draw upon the unique capabilities at EMSL to advance scientific breakthrough and discovery (see Figure 2.3.3).

In March 2004, the National Science Foundation (NSF) and EMSL created a formal affiliation and instituted a grant program. University students, faculty, and postdoctoral users of

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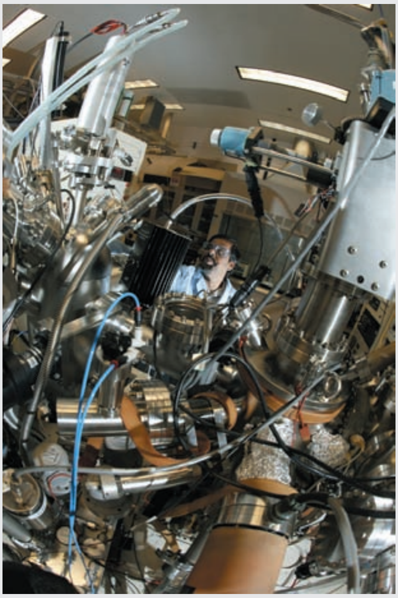

FIGURE 2.3.3 High-quality thin films and nanostructure prototypes are grown molecule by molecule, providing insights into development of new designer materials. Here, Environmental Molecular Sciences Laboratory Technical Lead T. Thevuthasan is shown with the Molecular Beam Epitaxy II, a prototype that was developed by EMSL researcher S. Chambers. Courtesy of the Environmental Molecular Sciences Laboratory.

EMSL resources and instrumentation can apply and receive up to $20,000 annually from NSF for travel and lodging expenses. The grants are to be awarded to those scientists whose research is supported by NSF programs in the directorates of Biological Science, Computer and Information Science and Engineering, Mathematical and Physical Sciences, and the Office of Polar Programs. The program is intended to jump-start the efforts to increase the impact of EMSL's user program, broaden its user base, and foster research partnerships with universities throughout the nation.

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[a] This box is based on material supplied by A. Campbell, director, Environmental Molecular Sciences Laboratory, May 2005.

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- Focus their attention on sending users back to their home institutions with high-quality, useful data;
- Engage in critical self-assessment, and consider it important to have mechanisms for taking account of feedback from users;
- Enjoy stable, long-term funding source(s), with local institutional support;
- Are often enhanced by having an enthusiastic and broad user base;
- Are directed by effective and energetic management; and
- Advance the technology (instrumentation and/or techniques and/or applications) through the operation of the facility.

The committee found several instances of successful facilities that are characterized by high-level recognition and backing (with funding) from the host institution. For example, at the Lawrence Livermore National Laboratory, the Center for Accelerator Mass Spectrometry is supported in part by laboratory director funds; at Northwestern University, NUANCE (Northwestern University Atomic and Nanoscale Characterization Experimental Center) is supported in part financially from the university president's office. The committee cannot overemphasize the importance of a clear and well-defined role for the host institution in the success of a midsize facility. The level and type of commitment from host institutions vary widely, but its presence was a constant in all of the facilities that the committee visited.

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3

Challenges for Midsize Facilities

The capabilities of new instruments are advancing at a remarkable rate. Such instruments enable and are essential to significant advances in materials research and development. But two competing trends are apparent when considering facilities that support the materials research enterprise: (1) Capital costs as well as the costs of maintenance and support are escalating to such an extent that individual institutions are experiencing serious difficulty in providing equipment to their user base and also maintaining it at a state-of-the-art level. (2) Individual sophisticated machines are becoming easier to operate, opening them up to a wider range of users and providing useful data more quickly and efficiently; in other words, automation is more common (for example, in x-ray diffractometers or scanning electron microscopes), but interpretation of the data acquired can be more difficult.

As facilities become increasingly sophisticated in structure and content, they require a complex network of support to maximize their effectiveness. As best put by the National Science Board in its recent report *Science and Engineering Infrastructure for the 21st Century*, "The current 22 percent of the NSF [National Science Foundation] budget devoted to infrastructure is too low to provide adequate small- and medium-scale infrastructure."[1]

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[1] National Science Board, *Science and Engineering Infrastructure for the 21st Century: The Role of the National Science Foundation*, NSB 02-190, Arlington, Va.: National Science Foundation, 2003, p. 2.

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LONG-TERM VIABILITY

Midsize facilities provide a stable and user-friendly interface between much of today's most advanced instrumentation and the research community. A core challenge for midsize facilities is that of maintaining their infrastructure for the long term in order to fully exploit the initial capital investments (often in the tens of millions of dollars in aggregate). Midsize facilities operate best with long-term commitments. Because these facilities necessarily outlast (and transcend) the single investigator's research project, their sustenance must come from sources that are more stable and long term than is an amalgamation of individual users with an overlapping need. This challenge is especially acute for smaller schools that often do not have the administration and management overhead or experience to develop a sustainable plan for the long-term operation of a midsize facility.

Diverse and Stable Funding

Funding sources for existing successful facilities are highly diverse and often depend on the local environment and the resourcefulness of the persons involved. Funding may come from a combination of federal and state government support, institutional funds (whether state or private), user fees, and donations. Funding is one of the most significant challenges facing midsize facilities for the following reasons:

- The escalating costs of instrumentation make it more and more difficult to identify sources of funding for the initial capital investment.
- The changing landscape of cost-sharing requirements for federal grants has placed many institutions at a disadvantage for securing the initial capital funds.
- In addition to the initial capital investment, a plan for stable long-term funding is necessary to cover the plethora of recurring expenses involved in sustaining facility operations.

The escalating cost of obtaining, operating, and maintaining advanced instrumentation is one of the greatest challenges facing materials research. Instrumentation typically evolves in several directions: it simplifies certain experimental procedures, it automates and standardizes certain techniques, or it provides entirely new functionality and capability through innovation. These forces tend to escalate the cost of instrumentation because of the substantial enhancements in capabilities provided. A common observation is that the cost of flagship tools has increased over time well beyond standard inflationary rates. See Box 3.1, "Escalating Costs of

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Instrumentation," for several examples. Critical equipment is routinely so expensive that a sophisticated organization for promoting the utility of and access to the equipment is required in order to make it worth the capital investment. As capital costs rise, so do the long-term maintenance and operations costs.

In terms of the initial accumulation of funds, a major issue identified is that of cost sharing for the acquisition of expensive equipment. Cost sharing is usually a standard requirement for funding by federal agencies, but the proportion is highly variable and has recently been removed entirely! For example, the NSF cost-sharing requirement increased from 0 to 30 percent over the past few years and has just recently been reduced again to 0.[2] For a $1.5 million transmission electron microscope (TEM), this cost-sharing requirement amounted to as much as $450,000. Meeting such an obligation would be a major obstacle for smaller institutions. Although the committee recognizes that an important objective of cost sharing was to encourage the host institution to be more responsible and committed to the facility, it observes that these financial requirements had become a serious barrier for some institutions wishing to participate.

In its recent announcement, the National Science Board approved the removal of all cost-sharing requirements for major awards and grants.[3] On the one hand, this change will help level the playing field by allowing institutions with fewer resources to compete more equitably with larger schools, but on the other hand, this change effectively decreases the buying power of NSF's grants by up to 30 percent. Investigators no longer have the leverage to entice host institutions to put in their own money, which would often have entrained other forms of institutional (and moral) support. As a result, fewer resources will likely be directed to facilities' infrastructure. Alternatively, institutions with access to additional resources may voluntarily choose to continue to use these resources in order to maintain the institution's preeminence and leadership position. Additionally, suitable incentives to encourage institutions to team up as partners may go a long way in overcoming limited funds and the consequent loss or denial of opportunities to participate in groundbreaking materials research.

A conservative estimate of (recurring) support costs for a $2.0 million instrument such as a focused-ion beam or a secondary ion mass spectrometer (SIMS) would have three components:

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[2] National Science Board, *Memorandum to Members and Consultants of the National Science Board,* NSB 04-157, Arlington, Va.: National Science Foundation, 2004, p. 2.

[3] National Science Board, *Memorandum to Members and Consultants of the National Science Board,* NSB 04-157, Arlington, Va.: National Science Foundation, 2004.

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BOX 3.1
Escalating Costs of Instrumentation

Nuclear Magnetic Resonance Spectrometers

Nuclear magnetic resonance (NMR) is a technique used by many researchers, often for determining the structure and the relationship between chemical components of a substance (see Figure 3.1.1). Through the first half of the 1980s, the cost of state-of-the-art high-field NMR instruments with a standard bore size was approximately $1,000 per megahertz (MHz). Thus, a 300 MHz instrument was priced at about $300,000, and a 500 MHz spectrometer (the highest-field NMR instrument commercially available at that time) sold for about $500,000. Wide-bore magnets often used in solid-state NMR were more expensive, but the cost increases experienced for spectrometers with these magnets have been similar to those outlined below.

When the new-generation 600 MHz instruments incorporating a higher-field magnet were introduced in the mid- to late 1980s, their price was over $1 million. This change represented a significant increase in the cost per megahertz for instruments operating at this higher frequency. The cost for the lower-field spectrometers also increased as a result of technology advances, but the increases were modest, on the order of 10 percent.

The next step up in frequency occurred in the mid- and late 1990s, when 750 MHz and then 800 MHz magnets were developed. Spectrometers incorporating these magnets were priced in the $2.0 million to $2.4 million range, another major jump in the cost per megahertz ratio. Later, in 2002, the first commercial 900 MHz systems were sold, with a price tag of approximately $5 million, representing another very significant jump in price. These trends in instrument pricing are illustrated in Figures 3.1.2 and 3.1.3.

Throughout the period of the 1990s to the present, the cost of the lower-field instruments, which have become workhorse spectrometers, remained roughly constant, although their capabilities increased. As each high-field magnet was developed, however, it provided increased sensitivity and resolution, which in turn enabled new-frontier research. Thus, despite the escalating costs, these instruments were attractive additions to shared instrumentation resources, and in fact they were essential for facilities concerned about providing state-of-the-art capabilities for users.

In the NMR area, another essential accessory, NMR probes (see Figure 3.1.1), also experienced significant price escalation as they incorporated incremental technical advances. The probe fits in the magnet and measures the NMR signal, which is the molecular signature of the sample being studied. In the 1980s, probes for solution NMR cost $12,000 to $15,000 each. During the mid-1990s, they were priced at around $20,000, and in 2005 they were $30,000 to $35,000. Probes with totally new designs that have been developed during the past 5 years to help enable innovative research are priced even higher. Microcoil probes range from $50,000 to $75,000, and cryogenically cooled probes, which were introduced at $180,000 in 2000, now are priced at $275,000 to $350,000. Well-equipped research instrumentation resources need these capabilities to support competitive programmatic research.

Secondary Ion Mass Spectrometers

Secondary ion mass spectrometry (SIMS) is a standard tool in the characterization suite of a materials research laboratory. A leading manufacturer of SIMS instruments is CAMECA, a company based in France. As Figure 3.1.4 shows, the average purchase price for popular configurations of SIMS instruments has steadily increased.[a] Note, however, that even after correcting for

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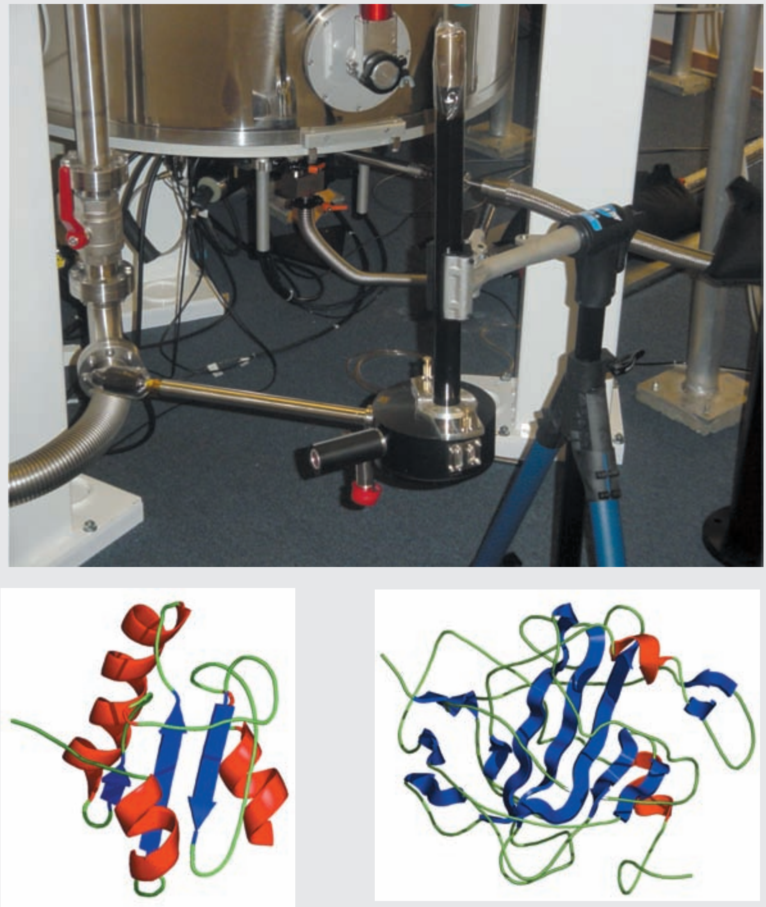

FIGURE 3.1.1 (Top) Cryogenic probes with ultrahigh-field NMR magnets enable efficient structural characterization of biomaterials (biological polymers or biological macromolecules). Pictured here is a Varian, Inc., cryogenic probe next to an 800 MHz NMR magnet that also has a cryogenic probe installed. Also shown are ribbon diagrams of the backbone structures (bottom left) for a functional mutant protein of thioredoxin (L78K), which to date has resisted crystallization, and (bottom right) for human carbonic anhydrase II, a 29 kilodalton enzyme. These structures were determined in solution by NMR to 0.22 nm and 0.29 nm resolution, respectively, using very high sensitivity probes such as the one pictured. Courtesy of Duke University Nuclear Magnetic Resonance Center.

continued

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BOX 3.1 Continued

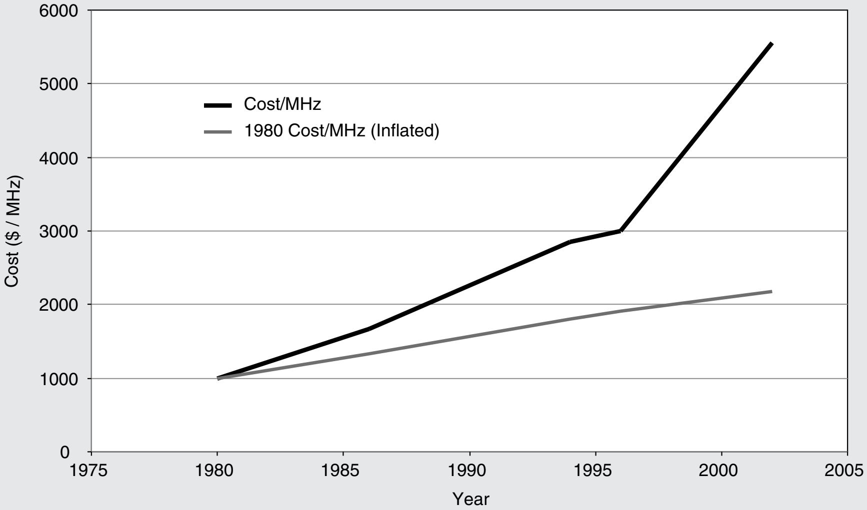

FIGURE 3.1.2 One measure of the capability of an NMR spectrometer is the frequency response of hydrogen in megahertz (MHz). Higher magnetic fields allow higher-precision measurements at higher frequencies. In this figure, the cost per megahertz of the highest-magnetic-field instrument available is shown over the past 20 years by the top line. The cost year-by-year is shown and compared to the Consumer Price Index-inflated cost of the 1980 500 MHz machine (bottom line).

inflation (as estimated from the Consumer Price Index) to measure the cost in constant dollars, the instrumentation's average cost grew significantly in the 1980s. This growth coincided with the introduction of significantly enhanced functionality. SIMS characterization techniques were first introduced in the 1950s but were not commercialized until the 1970s. The initial configurations were fairly simple. The first instruments incorporated a large-beam oxygen or cesium primary ion source (not mounted simultaneously) and a simple electron-beam neutralization gun. Over the ensuing years, key advances were made to the system, including the following:

- Primary beam mass filter, which improved the primary ion beam purity and allowed the simultaneous mounting of two ion sources;
- Ion sources and ion optics that allowed microfocusing of the primary beam;
- An improved charge neutralization system for bulk insulators;
- Dramatic improvement in the quality of the vacuum, permitting better detection limits for the atmospherics; and
- Sample rotation for improved depth resolution.

The foregoing discussion concerns the evolution of what might be considered the main-

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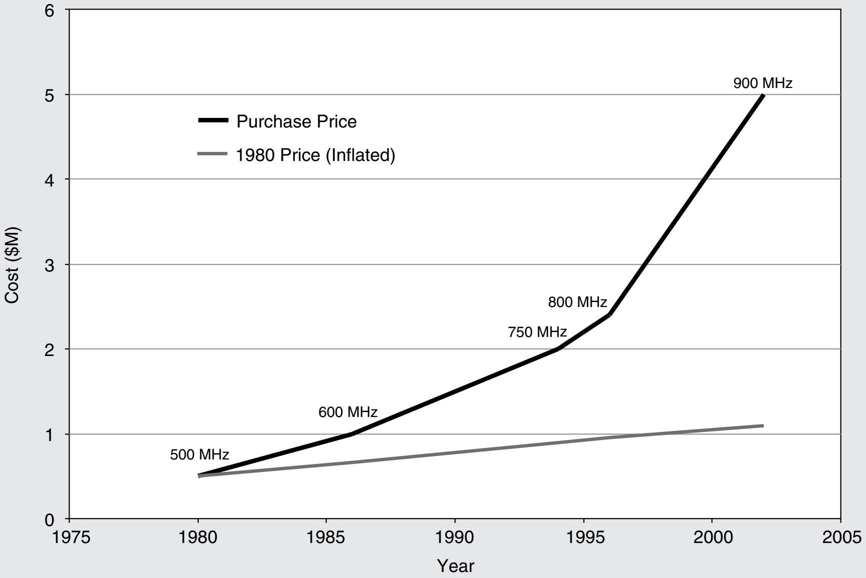

FIGURE 3.1.3 The purchase price of the highest-field NMR instruments—from 500 MHz to 900 MHz systems—when they became commercial products over the past two decades (top line). For comparison, the Consumer Price Index-inflated price of the best machine in 1980 is shown (bottom line). As higher-field magnets were introduced, the cost of these instruments has increased in major increments.

stream SIMS depth profiling instrumentation. Over the past 10 to 15 years, other configurations of SIMS instruments have become available to the materials research community. These include the following:

- Time-of-flight SIMS for sensitive, near-surface analysis of elemental and molecular species;
- Quadrupole SIMS designed for high-resolution depth studies and extremely low bombardment energies;
- Very large geometry instruments for sensitive, in situ isotopic ratio measurements;
- Specialty optics for submicron imaging, <50 nm resolution, with parallel detection for precise isotopic ratio measurements; and
- The coupling of MeV accelerators, for molecular ion fragmentation, to conventional SIMS instrumentation to measure very low-lying, non-naturally occurring (generally radioactive) isotopes.

Again, a caveat: the last three embodiments are very specialized and more sophisticated

continued

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BOX 3.1 Continued

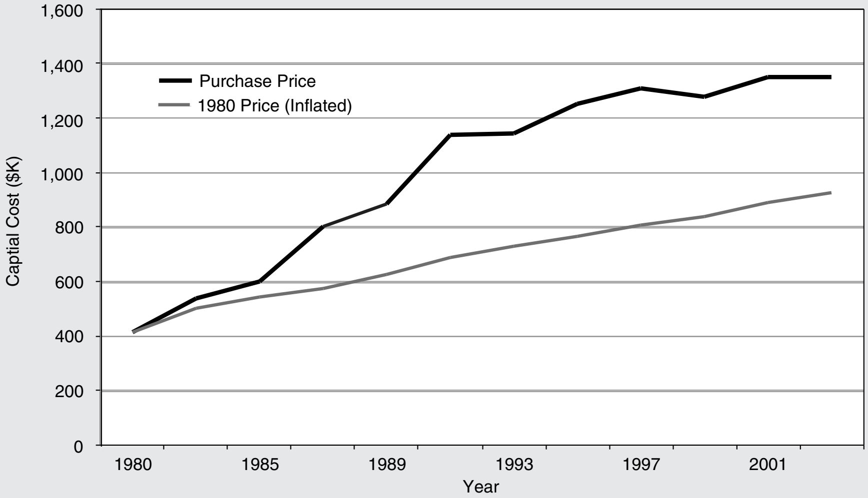

FIGURE 3.1.4 History of the average purchase price of top-selling secondary ion mass spectrometry (SIMS) instruments over the past approximately two decades. The cost year-by-year is shown (top line) and compared to the Consumer Price Index-inflated cost of the instrument package, circa 1980 (bottom line). The growing separation in the two trajectories indicates that the increase in the purchase price is driven by much more than just inflation. Note, however, that in some instances, the purchase price of SIMS instruments actually dropped, indicating that without the introduction of enhancements and new capabilities, instrumentation becomes more inexpensive as time passes.

than are the conventional analytical SIMS instruments. As such, they are much more expensive, with accelerator-based configuration generally built as a one-off, custom instrument.

Electron-Beam Lithography Systems

In 1981 a group of researchers in microfabrication at Bell Laboratories began requesting proposals from vendors to build an electron-beam lithography tool that combined a high-voltage, high-resolution electron column with the precise scanning and the field stitching capability made possible by a laser interferometer controlled stage. The result was that in 1985 a Japanese company, JEOL, shipped its first JBX 5DII, a 50 kiloelectronvolt (keV) system with a 3 inch x-y stage, to Holmdel, New Jersey. The price tag was about $1.3 million. The PDP 11 computer that controlled the system cost about $200,000. Since that time computers have become less expensive, but electron-beam systems have not. The cost of the electron-beam

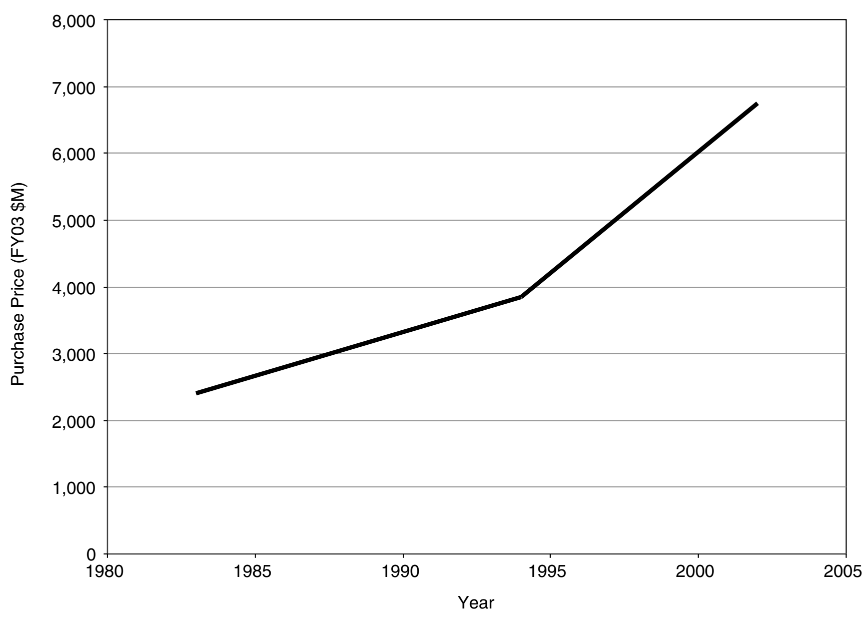

FIGURE 3.1.5 History of typical costs of electron-beam lithography machines over the past 20 years.

system has steadily grown as the high-precision stages have been required to accommodate first 4 inch, then 6 inch, then 8 inch, and soon 12 inch wafer sizes. In addition, vendors have included higher-brightness electron sources (e.g., thermal field emitters), which require ultra-high vacuum column components. Deflection amplifiers and scanning rates have improved from 2 MHz then to 50 MHz today. Nanolithography researchers have pushed for higher accelerating voltages to improve image resolution and contrast in order to explore ever-finer fabrication frontiers, and optoelectronics applications have pushed vendors to provide finer addressability. These improvements have driven the 1980s price (thermionic source, 3 inch, 50 keV) to $3 million to $4 million in the 1990s (thermal field emission [TFE] source, 6 inch, 50 keV) to $5 million to $7 million today (TFE, 8 to 12 inch, 100 keV) (see Figure 3.1.5).

The escalating cost of these systems stems partly from the small number of them built and delivered worldwide each year. The amount of engineering that goes into each generation of tool is enormous. The small volume leaves vendors reluctant to consider lower cost options,

continued

BOX 3.1 Continued

such as placing a newer column on an older or smaller stage. This route would create orphaned machines, which are difficult to service and upgrade.

Also responsible for the trend, however, is the varied nature of the user community. Systems placed in shared user facilities need to have the near-Angstrom-scale spatial coherence to produce gratings for optoelectronics one day and the ultrahigh resolution to attach contact electrodes to nanotubes or molecular electronics the next day. They need to have automated loaders to allow around-the-clock sample exchange and multisize substrate compatibility. The improved scanning speed allows access to greater design complexity or simply exposes faster and therefore performs for more users each year. The seemingly long list of specifications and features is driven by the need to support the broadest possible research base.

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[a] The reader should note that there is an alternative SIMS that employs a quadrupole mass filter rather than the double-focusing magnetic spectrometer of the CAMECA. These instruments have gone through similar price increases (albeit from a lower base) and enhancement of capabilities in the time frame from the 1980s to the present.

- A maintenance contract (approximately 5 percent of the capital cost per annum);
- A full-time professional and/or technical support staff person (about $100,000 per annum, including benefits); and
- Consumables, supplies, and replacement parts (about $50,000 per annum).

These costs amount to a total of about $250,000 per year. If that amount was to be recovered from user fees alone, a cost-recovery rate of $125 per hour would be required for a 2,000 hour year. That hourly fee significantly exceeds the stated level of tolerance (among academic users) of $100 per hour identified by the committee's survey, as discussed in the section "User Comments" in Chapter 2. (See Figure 3.1 for another example.) Any instrument downtime then becomes a further serious problem.

This cost analysis excludes the tool cost or depreciation that would be a major factor for establishing a commercial analytical service rate; that is, the commercial rate for the same services would be significantly higher. However, this additional constraint further exacerbates the cost-recovery gap. For its commercial users, a grant-subsidized facility must take care to avoid providing services that are otherwise available in the marketplace. This important precept is discussed further in the section below, "Cooperation and Noncompetition with Commercial Interests."

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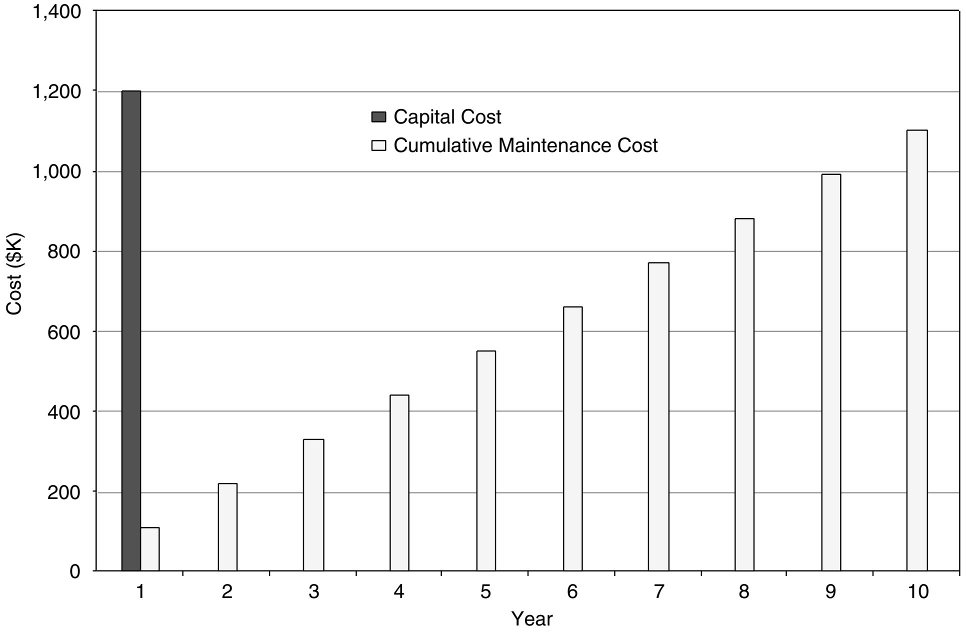

FIGURE 3.1 Example of rising costs of maintenance at midsize facilities: comparison of the capital expenditures and the cumulative operations and maintenance cost for a typical and modest field-emission transmission electron microscope. Because the annual maintenance costs are typically covered under a service contract, the price is the same in the first year as it is in the tenth.

To bridge the gap between cost recovery through user fees and the recurring expenses of maintaining and operating the facility, midsize facilities must identify alternative sources of ongoing support. The committee found that it is more difficult to cover ongoing maintenance costs than to obtain one-time capital funding! This lack of continuity is a critical issue—funding policy needs to be addressed in a serious fashion. The committee believes strongly that when a shared user facility is established and its operation has proven successful, continuity or stability of funding is required in order to realize the original objective. This funding is extremely important to enable a long-term plan of maintenance, equipment replacement, and staffing.

To maintain operations with a relatively high degree of confidence in their not being interrupted, many successful facilities visited by the committee have diverse sources of funding rather than relying on a single source (see Figure 2.2 in Chapter 2). A diverse portfolio of continuing support enables such facilities to minimize the risks associated with the reduction of any particular funding source,

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but it clearly requires more time and effort on the part of the scientists involved. For instance, several facilities at Cornell University are supported by funding from NSF and the National Institutes of Health, with the university providing administrative staff salaries. Other facilities such as the National Aeronautics and Space Administration (NASA) Research Partnership Centers (e.g., the Center for Advanced Microgravity Materials Processing at Northeastern University and others[4]), which derive a majority of their core funding from a single source (NASA, in these cases), would be dramatically affected by changes in their core grant.

Stable and Secure Staffing

Staffing at both technical and scientific levels is an essential ingredient for successful midsize facility operation. A dramatic example is provided by the Analytical Electron Microscope at the National Center for Electron Microscopy (NCEM) at the Lawrence Berkeley National Laboratory (the committee made one of its 2003 site visits to the Center; see Appendix D). After the retirement of the technician who ran this microscope, the number of publications from this instrument dropped from about 37 each year to 17, and then to 12 in the next 2 years. Eventually a new technician was hired, and scientific productivity started to rise. Another tribute to the importance of staffing was the high user demand for this machine, despite its age, because it was extremely well maintained and calibrated for quantitative x-ray microanalysis (a process that took the technician 2 years). The capability to make very accurate analyses is considered by the Center to be a great asset, and it could not be maintained in a laboratory without high-quality, dedicated staff.

This example illustrates a second important point, namely, the difficulty of hiring technical staff. Two years elapsed before a replacement was hired in this case. Technical staff are not trained in large numbers and are therefore in great demand. San Joaquin Delta College, which is one of the few colleges in California offering formal training for electron microscope technicians, quotes a ratio of jobs offered to graduating students of 15 to 1. Between 85 and 100 percent of its graduates find employment using their new skills, and the average placement rate has been 95 percent since 1992.[5] Similarly, a number of California-based semiconductor and nanotechnology companies have indicated to the California Nanosystems

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[4] See a listing available online at http://spd.nasa.gov/research_list_rpc.html; last accessed June 1, 2005.

[5] Information provided by J. Murphy, San Joaquin Delta College, during presentation to the committee at its second meeting, October 2003.

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Institute that there is a clear need for technically trained staff below the Ph.D. level.[6] Given these statistics, it is clear that opportunities are being missed in the training of students specifically for careers as technicians.

As discussed with the committee on its site visits, even when qualified personnel are available, the stability of their positions and the opportunities for a fulfilling career path are often lacking, especially in the university environment. Department of Energy (DOE) user facilities such as NCEM, with relatively stable long-term funding, can offer long-term career paths. The turnover of technical staff at NCEM is extremely low, and most staff members have spent well over 10 years there. It is possible for high-quality careers to develop over such long time frames. For example, one staff member who was hired as a photographer is now in charge of the image processing laboratory and teaches a range of computer skills to students.

In the case of many universities at which funding is often based on variable facility income—such as from user fees and individual-investigator grant funds—long-term stability and career paths for technicians can be much harder to achieve. As a consequence, the equipment purchased may not be fully utilized. One solution, used for example at the Center for Imaging and Mesoscale Structures at Harvard University, is to offer rolling 3-year contracts to support staff on soft money. This arrangement adds significant security, since the university assumes the cost for a short time if the grant is discontinued.

When permanent staff are not available, it is tempting to support microscopes and other equipment using a postdoctoral assistant or even graduate students on so-called soft money. This type of operation can work as a short-term solution, but once these limited-term employees leave, the equipment may sit unused. The constant turnover associated with student staffing may disrupt continuity of experience and user support, as was felt to be the case at the Washington Technology Center's Microfabrication Laboratory (see Box 3.2). In this particular case, career technicians were hired along with the students to provide continuity. Student or other temporary workforce solutions are best used to supplement rather than to replace permanent staff.

The issue of providing midsize facilities' support staff with an interesting and rewarding career path must be considered carefully, as there is little point in training and hiring technical staff if retention of staff is poor. In successful facilities, staff scientists' contributions are recognized in publications, and staff members often attend conferences and continue to take training classes. A modest budgetary

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[6] Private communication with D. Awschalom, University of California, Santa Barbara, October 2004.

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BOX 3.2
Microfabrication Laboratory at the Washington Technology Center

The Washington Technology Center is a state-chartered science and technology organization headquartered at the University of Washington in Seattle. It began as a microelectromechanical system (MEMS) initiative in 1997, to build core capabilities at the state's universities and to foster commercialization of university-developed MEMS technologies. Key to the success of the Washington Technology Center was the establishment of a 15,000 ft^2 Microfabrication Laboratory.

Available to both academic and industrial clients on a fee basis, the Microfabrication Laboratory has grown steadily since its inception. It has become one of the premier MEMS research and fabrication facilities in the Pacific Northwest, with 180 users from 40 academic research groups and 30 private companies, and annual revenues approaching $1 million. In a paper presented at the International Conference on MEMS, NANO, and Smart Systems in 2003, managers of the Microfabrication Laboratory discussed lessons learned from their experience:

> Growing utilization of old equipment led to increased downtime and decreased reliability, with an accompanying negative impact on research efficiency and timeliness of results. Furthermore, increased use of the Lab created bottlenecks in process flow and uncovered missing capabilities in the overall process offerings. This limited the scope of work that could be effectively performed, a real barrier to researchers who are the leading edge of MEMS research and development. . . . A series of improvements were undertaken to address the equipment and facilities issues to keep pace with user demand. Based on recommendations from Lab users and the audit team, specific process tools were identified and prospective sources sought.
>
> When the Lab was originally established, it was staffed primarily by students who had little professional-level semiconductor or MEMS processing experience. The natural attrition and turnover associated with student staffing created cyclical losses in the Lab's experience base and disrupted the continuity in user support. The accompanying growth of the user base placed an added strain on the Lab's ability to fully support the needs of new users. While students still represent a valuable . . . source of staffing, experienced engineers were recruited from the semiconductor and MEMS community to fill new and open positions in the Lab. The resulting increase in the experience base has had a dramatic effect on the Lab's ability to develop new processes, train new users and otherwise support a much broader client base. The maintenance staff was also doubled, recognizing that the ability to provide fully-functional, reliable and efficient process equipment is a cornerstone of the Lab's value and business growth.[a]

Another valuable lesson learned cited in the same conference paper involves the importance of keeping process tools and characterization equipment in top operating condition. With highly skilled professional staff, the Microfabrication Laboratory was able to make this priority a reality.

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[a] K.E. Ritala and E. Miller, "Success Factors in Commercializing University MEMS Technology Through the WTC's Microfabrication Laboratory," paper presented at the International Conference on MEMS, NANO, and Smart Systems, July 20-23, 2003, Banff, Alberta, Canada, p. 3.

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component in grant applications for professional growth and training of support staff would be a positive step. These considerations are critically important when considering the competition presented by employment opportunities in the industrial sector. Professional staff members can join industrial research laboratories with substantially more attractive compensation packages than those offered by midsize facilities. It is often the intellectual vitality, the interaction with students, and the challenge of research that draws them to midsize facilities.

The committee believes that current government agency funding models do not adequately recognize or allow for the support of staff to ensure the long-term and sustained contribution of instrumentation for materials research. The need for the participation of professional staff in facilities is an essential aspect in the operation of sophisticated instruments and their cost-effective use. When support from the host institution or federal agencies is continuous and stable, significant advantages accrue for the healthy operation of the facility. Long-term commitments made to a midsize facility contribute significantly to providing the necessary talented staff and hence to ensuring optimal use of the facility. For instance, the Center for Accelerator Mass Spectrometry at the Lawrence Livermore National Laboratory has a full-time staff of more than 15 Ph.D.-level researchers. More than half of them conduct independent research with funds obtained by writing their own proposals for research projects. With their scientific exploration and inquiry invested in the facility, the staff members are motivated to maintain and improve the equipment and are also interested in collaborative research projects with outside users.

Visibility to the User Community

Feedback received from facility users at the committee's town hall meetings and during its site visits clearly indicates that "there are more users out there"—in other words, some midsize facilities suffer from a lack of visibility and publicity. Responses to the committee's questionnaires indicated roughly equal rates of "undersubscription" and "oversubscription"—some facilities could have supported more users, while others had so many users that the lead time to obtain access was troublesome. As noted above, the visibility of a facility to those at the highest levels of the host organization is important, but more critical is the awareness of the local community about the facility.

Connections with new users are made primarily by word of mouth, by students who graduate from a facility, and by discussions at professional conferences. No single resource is available, however, that catalogues or identifies midsize facilities by categories such as region, available capabilities, level of interest in external users, or available resources for facilitating access. Only the NSF Materials Research

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Science and Engineering Center directory[7] and the National Nanotechnology Infrastructure Network[8] approach this level of centralized information and "advertising." Higher visibility can help maximize utilization of midsize facilities, but more importantly, it can enable better science opportunities and allow greater selectivity. That is, the best projects can only take advantage of the best facilities when they are aware of one another.

Sound Management and Operational Practices

Management and operational practices can have a major impact on whether users leave a facility with meaningful and reliable data. During its site visits, the committee observed a wide range of management approaches, suited to the different size, type, and complexity of materials science facilities. As discussed in this subsection, several common issues and challenges emerged from this variety.

Style of management dramatically influences a facility's output. Several facilities visited by the committee had bright, optimistic managers taking a strong role in promoting the facility to a wide range of users and constantly seeking new sources of funding and improvements to the capabilities of the facility. For instance, the relatively new Northwestern University Atomic and Nanoscale Characterization Experimental Center is heavily supported by a contribution from the university administration—a feat that was possible only because of the strong communication and leadership skills of the facility director—that is scheduled to decrease over 5 years. These managers reported that by making the facility easy to use, a wide range of users could be engaged and the best-quality research projects could be selected. Conversely, other managers did not promote their facilities as strongly, preferring that equipment be available primarily to local users (who had, after all, arranged for the funding in the first place).

The activities of very active managers, usually carried out in university settings by faculty members with many other commitments, are extremely valuable and should be rewarded. One suggestion for doing so is to carry out periodic assessments of funded facilities to evaluate their management and operational practices, as well as the experiences of users, and then to award additional funding (so-called outreach bonuses) on the basis of this feedback.

User feedback and facility assessment can contribute to optimizing a facility's usefulness. The Microfabrication Laboratory at the Washington Technology Center (see Box 3.2) is an example of a facility at which user feedback was gathered and

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[7] See http://www.mrsec.org/home/; last accessed June 1, 2005.
[8] See http://www.nnin.org/; last accessed June 1, 2005.

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used to target improvements, resulting in enhanced capabilities and a larger output from the user base. Such feedback is not always employed in facilities. However, the experience at the Washington Technology Center and other examples of which the committee was apprised suggest that some formal or informal mechanism for assessing users' experiences is important in optimizing a facility's usage.

It is normally clear when a laboratory is operating well, but suboptimal situations and how to improve them are not always so obvious. In providing the best possible infrastructure for materials research in the United States, facility managers should receive specific guidance. Likewise, the demanding nature and importance of management positions should be recognized by researchers applying for a facility grant and by the reviewers of these applications; that is, successful leadership and management should be recognized.

The value of outside reviews of facilities can be seen in the recent history of a large facility, the Advanced Light Source (ALS) at the Lawrence Berkeley National Laboratory (LBNL). In 1997, the DOE's Office of Basic Energy Sciences (BES) initiated an outside review of all four of its synchrotron radiation facilities. In the course of that review, it became apparent that the ALS should be reorganized so that, rather than devoting its efforts primarily to construction of the facility, it would focus primarily on operation for scientific and technological research using the synchrotron radiation. The review committee convinced both the BES and LBNL leadership that such a change was necessary.[9]

With BES support, LBNL proceeded with a reorganization that has increased the scientific productivity of the ALS considerably. One measure of the effectiveness of the change is the increase in number of users from about 300 in 1997 to about 1,400 in 2002. It should be noted that all of the BES synchrotron radiation facilities have had to go through such reorganizations and that the impetus for almost all came from external review committees.

The efficient use of resources is at the core of any effort to extract more from a flat-funded research budget. In general, the committee found local facility management to be remarkably efficient and productive. However, a broader view requires campuswide and multicampus exercises in improving efficiency if a larger research community is to be served. A start has been made in the very recent campuswide and regional infrastructure surveys being conducted by various universities, a development that seems to reflect a sensible approach toward avoiding costly duplication of facilities

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[9] Basic Energy Sciences Advisory Committee, *Report of the Basic Energy Sciences Advisory Committee Panel on Department of Energy Synchrotron Radiation Sources and Science*, Washington, D.C.: Department of Energy, November 1997. Available online at http://www.sc.doe.gov/bes/BESAC/syncpanel.pdf; last accessed June 1, 2005.

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http://www.nap.edu/catalog/11336.html

such as clean rooms and expensive instruments, or at the very least to facilitating an informed prioritization. Regional cooperation in these efforts can have a similar effect, and it should be encouraged as a best practice. See Box 3.3, "Consortium Approach to Extraterrestrial Sample-Return Missions," for an example of a regionally networked approach to a fascinating scientific opportunity.

The committee carefully considered the notion of quantitative performance metrics. Ultimately, of course, midsize facilities should be optimized for "usage"—some intangible measure of the ratio of the level of invested resources to the delivered output. With the data from its questionnaires and its site visits, the committee found it tempting to construct estimators of usage per unit of investment capital or of operating budget. However, in part because midsize facilities are so diverse and in part because of the limited extrapolating power of the data sample, there were no clear answers. A more complete and statistically robust data set with consistent and uniform definitions would enable more quantitative measures. For instance, accounting schemes are not standardized across facilities, across programs, or across agencies, so even just the denominator is hard to determine. Likewise, not all midsize facilities have the same purpose (some are directed at advancing research, some focus on education, and so on). This understanding of the diversity involved is one of the reasons that the committee advocates the combined use of user-feedback mechanisms and facility reviews by committees of scientific and management experts.

Maintaining a Balanced Suite of Equipment

It is important that facilities have a balanced suite of equipment that enables users to exploit the full capabilities of the instrumentation. For instance, a midsize TEM facility requires instrumentation for x-ray energy dispersive spectroscopy and electron energy loss spectroscopy as well as sample-preparation equipment. Synthesis and/or preparation of materials samples, for example, can present a serious obstacle, especially for users obliged to travel significant distances—a problem so critical, in fact, that the nation's need for crystal-growing facilities was the subject of an October 2003 DOE workshop.[10]

In the committee's discussions with facility managers and users, it was clear that an important attractor for users is one-stop shopping for the fabrication, synthesis, and characterization of materials and the measurement of their properties.

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[10] Department of Energy, *Design, Discovery and Growth of Novel Materials for Basic Research: An Urgent U.S. Need*, Washington, D.C.: Department of Energy, October 2003. Available online at http://www.science.doe.gov/bes/dms/Publications/DMSE_Sponsored/Xtal-Growth.pdf; last accessed June 1, 2005.

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BOX 3.3
Consortium Approach to Extraterrestrial Sample-Return Missions

The San Francisco Bay Area is the home of two national laboratories and several universities. Each of these institutions offers extensive analytical and technical capabilities. In 2003, the Bay Area Particle Analysis Consortium (BayPAC) was formed with the Lawrence Livermore National Laboratory (LLNL), the Advanced Light Source (ALS), the Space Sciences Laboratory (SSL) at the University of California at Berkeley, and the Stanford Synchrotron Radiation Laboratory (SSRL) (see Figure 3.3.1). The approach of the consortium is to leverage technical and analytical expertise at each of the institutions so as to maximize the science return from the Stardust mission and future sample-return missions of the National Aeronautics and Space Administration (NASA).

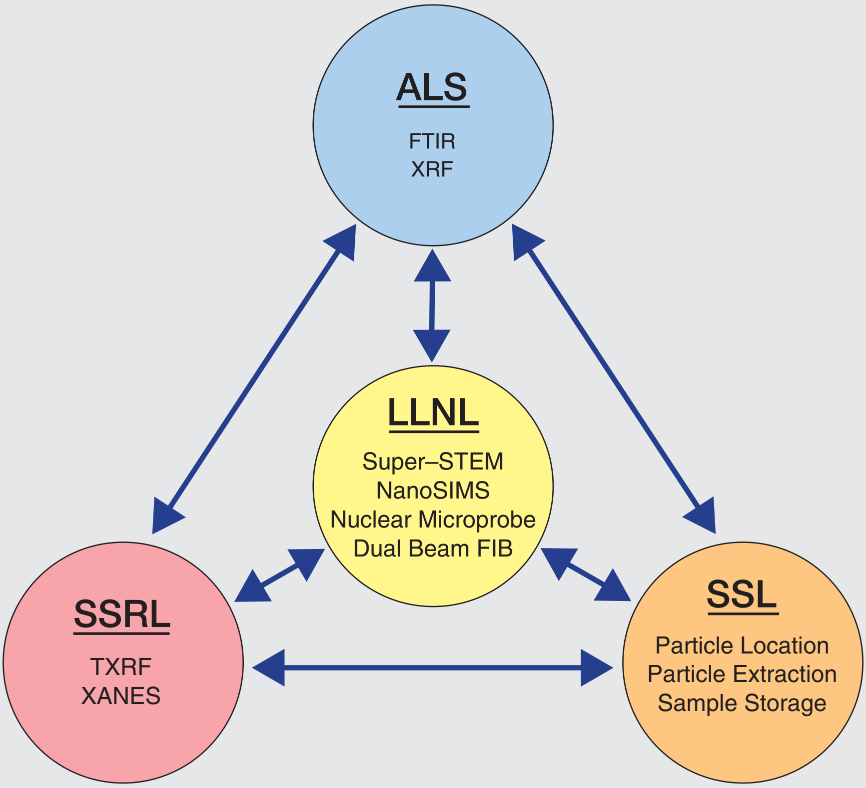

FIGURE 3.3.1 A diagram showing the interaction of institutions in the Bay Area Particle Analysis Consortium (BayPAC). Note the hub-and-spoke arrangement. See the text later in this box for definitions of the acronyms.

continued

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BOX 3.3 Continued

Stardust was launched in February 1999. It is the first "solid matter" sample-return mission since *Apollo 17* in 1972. Unlike the Apollo missions that returned rocks to the laboratory, Stardust will return just micrograms of dust in the form of several thousand individual particles, most of them less than 10 micrometers in diameter. BayPAC is preparing to confront the technical and analytical challenges that will be presented by the Stardust samples when the sample-return capsule is opened in 2006.

The SSL is developing methods to extract captured particles from the aerogel collectors (silica aerogel is the capture medium used on Stardust); LLNL is developing NanoSIMS (-secondary ion mass spectrometry), ion microprobe, nuclear microprobe, dual-beam focused-ion beam (FIB), and Super-STEM (-scanning transmission electron microscopy) methods for the analyses of individual particles; SSRL is refining total reflection x-ray fluorescence (TXRF), x-ray absorption fine-structure spectroscopy (XAFS), and x-ray absorption near-edge structure (XANES) techniques; and ALS is refining x-ray fluorescence (XRF) techniques and providing a beam line for Fourier transform infrared (FTIR) spectroscopy. Since the consortium was formed, NASA has provided several new grants to BayPAC members.

The membership of BayPAC provides a wide range of expertise from the fields of chemistry, materials science, geology, physics, and astrophysics that enables a unique level of interpretation and analysis of acquired data. The investment in the analytical and technical capabilities developed for Stardust by BayPAC can be further utilized on future sample-return opportunities such as Hayabusa (a Japanese mission to an asteroid) and NASA's proposed Gulliver mission to Mars satellite Deimos.

Multiple particle-capturing studies are in progress because small sample return appears to be the way of the future, and NASA appears to be committed to a long-term effort in this arena. Specialty technologies are being developed to capture samples from asteroid surfaces, and hypervelocity capture is being studied as well. Facilities at the Johnson Space Center, McDonnell Center for Space Sciences at Washington University, and in England are also involved in these efforts.

Users were more satisfied with midsize facilities that provide a variety of techniques and tools to accomplish their tasks; the complementary nature of synthesis/fabrication tools and characterization/measurement tools was noted by many users. Similarly, the committee found that, in general, facilities that offer equipment for training, education, and practice alongside topflight cutting-edge tools are regarded more highly and engage a broader group of users.

Suites of instruments at successful midsize facilities strongly reflected the usage patterns of the local community. If certain instruments were not sustainable (through lack of use, high use by relatively few researchers, or costliness of operation), they were passed off to individual investigators. Heavily used instruments became top priorities of facilities; in some cases, a facility's director sought to obtain equipment that was popular elsewhere in order to attract additional users to the facility. The committee found space and resources to be highly optimized at successful facilities.

A balanced instrument suite not only includes existing equipment but some flexibility to develop new tools in response to the individual and sometimes unique needs of researchers. A potential consequence of the development of new instrumentation or techniques is the creation of new intellectual property (IP). Facilities housed at national laboratories and academic institutions are generally not well equipped to turn IP into a value statement, particularly when the development is incremental or very application-specific. In part because facilities do not have secure resources, the instrumentation efforts must be less exploratory and more focused. Although universities are increasingly encouraging the licensing and transfer of new technologies developed on campus, the committee doubts that development of IP could become a serious component of a facility's revenue stream: the lucrativeness of technology transfer is simply too unpredictable, and the institutional overhead is not designed to allow the facility itself to profit directly.

NETWORKING WITH OTHER FACILITIES TO PROVIDE BALANCED RESOURCES

In some instances it is not financially possible to support a complete suite of instrumentation at a single facility or at one institution. A useful solution has been to develop a network with other facilities that can effectively provide users with needed access in a timely fashion. Support for such networking should be a recognized priority of federal agencies.

In other cases, particularly where different but complementary equipment might be needed, it is often not feasible for a single institution to support all of the technologies required. Recognition of this limitation is becoming increasingly important for projects that are interdisciplinary—many activities in the materials science area are increasingly so, especially those dealing with biological materials. For example, investigations of macromolecular structures might very well need good access to synchrotron sources for x-ray crystallography, a neutron source such as the Spallation Neutron Source for neutron scattering, ultrahigh-field NMR instrumentation, and cryogenic electron microscopy. Facilities for each of these instrumentation types range from midsize to very large and are rarely, if ever, present in one location. In such situations, effective models for the support and networking of these capabilities would have a very positive impact on the timely advancement of materials research projects and the continued development of frontier science. The National Nanotechnology Infrastructure Network (NNIN) (see Appendix F for details) and the Network for Computational Nanotechnology approaches recently developed by NSF are a major step forward in this regard.

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One of the primary motivations for the formation of the NNIN was the benefit of pooling resources (tools, staff, and funds), and its success can prove the virtue of this goal. NNIN has a formal governance structure for coordinating activities across the different sites; it is highly organized because of its central mission. The management structure for NNIN is probably larger than would be appropriate for a national association of midsize facilities loosely affiliated for the purposes of communication, referrals, and shared planning.

As noted earlier, midsize facility users predominantly come from the local area—in academic settings, this might be just the on-campus community. In fact, several major universities (e.g., Rice University and Harvard University) have completed a campus-wide inventory of their instrumentation, motivated by the opportunity to optimize their investments. These efforts also provided information on instrument use. Certain materials research tasks, such as fabrication, require quick and easy access to tools, driving the need for local facilities. Other tasks, such as analysis and synthesis, are already handled predominantly through remote service providers. These observations suggest that, at second glance, regional consolidation of midsize facilities would not be easy. In fact, it might hinder certain phases of the research enterprise, at least until the scientific user community adapted. The fact remains, however, that in a revenue-neutral environment, solutions that make existing resources available to a broader community will be necessary.

It is equally important that, within a given university, efforts are made to avoid duplication of facilities and to coordinate and consolidate capabilities, particularly in large institutions with multiple user facilities (such as major research universities). Sometimes the greatest barriers to networking or teaming with other facilities exist within different facilities at the same site. That is, the committee found that midsize facilities are dominated by local users, and in such circumstances, networking with another facility on campus can be perceived to have a negative impact—the new user community could easily dominate the facility. Similarly, connecting across departments in a university situation may incur additional difficulty because of administrative involvement.

The committee recognizes the challenges described above, but successful proofs of principle have been demonstrated by a number of universities, and most national laboratories have been required to address this issue for quite some time. Networking with a neighboring facility is a partnership for coordination and communication, not a way to transfer users. For instance, regular discussions taking place at Purdue University between two microscopy facilities (one for physical sciences and one for life sciences) represent a form of networking. While on-site networking represents a prime example of small regional networking, it may not evolve at the same rate that longer-distance networking relationships develop.

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Networking has a concrete meaning in terms of cyberinfrastructure as well; modern computer interfaces and high-speed networks make operation of many instruments “at the console” a virtual experience. Remote access has often been touted as a route to engage nonlocal users; through video or computer interfaces, remote researchers can either directly manipulate the controls or watch as other experts perform the tasks. The committee’s judgment is that, while remote access can enhance the radius of effective impact for casual education and training of a midsize facility, much of the vitality and value of facilities is obtained in person and on site. That is, routine analysis tasks can be dispatched to a remote facility, but researchers pushing the limits of scientific and technological know-how invariably prefer to visit the facility in order to interact with the instrumentation and professional staff personally.

BALANCING COMPETING PURPOSES

Smaller and midsize facilities often face problems posed by competing purposes. It is important that these facilities recognize these potential challenges and take steps to minimize conflicts, both when planning the creation of a facility and also during its operation.

A major issue in this regard is that of achieving the appropriate balance between the need to train students (with equipment breakage being an inevitable part of the learning process) and the need to maintain state-of-the-art performance. Several midsize facilities, such as the Microfabrication Laboratory at the University of California at Berkeley and the NanoScale Science and Technology Facility at Cornell University, achieve this goal with a strictly organized training and sign-up system for each tool: users are simply not permitted to use a tool until they have received training and certification. However, this system appears to work best for larger facilities with multiple tools, where a large pool of technicians or advanced students is available to conduct training.

In other facilities, such as NCEM, users are generally expected to be competent in the use of basic instrumentation when they arrive, and then they receive technicians’ specialized help in the use of advanced equipment. This approach has proved a challenge to NCEM staff, given some users’ expectation that the staff will train students in basic microscopy! For facilities that are in great demand, this problem is usually minimized by giving preferential treatment to users who already have the required basic knowledge, thus reducing the facility’s teaching load. However, researchers from smaller universities that cannot provide such basic training can thus be put at a disadvantage. Given adequate resources, each facility would ideally operate basic as well as advanced equipment, but this approach can be a challenge,

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given the reality of limited resources and the preference (of researchers and agencies) for funding advanced equipment.

A related and equally important issue is the need to balance the development of instrumentation, staff-initiated research, and the routine provision of services. Taking an advanced tool offline so that it can be used for instrument development, for example, can disrupt the operation of a facility. Facility managers who schedule this sort of activity view instrument development as an essential part of their mission and as one that benefits their facility in the long term. In many cases noted by the committee, facility members' research activities have in fact been based on development of the facility's instruments. For example, 10 years ago the Center for X-Ray Optics at LBNL undertook a major effort to adapt an electron-beam lithography tool so that it could operate with polar pattern generators rather than conventional rectangular scanners. This system became a research focal point because of its unique fabrication capability, and it has been used since to make world-class diffractive optics for the ALS at LBNL and elsewhere.

Facility members given an opportunity to enhance and extend the equipment, even by making small modifications or developing accessories, have a much greater stake in ensuring that their tools operate at as high a level as possible. An ongoing instrument development activity, however small, should be considered in planning for a facility to ensure balance in the basic activities of a midsize materials research facility.[11]

Also important is achieving a balance between outreach and research. Time spent on educational outreach, for example, to local elementary and high school students, although an important and rewarding experience, can detract from research time. This issue, of course, is common to every NSF program, but there are alternative forms of outreach that may in fact help to enhance the unique opportunities offered by midsize facilities. For instance, an interesting option would be to direct outreach toward the training or support of technicians, alleviating to some extent the staffing problems typical of many midsize facilities.

A related issue, the importance of which is increasing given the availability of high-speed computer links, is that of balancing remote operation and hands-on experience. From one perspective, as a teaching tool, hands-on experience is irreplaceable; in addition, visits by students to a facility allow them to interact with

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[11] One caution, however, is that one-of-a-kind instruments can become orphaned because commercial repairs may be unavailable, a consequence that should be weighed, anticipated, and mitigated where possible.

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other researchers and thus broaden their experience. From another perspective, remote operation can be more cost-effective and can engage a broader community.

One final issue involving balance relates to the openness of access to facilities for research in materials. The process that potential users must follow to gain access needs to reflect a balance that minimizes the time before experiments can be scheduled while maintaining safety and security. Once potential users have been approved and are present at a facility, their having the greatest possible access to the facility's tools—especially outside normal working hours—is extremely important. Such access will ensure the best use of limited time and resources and will promote the rapid developments associated with progress in areas such as nanotechnology. Restrictions that limit such access are detrimental to the research enterprise. Indeed, the Berkeley Microlab's experience was that tools that can be self-scheduled by students for use outside standard business hours were used more efficiently than were tools run by staff during business hours. In general, universities offer a different environment for balancing efficient access with security and safety than do the national laboratories; each environment achieves its own best compromise.

COOPERATION AND NONCOMPETITION WITH COMMERCIAL INTERESTS

It can be tempting for midsize facilities to recoup operating costs by providing analytical services to commercial users. The issue is that government-funded facilities can, in principle and sometimes in fact, perform analytical research at costs substantially below those of commercial analytical service laboratories or nanofabrication laboratories, since the commercial laboratories must recover substantially greater expenses. For instance, because the recovery of the cost of depreciation for government-funded capital investments at universities is not allowed, many overhead costs are not recognized, and no profit is generally sought; such facilities arrive at low figures when they prepare their "cost-recovery" user fees. These facilities might thus charge only an amount necessary to cover their direct, out-of-pocket costs. This accounting method is perceived by commercial laboratories as allowing unfair competition, since they must realize all of their costs in their pricing structure. It is viewed as tax dollars in effect supporting a competitor.

This issue has been a problem since the 1970s, when major instrument purchases were funded by the federal government and commercial laboratories began operation in the same time frame. Recognizing the problem, the NSF issued "Important Notice to Presidents of Universities and Colleges and Heads of Other National Science Foundation Grantee Organizations, Notice No. 91" (Important

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Notice 91)[12] during the 1980s. The issue was again addressed in 1998 by NSF in "Important Notice to Presidents of Universities and Colleges and Heads of Other National Science Foundation Grantee Organizations, Notice No. 122" (Important Notice 122)[13] and by the Office of Management and Budget (OMB) in Circular A-21.[14]

Current NSF policy recognizes and encourages cooperation between universities and the industrial and manufacturing sectors. In advanced study and research, such cooperation not only promotes a more rapid development and dissemination of knowledge, but it also contributes to economic development.

Use of NSF-sponsored facilities for direct collaboration with the industrial and commercial sector is allowed. If the collaboration is open and nonproprietary and the results are published in a timely manner, it may be appropriate to charge the lower fees generally charged to academic users. Otherwise, full commercial rates should be charged, as explained below.

Note that the preceding statements distinguish between "collaboration" and "competition" with a commercial partner—often the area of difficult judgment. Additional local oversight of this issue could be helpful. For instance, when preparing the annual reports for their facilities, managers should describe all partnerships with commercial entities; each activity should be categorized as collaborative, full-cost-recovery services. This effort would clearly delineate all nonproprietary work and put it in the public domain, even though it might never be formally published in a scientific journal.

It is the responsibility of each university's administration to ensure that a policy is in place and is properly followed for determining which fee structure to use. This committee recommends that all facilities funded in part or in whole by the federal government adhere to the federally mandated guidelines. Some facilities have in fact developed policies that convey the letter and spirit of the NSF and OMB notices.

Usage of NSF-sponsored facilities is specifically governed by NSF Important Notice 122. Potential commercial users of such a facility are encouraged to become familiar with this announcement. OMB Circular A-21 is meant to govern all facilities that are funded in whole or part by the federal government.

Because of the keen sensitivity to the issue of unfair competition between commercial analytical service and fabrication laboratories and federally funded

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[12] NSF Important Notice 91 was replaced by Important Notice 122, but the earlier notice can still be viewed online at http://prism.mit.edu/nsf.in91/in91txt.htm; last accessed June 1, 2005.

[13] NSF Important Notice 122 is available online at http://www.nsf.gov/pubs/1998/iin122/iin122.txt; last accessed June 1, 2005.

[14] OMB Circular A-21 is available online at http://www.whitehouse.gov/omb/circulars/a021/a021.html; last accessed June 1, 2005.

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facilities, the committee endorses several guidelines here for the provision of services by midsize facilities to the industrial and commercial sector. These guidelines are a modified version of policies developed by the Cornell Center for Materials Research:[15]

1. Commercial use of the facility must not interfere with the research mission of the facility.
2. Appropriate fees must be charged to recover full costs.
3. Fees for services to commercial businesses must not be less than fees charged for equivalent services from viable commercial vendors or facilities.
4. Excess capacity must be available to provide the services to the commercial sector.

It is the responsibility of each facility's manager to establish (using reasonable judgment) whether equivalent services are available from the private sector. In ambiguous cases, a member of the organization, educational institution, or national laboratory management who is not directly involved in the management of the facility should assume responsibility for establishing whether services are equivalent.

In determining whether equivalent services are available, a facility's manager should do as follows:

1. Identify the specific activities required by the potential commercial user.
2. Take into account the capability of the compared instruments, the fragility of the specimens involved, the specialized expertise of the technicians involved, the need for special adjustments or accessories, and the number of samples being tested or the frequency with which the user must repeat processes.
3. Document the results of the assessment of equivalent services on a case-by-case basis as requests from potential commercial users are received.
4. Have on hand current pricing information from representative commercial laboratories if the manager intends to provide services to the commercial sector.
5. Avoid allowing such documentation to significantly interfere with the research-related activities of the facility's manager.

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[15] Cornell Center for Materials Research, *Policies and Procedures for Shared Experimental Facilities*, Ithaca, N.Y.: Cornell University, November 2000. Available online at http://www.ccmr.cornell.edu/images/pdf/CCMR_SEF_Policy.pdf; last accessed June 1, 2005.

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SUMMARY

Long-term infrastructure affects every aspect of a facility's long-term viability, ranging from the ability to plan for instrument acquisition and replacement to the retention of skilled staff and the ability to define and carry out a sound management plan. A related challenge for midsize facilities is that of publicizing their capabilities to attract the best research. As discussed in Chapter 4, current funding models (within agency programs) do not address these needs well.

Midsize facilities in materials research have been traditionally thought of as independent units that function individually. Because of growing opportunities and increased demands, there is an increasing need for efficient networking and interaction between facilities in order to avoid unnecessary duplication—and to ensure that instrumentation is present in regional or local facilities in proportion to the needs of the regional or local communities. There is currently no framework to facilitate these types of interactions for planned or existing facilities.

Another common challenge involves the difficulty of balancing competing purposes, such as training versus research. A key strength of midsize facilities is their flexibility, but this characteristic can also be a weakness—efforts to maximize usage, train students, and facilitate world-class research (for instance) can interfere with one another.

Finally, the close parallels between midsize facilities and commercial analytical service laboratories in materials research can provide challenges. Compliance with federal guidelines and regulations in these areas is critically important to maintaining a healthy symbiosis between midsize facilities and commercial ventures.

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4

Investment in Midsize Facilities

The primary investors in midsize materials research facilities are the government agencies (the National Science Foundation [NSF] and the Department of Energy [DOE]) and the universities themselves—the latter through start-up packages for new faculty and provision of matching support when needed. Other investors include the Department of Defense (DOD), some foundations (the Keck Foundation, for example), and state governments, especially in state-affiliated schools. It should be noted that the DOD is a primary supporter of domestic materials research, but the majority of the awards that it makes are to single investigators. The DOD does not, in general, establish or specifically support midsize materials research facilities.[1]

In this chapter, the committee comments on the programs of support for midsize materials research facilities. Selected specific programs are described in more detail in Appendix F. Investments include the initial capital expense of equipment, the building or modifying of suitable space for installation, and yearly operating expenses (staff, maintenance, consumables, and so on).

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[1] Although, for instance, the Defense University Research Instrumentation Program does explicitly provide for instrumentation for researchers supported by DOD grants.

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GENERAL SCOPE OF SUPPORT

The Division of Materials Research (DMR) at NSF is by far the major investor in the smaller and midsize facilities used in materials research at universities. DMR participates in several programs that provide most of the equipment. Two programs—Major Research Instrumentation (MRI) and Instrumentation for Materials Research (IMR)—only fund equipment purchases and, until recently, typically required a 30 percent match (now reduced to zero) from nonfederal sources. Some NSF/DMR funding of equipment is also available in center programs, such as the Materials Research Science and Engineering Centers (MRSECs). Finally, a small proportion of individual-investigator grant funding is used to purchase less-expensive equipment. Generally, NSF does not provide direct support for yearly operations expenses, expecting that these funds will derive from user fees obtained from other sources, such as individual-investigator grants, center grants, or university subsidies.

The DOE typically purchases major equipment for use at its own facilities, only a few of which are at or associated with a university (the University of California at Berkeley, the University of Illinois, Iowa State University, Kansas State University). There is no general equipment program at the DOE that supports the purchase of equipment for central facilities at non-DOE-affiliated universities. However, the budgets for operations of DOE-funded facilities are included in the yearly DOE budgets. Consequently, user fees are typically very small to nonexistent at DOE facilities.

In distributing its facilities questionnaires, the committee identified more than 270 candidate facilities. (See Appendix C for a list of these facilities.) While many of the facilities fit the definition of midsize materials research facilities, not all did. In the summer of 2003, the committee visited nearly 50 facilities in five regions of the country (these facilities are listed in Appendix D). On the basis of responses to its questionnaires, the site visits, a review of the awards issued by NSF, discussions at the committee's town hall meetings, and the committee's own best judgments, it seems likely that there are on the order of 500 facilities nationwide that provide essential instrumentation support for materials research. This estimate is perhaps generous to a certain degree, but it provides a good basis from which to understand the role of midsize facilities in the overall enterprise. If every such facility chose to purchase the next generation of instrumentation, it would well exceed any plausible budget scenario.

Based on the survey responses, the total capital investment (purchase price) in the 56 responding midsize facilities is \$529 million (average = \$10.2 million, median = \$6.8 million). The annual operations budgets average \$1.1 million per year, with a median of \$0.51 million per year. The current annual investment in

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new equipment for these facilities is also difficult to estimate, since the investment by universities, foundations, and states is not compiled in any one source.[2] A conservative estimate would put the total capital investment in these midsize facilities at several billion dollars, with operations budgets totaling several hundred million dollars per year.

National Science Foundation

Although the NSF's funding programs are not a conclusive indicator, an examination of their internal consistency provides some insights about the features of federal support for midsize facilities. DMR had an annual budget near $250 million in 2003.[3] This budget supported individual investigators (53 percent), centers (24 percent), large facilities (15 percent),[4] and focused research groups (8 percent). Centers include the MRSECs and the NanoScience and Engineering Centers. Since there is no explicit midsize facilities program within DMR, the focus here is on support for instrumentation. In addition to the IMR program, DMR also, more recently, initiated the Instrumentation for Materials Research—Midscale Instrumentation Program (IMR-MIP). Some statistics about the program follow:

- In FY 2003, the IMR program supported about $6 million in awards.
- The IMR-MIP was expected to award up to a total of $3.5 million across 3 to 4 awards in FY 2004.
- In general, about 12 percent of the DMR budget is directed toward capital equipment purchases ($30 million in FY 2003).

Instrumentation for materials research can also be supported at NSF by so-called allied funding. For instance, some equipment that is used for materials research as

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[2] A 1993 survey of academic research instruments and instrumentation needs cofunded by NSF and the National Institutes of Health identified systems of instruments at more than 300 institutions; these systems of instruments totaled $6.3 billion in aggregate cost. (See *Characteristics of Science and Engineering Instrumentation in Academic Settings: 1993*, Arlington, Va.: National Science Foundation, 1993.) This extensive survey has not been updated for more than a decade; more recent surveys have focused on measuring net assignable square feet for research space.

[3] Presentation by T. Weber, National Science Foundation, at the National Research Council's Solid State Sciences Committee meeting, April 2004.

[4] These are the national user facilities: Center for High Resolution Neutron Scattering (Gaithersburg, Maryland), Cornell High Energy Synchrotron Source (Ithaca, New York), National High Magnetic Field Laboratory (Tallahassee, Florida), Synchrotron Research Center (Madison, Wisconsin), and National Nanofabrication User Facility (University Park, Pennsylvania) (partial support).

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well as for other sciences and engineering is purchased through programs in divisions of NSF other than DMR. For example, nuclear magnetic resonance (NMR) instruments are used to characterize many molecular substances as well as polymers. The latter topic is generally considered materials science. Thus, NMR apparatus funded by the Division of Chemistry (CHE) at NSF may also support some materials research activities. Indeed, some equipment funding is done jointly between divisions. CHE also participates in the Major Research Instrumentation program at levels similar to DMR's participation in the program.[5] The committee's crude estimate is that perhaps as much as 20 percent of the CHE MRI program may be considered as supporting materials research.

Another example of allied funding is through agency-wide programs, such as the Major Research Instrumentation program. The MRI program assists institutions in the acquisition or development of major research instrumentation that is, in general, too costly for support through other NSF programs. About 10 percent of the annually awarded MRI funds are directed through DMR, about $10 million in FY 2003. The maintenance and technical support associated with these instruments are also supported during the period of the award (usually less than 3 years), although typically more than 90 percent of each award goes directly toward capital costs. Figure 4.1 shows recent trends in support for the equipment portion of the DMR budget and the DMR-captured MRI awards. The average size of an MRI award within DMR in FY 2003 was $235,000 per year, with an average duration of less than 2 years; there are typically only several awards each year made for more than $1 million (including matching funds) through DMR.

In the late 1990s, there was widespread recognition at NSF that investment in major instrumentation was insufficient. Increases in the MRI budget are reflected in the increases in DMR spending. Thus, the NSF annual investment in instrumentation for materials research, including the required matching of 30 percent from nonfederal sources, can be estimated at nearly $40 million per year in 2003—up from about $30 million per year in 1999. As discussed above, the capital equipment investment in the responding 56 midsize facilities is $529 million (purchase price). The committee did not attempt to determine the average age of the equipment in these facilities, but based on the collective experience of the committee at the members' home institutions and on observations made during the site visits, the average age is over 10 years. Using the average U.S. inflation rates over the past 10 years (about 23 percent, a period of historically low inflation), the committee estimates the replacement cost of that equipment to be about $650 million. It is

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[5] This section is based on material supplied by A. Ellis, director, Division of Chemistry, National Science Foundation, 2005.

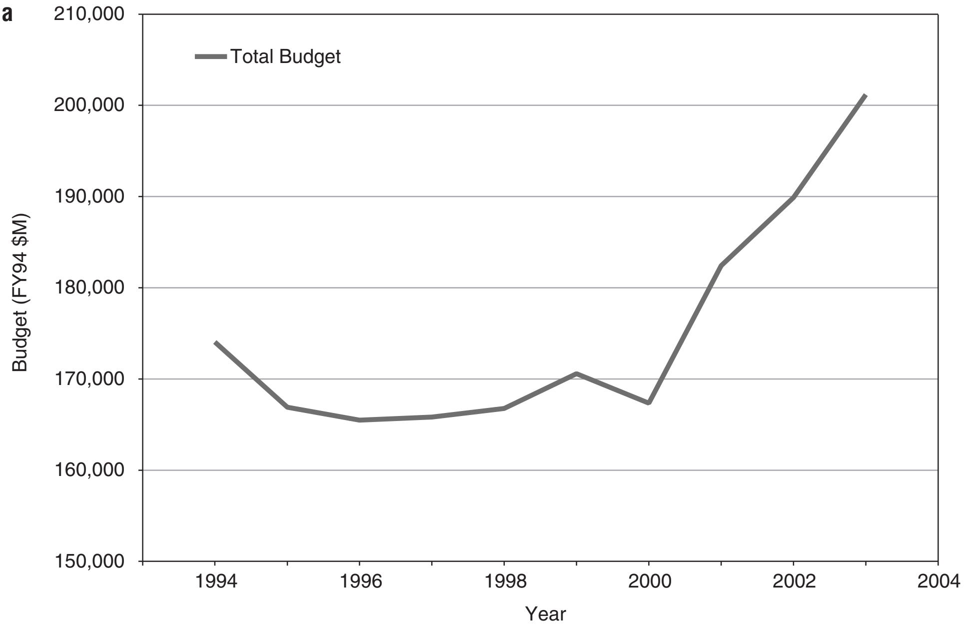

FIGURE 4.1 (a) Recent history of the budget of the Division of Materials Research (DMR) at the National Science Foundation (NSF). (b) History of the level of support provided for capital equipment purchases through NSF's Division of Materials Research. (c) History of Major Research Instrumentation (MRI) program awards within the DMR from 1997 through 2003. About 90 percent of the average award is used directly for capital equipment purchases. Because of different cost-sharing levels over time and per institution, these awards are moderately leveraged to acquire equipment. In each year, several single awards were for $1 million or more, although on average, 80 percent of the awards were $500,000 or less. Data provided by the DMR program office at the National Science Foundation.

FIGURE 4.1 continues on next page

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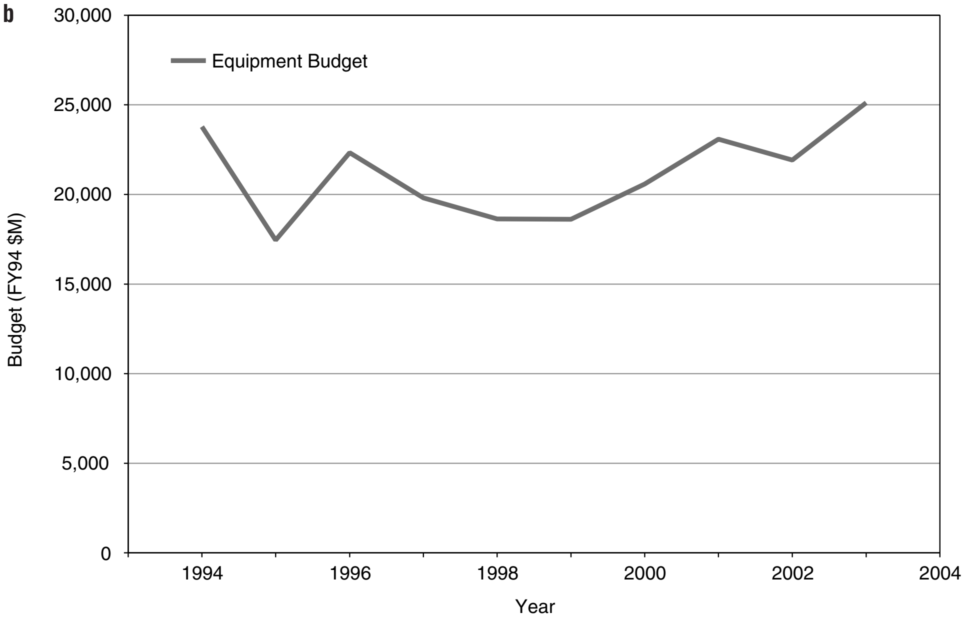

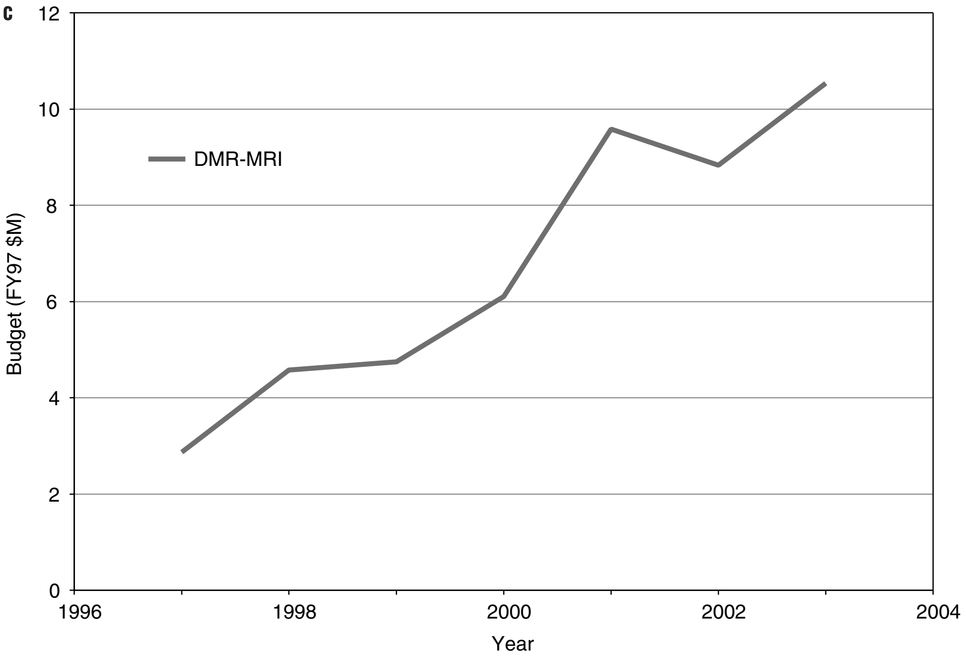

FIGURE 4.1 Continued

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not clear if this inflation rate is applicable, since exact models of the older equipment are no longer available. Generally, newer equipment also has capabilities that are enhanced or even entirely new. However, for present purposes, the exact rate is not an essential component of discussing future challenges. If the committee's estimates of the total cost of all equipment in all 500 or so materials-related facilities are reasonable, the total replacement cost is a factor of 2 to 4 larger (about \$1 billion to \$2 billion).

Department of Energy

DOE's materials research programs are managed by the Office of Basic Energy Sciences (BES). BES does not have a specific program for funding instrumentation at universities. Support for acquisition of some instrumentation is provided as part of the normal grant process; in general, it is a small amount, although major equipment can be requested if justified by and required for the proposed research. At the national laboratories, however, the DOE provides some support for instrumentation purchases in conjunction with research program funding.

While the DOE does not have a targeted program to fund significant equipment purchases in non-DOE-affiliated laboratories, it plays an indirect but important role in supporting the operation of many facilities in such venues by providing support for user fees. In 2003, BES provided support for about \$175 million worth of single-investigator research at universities.[6] This research is largely materials-related, and the "Materials and Supplies" portion of the single-investigator award is not significantly different from those at NSF. These budgets are in part used to pay user fees at midsize facilities. Other agencies that directly support materials research, such as the DOD and the National Aeronautics and Space Administration (NASA), also support facilities through the provision of user fees. Clearly, a relatively modest, consistent investment by DOE in a university-based facility has had significant positive impact, however, such as at the Center for Microanalysis of Materials, Frederick Seitz Materials Research Laboratory, at the University of Illinois at Urbana-Champaign.

DOE's BES also directly operates and fully supports a suite of smaller and midsize facilities—including four existing electron-beam microcharacterization centers, as well as five nanoscale science research centers (transitioning from construction to operations in FY 2006)—at which there are no user fees for nonproprietary work. The electron-beam characterization centers are well established.

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[6] Presentation by P. Dehmer, Department of Energy, at the National Research Council's Solid State Sciences Committee meeting, April 2004.

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Their status was reviewed in 2000 in a report by the DOE Basic Energy Sciences Advisory Committee.[7] In addition, facilities for materials synthesis are being created, such as the Molecular Foundry at the Lawrence Berkeley National Laboratory (LBNL), which should become available in the next year or so.

Construction of the new nanoscience centers is a $350 million DOE initiative to construct and equip five regional facilities to operate in the manner of a large facility. Each center is expected to have an operating budget of $15 million to $20 million per year and is designed to take full advantage of the significant national laboratory infrastructure in which it is embedded. The technical and conventional construction projects are managed much as a large facility would be planned and reviewed. The process involves multiyear planning, formal management plans, four critical design reviews by professional staff, detailed budgets, standardized program management and accounting, and so on.

Future access to these facilities by external users will be based on the scientific merit of user submissions, evaluated during a cyclic, formal proposal process. As in the case of synchrotron users, there will be no charge for access to the facilities and expert staff. Therefore, the long-term user support and maintenance of the equipment will be highly dependent on the constancy of the operations budget from the DOE, which is both owner and operator. The next few years will provide valuable new lessons as these facilities complete their construction and develop a user community.

The national laboratories are generally well stewarded, both in terms of instrumentation and long-term staff, especially when compared with university-based facilities. Some are close to universities and industrial complexes (e.g., LBNL and the Lawrence Livermore National Laboratory in the San Francisco Bay Area, and the Argonne National Laboratory [ANL] in the Chicago area). Others are more remote (e.g., the Oak Ridge National Laboratory [ORNL] in Tennessee and the Ames National Laboratory at Iowa State University). The committee's observations suggest that these laboratories play an important role in the nation's research infrastructure but that they cannot, because of their mission and limited number, provide more than a nucleus to address current national needs. Nonetheless, there are major opportunities for significantly enhancing their connectivity to universities and industry.

For instance, the committee's site visit to LBNL's National Center for Electron Microscopy (NCEM) revealed that it was a well-run and successful facility, serving

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[7] Basic Energy Sciences Advisory Committee, *Review of the Electron Beam Characterization Centers*, Washington, D.C.: Department of Energy, 2000. Available online at http://www.sc.doe.gov/bes/BESAC/e-beam report.pdf; last accessed June 1, 2005.

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a large number of users, the majority of whom came from outside the immediate geographic area. However, NCEM was unable to obtain capital funding for a much-needed "workhorse" instrument but was able to secure support for a "racehorse" instrument. A workhorse instrument at the nearby University of California at Berkeley campus had been installed, but access to the broader community was limited. Clearly, rather straightforward arrangements could be made to adopt a hub-and-spoke model among both of these instruments, thereby serving both constituencies well.

Likewise, the excellent Shared Research Equipment (SHaRE) User Facility and Program at ORNL allows students from various locations in the country to work with experienced researchers on advanced transmission electron microscopes (TEMs) to obtain high-quality advanced data. However, because of the limited time available on the instruments, the overall number of users served this way is very constrained. Budget constraints have also forced the travel support to be eliminated from this program. The parallel electron microscope facilities at ORNL are generally open to multiple users as midsize facilities; they operate either in a mission-oriented fashion or at a higher level of research capability. Accordingly, these excellent facilities can only be made available to a limited number of experienced researchers within the time commitments and accessibility of a national laboratory. Thus, while providing much-needed facilities for excellence in research, it is not possible for them to service the broad materials community, which requires immediate and ongoing characterization capability.

No discussion of the DOE's involvement in midsize facilities and instrumentation would be complete without reference to the Transmission Electron Aberration-corrected Microscope (TEAM) project, undertaken by five electron microscopy centers with support from BES (see Appendix F for background information). The TEAM project concept has been endorsed by a subcommittee of DOE's Basic Energy Sciences Advisory Committee. Funding at the level of $25 million has been approved for research, development, and testing, and the construction of an initial instrument to be located at LBNL. Data gathered by the committee suggests that several different U.S. institutions are scheduled to receive Cs-aberration-corrected TEMs and monochromated TEMs in the next year or so.

Other Agencies

The National Institutes of Health (NIH) has become an important contributor to midsize facilities in particular and has even begun to support several such facilities in areas related to materials research (see Appendix F for further discussion). About 50 biotechnology research resource centers are supported under the P-41

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grants program (grants for Biomedical Informatics/Bioinformatics).[8] Each of these centers is required to participate in five different types of activities (listed below). It is standard practice for these facilities to "spin off" the service-work user facility component as a stand-alone entity for accounting reasons and institutional preferences. The types of activities are these:

1. Technological research and development,
2. Collaborative research,
3. Service,
4. Training, and
5. Dissemination.

Perhaps surprising to some, NASA has become increasingly involved in materials analysis using sophisticated instrumentation. Its recently established program has arisen out of an emphasis on the microanalysis of extraterrestrial samples returned to Earth: the Sample Return Laboratory Instrument and Data Analysis Program (SRLIDAP) at NASA was specifically formed to foster the creation of midsize facilities dedicated to this type of analysis. Funded SRLIDAP projects include an automated aerogel mining device (for recovery of Stardust particles), a next-generation superscanning transmission electron microscope, extremely low-blank rare-gas mass spectrometers, a resonance ionization mass spectrometer, NanoSIMS (high-spatial-resolution secondary ion mass spectrometers), laser scribing (to cut Genesis wafers) focused-ion beam microsample preparation, and synchrotron x-ray fluorescence microanalysis facilities. Although the entire scale of NASA's investment in facilities-based materials research is small compared with the more traditional agencies' investments, the surge of public enthusiasm and interest in extraterrestrial sample analysis will continue to drive NASA's support forward.

DISCUSSION

The operations budgets of the 56 respondent midsize facilities totaled $66 million per year. On average, these expenses are covered by user fees (35 percent), direct support from federal programs (e.g., center programs) (35 percent), support from the host institutions (27 percent), and a small contribution from state or other sources (3 percent). There is considerable variation in these proportions among

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[8] National Center for Research Resources, *NCRR Highlights 2000-2001*, NIH Pub. No. 02-2309, Bethesda, Md.: National Institutes of Health (NIH), January 2002, pp. 12-13.

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facilities, with some running almost entirely on user fees and others running almost entirely with some form of university support. The patchwork of support at a given facility depends on many local factors, which are often unique to that institution. Conservatively, the operations cost of all materials-related facilities is several hundred million dollars per year. Given the committee's findings during its site visits, this expenditure is too low for efficient operation. To place it in perspective, this figure is roughly equivalent to the entire DMR budget ($250 million per year in 2003) of NSF.

Some of the needs of midsize facilities have already been recognized by the National Science Board (NSB) in its report *Science and Engineering Infrastructure for the 21st Century*. For instance, that report states:

> While there are special NSF programs for addressing "small" and "large" infrastructure needs, none exist for infrastructure projects costing between millions and tens of millions of dollars. This report cites numerous examples of unfunded midsize infrastructure needs that have long been identified as high priorities. NSF should increase the level of funding for midsize infrastructure, as well as develop new funding mechanisms, as appropriate, to support midsize projects.[9]

The NSB report focuses on the challenges associated with "chronic underinvestment," however, and the present report focuses on the opportunities for optimizing the current investment. That being said, however, the committee recognizes and applauds DMR's response to the NSB report with the introduction of the IMR MIP (see further discussion in Appendix F).

Facilities' maintenance of their sophisticated instruments includes the cost of replacement parts and maintenance contracts with the manufacturer. Because of tight budgets, many facilities do not have replacement-parts reserves. Often they seek contributions from every conceivable source, but if the contributions are not forthcoming, the instruments sit idle. Grant programs are not a viable recourse for replacement parts, because the application and awards process is much too slow. Maintenance contracts have become very expensive, often exceeding a yearly cost of about 5 to 10 percent of the initial capital cost. In some sense, budgeting for the maintenance costs has been unrealistically low for many years, because 5 to 10 percent is a typical figure for maintenance of capital items in industry and at universities in general. In addition, for many manufacturers the profit margin on equipment sales is low, while on maintenance contracts it is high. This tendency puts considerable pressure on university and government facilities. A large fraction

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[9] National Science Board, *Science and Engineering Infrastructure for the 21st Century: The Role of the National Science Foundation*, NSB 02-190, Arlington, Va.: National Science Foundation, 2003, p. 3.

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TABLE 4.1 Key Instruments in Materials Research and the Initial Capital Investment Necessary to Acquire Them

Instrument	Today's Purchase Price ($ million)
Electron-beam writer	2.5–5.0 (50 kV vs. 100 kV)
Dual-beam focused-ion beam	2.0
Reactive-ion etcher	1.0
Field-emission gun transmission electron microscope (TEM) (fully equipped)	2.5
Aberration-corrected TEM	4.0
Nanoscale secondary ion mass spectrometer	2.0

of facilities take the risk of operating without full or even any maintenance contracts, since they cannot afford them.

These analyses underscore the scope of the budget problem for midsize facilities. Replacement costs for current aging equipment in the 500 or so midsize facilities are estimated to be $1 billion to $2 billion. The management of this enterprise is larger than any one agency's program in materials research. For instance, NSF support (including matching funds) is a little more than $30 million per year for such equipment. Assuming a standard 10 year depreciation timescale and a goal of a nominal 10 year replacement of the inventory, NSF can only service up to 30 percent of the perceived needs of the existing midsize facilities. The investment needed to replace current equipment is far too great to be realistic—leading to the conclusion that sharing facilities and resources is increasingly necessary for the future.

Table 4.1 gives illustrative costs of some of the impressive new instrument capabilities. Comparing these figures with the average NSF-MRI award in DMR ($0.24 million in 2003),[10] it can be appreciated that there is no federal governmental mechanism through which research institutions can obtain these state-of-the-art machines. Only very few would be able to acquire them, with huge demand for their capabilities. Once again, this problem can be addressed to a large extent by the establishment of facility centers open to a community of qualified users, both internal and external. Not every institution can have all or even some of these instruments. However, there is a general belief that they should all expect to have reasonable access to a shared facility for the most groundbreaking research.

The diversity of funding sources for midsize facilities is both a boon and a bane. It allows facilities to develop some autonomy by not being embedded within a single agency, but it also allows them to fall between the cracks of agency

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[10] Division of Materials Research program office, National Science Foundation.

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programs. For instance, when a midsize facility (or a significant instrument acquisition) is proposed, no one agency program manager (or even peer review panel) has sufficient expertise or resources to evaluate the proposal against other activities in the same region. It is often up to the proposal author to consider these types of issues. Likewise, because midsize facilities have no clear program steward, they often do not formally close down or release resources when the facilities are no longer effective. (The committee did encounter several facilities which, owing to a lack of operating funds that year, were unable to operate or share equipment with users.) In an era of constrained resources, focusing operations on the most effective facilities is a serious consideration.

In summary, the committee estimates that the midsize materials research facilities enterprise in the United States numbers more than 500 separate facilities and represents a domestic capital investment in excess of $1 billion, with an annual operating cost of more than $100 million. Not only does the scope of this enterprise represent a significant national investment, its management is something that exceeds the capability and resources of any one federal funding agency.

INTERNATIONAL CONTEXT

The United States is unique in many respects, including in its scientific enterprise. Compared with its major technological competitors (Japan, Germany, the United Kingdom, France[11]), it is significantly larger geographically, has a larger population and economy, and is more ethnically diverse. Moreover, no single, overriding paradigm dictates how research is conducted: there are a variety of funding agencies, the possibility of local (state) support, a number of charitable foundations, and an approximately equal proportion of private and state research universities. The problems that the nation faces and needs to address are therefore largely relevant only to the U.S. environment. However, quoting from the National Academies report *Experiments in International Benchmarking of US Research Fields:* "There continues to be concern among top university researchers that facilities and equipment for materials research in several foreign universities now outclass those at most universities in the United States."[12]

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[11] The European Union (EU) is roughly similar in size and population to the United States, yet with a few notable exceptions (e.g., the European Organization for Nuclear Research) most scientific decisions and funding strategies still largely reside within each individual country. Recently, however, several EU-level programs for instrumentation have arisen.

[12] National Academy of Sciences, National Academy of Engineering, and Institute of Medicine, *Experiments in International Benchmarking of U.S. Research Fields,* Washington, D.C.: National Academy Press, 2000, pp. 2-26.

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Some important features are revealed by considering how these same issues are approached in other countries. Japan has the extremely impressive National Institute for Materials Science in Tsukuba, with about a thousand researchers and a remarkable array of equipment (e.g., over 35 advanced TEMs, including two high-voltage, high-resolution microscopes that no longer exist in the United States after the decommissioning of the NCEM microscope in 2004).[13] The Japanese facilities, like those in the major national universities, reside largely in the groups of individual investigators rather than being multiuser operations.

The Max Planck and Fraunhofer Institutes form the backbone of the German research system. Again, each is better equipped than the U.S. research universities but is comparable to the U.S. national laboratories. The committee's experience here is that the permanent technical support staff is a key component of these facilities, an aspect that is strongly supported by the German education system.

In the United Kingdom, excellent facilities are found at the elite institutions (e.g., Oxford and Cambridge Universities). These are continually upgraded (e.g., Oxford already has an aberration-corrected TEM) and are well supported with technical and scientific staff. However, there tend to be fewer users from outside those institutions.

Many of the midsize facilities in France are supported by the Centre National de la Récherche Scientifique (CNRS). Thus, many of the scientists are permanent government employees themselves (see Box 4.1, "Materials Research Facilities in France," for more information).

The smaller European countries with on the order of 10 million population each (e.g., Belgium, the Netherlands, Sweden) tend to have a few highly funded, well-supported centers that are national resources and are extensively used by many colleagues on a national and international level. Examples include the high-resolution electron microscope (HREM) laboratory at the Middelheim Campus, University of Antwerp, Belgium; the Dutch National Center for HREM in Delft, Netherlands; the Swedish National Center for HREM at the Lund Institute of Technology; Interuniversity MicroElectronics Center in Leuven, Belgium; and Materials Analysis at Chalmers University of Technology, Goteborg, Sweden. The model of these smaller countries is one to note especially. These are stable, well-funded facilities that serve a large number of users. They are successful because of a combination of recognized need, enthusiastic collaboration, and continued oversight from the government and scientific community. It is also undoubtedly advantageous that these countries are geographically small, so that national facilities are never more than a few hours' drive away.

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[13] It is interesting to note that Japan is investing in nanotechnology at about the same level as the United States even though it is a country with about 40 percent of the U.S. population.

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BOX 4.1
Materials Research Facilities in France

The materials research system in France offers an interesting counterpoint to that in the United States. Outside of the corporate laboratories, research in France is performed at universities or national laboratories, which are directed at a specific technology, such as atomic energy (Commissariat à l'Energie Atomique [CEA]), or in a series of laboratories working on a broad base of topics called Centre National de la Récherche Scientifique (CNRS). CNRS is a large, 25,000-employee operation with many sites around the country. The main characteristic of CNRS is that the scientists are government employees who benefit from lifetime employment. There is a management body in charge of the evaluation of research teams, but the management also includes union heads whose main focus is on stability of employment.

In recent years, in an effort to decentralize the entire government, the French government has created 22 regions and has passed on some of the funds and administrative responsibility to these regions. Thus, today the CEA is still centrally administered, but the CNRS laboratories have more and more of their activities locally operated. The university faculties are paid by the Ministry of Education, and the universities are run by a central government body. Occasionally, regional governments fund large equipment investments to give the region a good reputation and to attract executives and high-tech companies. Except for synchrotron research, the committee was not able to identify central facilities for the support of materials research funded by the French national government. However, there are a few regionally funded materials-related facilities established to support universities and industry in that region. There are a microscopy facility in the Grenoble area that supports university and industrial research in that region and the well-known laboratory in Toulouse. Another facility, to be located in an industrial park near Rousset in Provence, is in the planning stages. These are targeted directly at the aerospace and semiconductor industries in the region.

GENERAL COMMENTS ON FEDERAL AGENCY POLICIES

Midsize facilities for materials research do not have a programmatic or thematic home across the agencies or in any particular agency. The lack of a specific program of support is only part of the problem, however. When the lack of a specific program of support is combined with a general lack of communication and coordination among facilities, users, and agencies, issues of a more serious nature can arise.

As described in this chapter and Appendix F, midsize facilities have many sources of partial programmatic support across the federal research agencies. However, as pointed out earlier, the important challenges that midsize facilities face are not well met by any specific program. In particular, there is no strong support for the long-term infrastructure that a midsize facility requires in order to be successful continually. The closest model may indeed be the P-41 centers of NIH or the SHARE Facility component of the NSF MRSEC. For the P-41 centers, the five

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explicit components of technological research and development, collaborative research, service, training, and dissemination combine to make a facility that serves the need of a diverse user base and addresses a broad set of research avenues.

During the committee's site visits, several facility directors characterized the NSF model of support for instrumentation as "fund and forget." That is, awards for important instrumentation often provided sufficient sums of money to acquire the instrumentation, but resources were typically insufficient to sustain operations and maintenance of the instrument. And, there was typically no follow-up after an award was received, to certify that the instrument was meeting the needs of the researchers and being managed effectively. As many members of the community were concerned by the lack of follow-up as by the insufficient resources.

This lack of stability and predictability of support for research facilities and instrumentation has recently been recognized and discussed by the National Science and Technology Council's (NSTC's) Research Business Models (RBM) Subcommittee. This subcommittee has held a series of four workshops in order to identify issues through community input. One of the subcommittee's early observations about facilitating multidisciplinary research concerned the need for "stability and predictability of support for research facilities and instrumentation independent of individual projects."[14] The RBM Subcommittee will continue to report to the NSTC and to recommend improvements to the federal research process.

Another agency-specific lesson became apparent to the committee: DOE's BES is a strong supporter of materials research, most notably at the national laboratories. Despite DOE's significant commitment and investment in research infrastructure and workforce development, BES supports only one materials research facility in the nation that is not housed in a national laboratory.[15] The most significant example of a DOE-supported materials research facility based at a university (not affiliated with a national laboratory) is the Center for Microanalysis of Materials (CMM) at the Frederick Seitz Materials Research Laboratory of the University of Illinois at Urbana-Champaign. It is a striking example (see Box 2.1 in Chapter 2). The CMM is nationally famous for its world-class instrumentation, first-rate support staff, and well-maintained facility. Some (non-Illinois) facility directors referred to CMM as "paradise" and a "utopia" for materials microanalysis. For an agency's single investment in a midsize facility at a university to result in

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[14] Research Business Models Subcommittee, "Progress and Next Steps," Washington, D.C.: National Science and Technology Council, March 16, 2004. Also available online at http://rbm.nih.gov/20040316_RBM_status_report.ppt; last accessed June 1, 2005.

[15] DOE's BES supports two other midsize facilities based at universities—the Notre Dame Radiation Laboratory at the University of Notre Dame and the James R. McDonald Laboratory for Atomic, Molecular, and Optical Physics at Kansas State University—but they are not focused on materials research.

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such high praise is surely remarkable and thought-provoking. Embedded within the Ames National Laboratory at Iowa State University, DOE's Materials Preparation Center also draws impressive praise.

The committee draws a careful distinction between gaps in federal agency programs and the predisposition of peer review panels—composed primarily of members of the materials research community. The committee notes the important role that perceptions of proposal reviewers and funding agencies play when assessing funding requests related to midsize facilities. Applications for workhorse machines for routine characterization are often not as well received as those proposing racehorse types, yet both are important for the national infrastructure. At NCEM, workhorse machines (basic microscopes) have been almost impossible to obtain because of the facility's focus on advanced microscopy. NCEM has been able to acquire such instruments only through special arrangements with manufacturers during the purchase of racehorse machines. It was noted that two $0.5 million machines for standard characterization are a lot less exciting to a funding agency and its peer review community than is a single $1 million cutting-edge machine. The Center for High Resolution Electron Microscopy at Arizona State University has experienced similar constraints: a basic microscope was purchased using funds awarded by the federal Department of Education.

This observation bears repeating: A large component of the racehorse-versus-workhorse issue is related to the perceptions of value and impact within the materials research community. For example, many researchers' perception of impact is strongly tilted toward sophisticated rather than basic instruments. Consequently, the former are valued more highly than the latter by the community. This is reflected in the way that the peer community evaluates research proposals. If the materials research community is to seriously exploit the full potential of midsize facilities, it will need to do its part to change the internal culture.

In a similar vein, it was noted that instrument development is likely to be less well received than is instrument purchase in the peer review proposal system, although NSF explicitly supports some instrumentation development under the MRI program (these projects are in the minority in the list of approved awards). Instrument development at a facility can enhance the working environment greatly, as well as providing remarkable innovations. A balanced portfolio combining advanced with basic equipment, and off-the-shelf instruments with instrument development, is important when judging competing facility requests.

It is clear that the survival of many facilities hinges on the recovery of expenses through user fees. However, whenever a grant is awarded, the negotiation of the award between the agency and the principal investigator involves a degree of cost trimming. Since student and postdoctoral salaries are invariable, the category that often is easiest to prune is support for services (i.e., facility costs). As a conse-

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quence, the amount of support for facility usage throughout the duration of the grant is reduced to a level that is not in accord with the research needs. The importance of providing adequate funds to cover facility costs, perhaps as a guideline percentage line item, should not be underestimated.

The committee emphasizes that it is not advocating for or against user fees: this cost-recovery mechanism is simply a business tool that many midsize facilities use to generate operating revenue in order to meet the demands of a realistic budget. Some facilities, such as those embedded within the DOE national laboratories, are able to secure this support directly from the agency and therefore do not employ user fees. Of course, by supplying individual investigators with research awards that include funds for the payment of user fees, federal agencies are inevitably underwriting this part of facility operating budgets.

There are some consequences to these different approaches. In a free market, one would expect users to flock to facilities that do not charge user fees because of the perceived bargain. (For instance, as reported at the CMM, eliminating user fees more than tripled usage.) A significant backpressure is supplied, however, through the problems of oversubscribed resources: time-until-access can exceed several months, or on-site training can be compromised. That is, many users prefer to "pay to do it now rather than wait in line to do it for free." In an environment in which users are not well informed about their consumer choices, however, these trade-offs are not always realized.

Midsize facilities provide access to and support for relatively expensive equipment. It is common practice among U.S. institutions for investigators to negotiate with vendors as individuals for each single instrument. Different facilities will negotiate for different instruments because of different resources and needs, but when these needs overlap, there is potential for both redundancy and inefficiency. One could imagine that cost savings might accrue from a consolidated equipment purchase, spread among several competing institutions over a period of time. In this scenario, one might imagine identifying a national infrastructure need for 10 focused-ion beam machines over the next 5 years; the net cost to the federal program could be much less if the acquisition was proposed as a consolidated purchase at the national level rather than as a series of one-time negotiations. The machines would not be identically configured, of course. The concept of a national strategy would result in a much stronger (and more highly leveraged) infrastructure. The DOE TEAM project echoes some of this type of thinking, as do the DOE Nanoscale Science Research Centers.

However, the committee's enthusiasm for this possibility is restrained by the question of the feasibility of such intimate coordination and agreement and the risks involved in being overly prescriptive. For instance, the one-time negotiations that secure instruments for midsize facilities are often dominated by very special

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and very local circumstances that allow the investigator unique bargaining power. Generalizing equipment purchases to provide for a national strategy would not, in general, take advantage of these possibilities.

Additionally, the individual and specific needs of different facilities would be challenging to simultaneously identify and coordinate in order to build a competitive national bid. Clearly, though, the nation has identified a need for intense synchrotron radiation sources, and the national light sources are therefore coordinated and connected. Regional facilities (or facilities working together within a region), therefore, could benefit by coordinating their needs for joint acquisition strategies. One example might be the joint purchase of similar instruments from the same vendor by two facilities within a region. Similarly, one facility might work with a larger and more-experienced facility to develop a stronger negotiation with a common vendor. Another possibility might be that of bundled service and maintenance contracts within a region. In general, to the extent that strategic partnerships can be formed with vendors to reduce the costs of acquiring and maintaining equipment, they should be pursued.

THE CASE FOR REGIONAL AND REGIONALLY NETWORKED FACILITIES

The National Nanotechnology Infrastructure Network (NNIN) is evidence that a regionally diverse network of midsize user facilities can be organized, funded, and managed in a way that will make advanced fabrication tools and staff available to hundreds of research programs each year (see Appendix F for details). Furthermore, it testifies to the recognized need for this type of infrastructure. However, the NNIN grew from the smaller National Nanotechnology Users Network, which in turn grew from a single national facility. This evolution spanned more than two decades. With the exciting high-growth path currently occurring in nanofabrication and nanocharacterization, it remains a significant challenge to extract the necessary efficiencies far more rapidly and to organize the materials research infrastructure in a way to meet the demand.

All facilities serve a region of primary users; some facilities serve a national region and are thus national facilities, and some serve an individual investigator's research group. A "regional facility," however, is commonly understood to be a facility that serves a relatively large geographic region, perhaps larger than an individual city but smaller than the largest states (somewhat like the smaller nations of Europe).

The primary drivers for regional facilities are improved access to and improved utilization of the resources (instrumentation and personnel). Midsize facilities in materials research are natural candidates for regionalization according to the following analysis:

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- *Appropriate level of investment.* The capital and recurring investment costs for midsize facilities are of a scale that can be afforded regionally—that is, dozens of such facilities could be afforded nationally. As a counterexample, synchrotron light sources are simply too expensive to provide each of the 50 states with its own such world-class laboratory.
- *Sufficient users.* On the basis of its site visits, town hall meetings, and questionnaires, the committee believes that a relatively broad and uniform community of users for midsize materials research facilities has been identified.
- *Untapped potential.* As mentioned above, a clear message from users was a lack of knowledge about existing midsize materials research facilities. The committee found that many facilities managers (about 40 percent) indicated that they had resources to serve additional users. High utilization is desirable for maximum scientific output. It helps to generate needed funds for instrument maintenance costs and to justify tool upgrades and replacement. The committee warns against "oversubscribing," however, since this practice can create long queues and bottlenecks that delay research and is generally unable to absorb or accommodate outages. The committee observed many effective management styles for controlling this issue, including staff ownership of scheduling for certain tools, Web-based reservation systems, e-mail distributions, Web posting of tool status, and so on. The networking model (see below) describes a method of provisioning these available resources to best use.
- *Networking.* The committee identified several examples of facilities that serve relatively large regions, but most impressive were facilities within the same region or in neighboring regions that work together. Such networking between facilities (e.g., between Harvard University and the Massachusetts Institute of Technology, or between the Northwestern University Atomic and Nanoscale Characterization Experimental Center and the Electron Microscopy Center at ANL) greatly benefited the research and the users. As observed above, hub-and-spoke arrangements appear to be very effective. This form of networking allows a central "hub" resource to specialize and capitalize on cutting-edge research, while so-called spokes focus on educating, training, preparation work, and even workhorse services. Each element retains some autonomy and self-direction, but is able to draw on the expert resources of its neighbors.

The committee notes in passing that NSF supported a Regional Instrumentation Facility program in the 1970s and 1980s. These regional facilities were phased out because they failed to develop the important networking relationships with

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one another and with their users. That is, the facilities failed to effectively serve their regions because many became entirely focused on the on-site investigators' goals.

Regional facilities are, therefore, a natural option when considering strategies for optimizing the nation's facility investments for materials research. By combining resources on a local scale, they retain the flexibility and responsiveness necessary to serve their users' diverse needs, but they are large enough to significantly leverage individual resources. In fact, midsize facilities are already regional facilities in cases where the region perhaps consists of several campuses (on average).

The committee notes, however, that even the largest midsize facilities are still dominated by local users. That is, the size of facilities does not correspond directly to the scale of the geographic regions that they serve. The committee emphasizes this observation. The scale of a facility is not a linear function of its size, investment, and user base. The largest "regional" facilities are indeed national facilities, and the smallest "regional" facilities simply serve the needs of one principal investigator's laboratory. At face value, the optimal region to be served by a facility is determined by the distance that users can travel by car in part of a day (echoing the users' survey responses). However, it is clear that many existing midsize facilities serve regions that are considerably larger and smaller than this scale: the variations depend on the type of instrumentation available and the type of research to be performed.

In order to properly exploit the opportunities of networking midsize facilities at the next level of aggregation, a different type of "regional facility" must be envisioned. The committee believes that a successful regional network requires a minimum level of interconnecting architecture. Through the use of advanced computing and networking infrastructure, professional societies, user groups, individual outreach activities, mutual use agreements, and other cooperative instruments, midsize facilities can better communicate and coordinate their activities—with each other, with the research community, and with the federal research agencies.

Another consideration in regional networking is differences in access time and usage costs. As described earlier, some midsize facilities employ user fees to recover expenses, while others do not. How can such obvious differences in upfront cost be addressed in a regional network in which users are better informed about their range of options? Organizing regional networks around differences in scientific capability is one possibility. But the committee is quick to offer a cautionary note: regional networking or consolidation, if inappropriately implemented, can lead to elitism and an increasing gap between facilities. The essential ingredient is a scientific and research-based partnership among the participants in terms of capability and functionality so that the whole remains greater than any one part. Ultimately, of course, regional networking makes the whole greater than the sum of all its parts.

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A leading example of regional networking is the hub-and-spoke model. Rather than concentrating resources at one point, a set of midsize facilities can coordinate to form a hierarchical network. The hub facility might focus on the most advanced opportunities (i.e., racehorse equipment and professional staff training), while the spokes might specialize in instrumentation and services that are more conventional and more widely used (i.e., workhorse equipment and training). Alternatively, a spoke facility might specialize in a specific set of techniques or capabilities, whereas the hub might retain a broader suite of capabilities. An advantage of the hub-and-spoke model is that the spoke facilities drive the active and two-way relationship between the hub facility and the broader community. An additional advantage of this style of networked facilities is that institutions with different levels of resources can participate. As evidenced by the success of both the CMM at the Frederick Seitz Materials Research Laboratory at the University of Illinois at Urbana-Champaign on a local level and the NCEM at LBNL on a national level, the DOE national laboratory infrastructure can provide an excellent home for such racehorse and hub facilities. However, the extent of this success can be limited by laboratory site access issues, available instrument time, or just general location.

The hub-and-spoke model offers certain economies. A spoke facility with older or less-sophisticated equipment could handle much of the work and serve as a filter for research that makes use of the most sophisticated equipment at the hub facility. Appropriate use of this model might also result in some cost savings, since not every facility would need to have state-of-the-art equipment. A systematic way of gaining access to such high-end capabilities could lessen the drive for every facility to upgrade.

For instance, a hub facility might incur longer lead times for access because of a higher subscription rate. A spoke facility might offer easier and faster access. Similarly, federal agencies invested in a regional network might offer individual investigators research awards with appropriate incentives; for instance, support for user fees at networked facilities might be included as a separate line item.

A key challenge of regional networking is that of identifying the stewards for managing the network and identifying the incentives for encouraging them to do so. Mission agencies currently do not plan to form any new facilities outside of their current geographic infrastructure, for instance, and yet a relatively modest investment by DOE at the University of Illinois facility has had huge impact. Any new such regional facilities may need to be set up with key participation of the universities. (For instance, the State of Ohio helped create and fund a microstructural characterization facility at Case Western Reserve University, a private institution, to ensure that industry in Ohio had access to state-of-the-art instrumentation.) The difficulty is that the purchase of advanced instrumentation is often associated with individual personalities and institutional pride. It is not clear

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how many deans and research provosts will be willing to help support—in cash or in long-term staff—a facility at another site or campus. A federal research agency could assume stewardship through an incentivized role: institutions that collaborate in the siting and long-term staffing, as well as set up a long-term management contract for the running of the facility, could be given priority for support of midsize facilities.

A final important—and rather general—consideration is the role that midsize facilities have in providing research and training opportunities to minorities and traditionally underserved populations—especially those at smaller schools. Because of the large infrastructure burden placed on institutional hosts of midsize facilities, success stories tend to be well correlated with available (but creatively secured) resources. Smaller schools, and especially those without strong research traditions, are increasingly able to obtain sophisticated instrumentation, but because of the combination of the lack of experience, training, and on-site resources, they are often unable to provide the necessary infrastructure to support a successful midsize facility. That is, the infrastructure burden for today's expensive research tools can discriminate among institutions on the basis of their resources.

A clear advantage of a regional facility network, especially the hub-and-spoke model, is that smaller schools could opt to participate in a larger network, when they choose to create a midsize facility, to fully utilize a sophisticated instrument—thereby leveraging their contribution off the pooled resources and experience of the other participating facilities, especially the hub. By taking on a well-defined role in the region with a specific research and training responsibility and a connection to the hub, a smaller school's midsize facility initiative could be substantially enhanced—and have broader impact. A well-planned hub-and-spoke model for regional teaming would provide a safety net for smaller schools and empower their participation in the larger research and training enterprise. That is, no school should be too small for a midsize facility if it is well matched to a region's needs and opportunities.

Implementing a system of regional facilities is challenging in a budget-conscious environment. However, not only is the outlook for federal budgets quite constrained, but the committee was also tasked to consider revenue-neutral solutions. Given these constraints, the committee proposes that facilities participating in the regional network should be chartered with maintaining their capabilities at the state of the art as a whole, and that increased complementarity should be developed at the participating institutions. That is, given the requirement to remain revenue-neutral, the committee identifies formation of and stewardship of a network of regional facilities as a higher priority than that of expanding other single, atomistic facilities.

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Optimizing the Effectiveness of Midsize Facilities

Midsize multiuser facilities play a major role in materials research. They give a broad range of researchers access to equipment and expertise for fabricating, characterizing, and measuring the properties of materials. They serve critical national and strategic needs in advancing the basic sciences. Furthermore, the developments in instrumentation (such as electron-beam writers) that underpin critical tools for industry are often achieved in midsize facilities. Likewise, these facilities play an essential role in the education and training of future scientists and engineers by ensuring that students have familiarity and experience with the latest instrumentation and techniques.

It is widely perceived that midsize facilities for materials research are not optimally developed or fully utilized. The 1999 National Research Council report *Condensed Matter and Materials Physics: Basic Research for Tomorrow's Technology,*[1] for example, found that a great burden had been placed on small research centers in universities and government laboratories and that it was appropriate to strengthen this part of the nation's research infrastructure. Today, that finding is as relevant as ever.

Facilities have a number of important functions:

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[1] National Research Council, *Condensed Matter and Materials Physics: Basic Research for Tomorrow's Technology*, Washington, D.C.: National Academy Press, 1999.

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- Enabling forefront science and technology,
- Acquiring the necessary research equipment and instrumentation,
- Developing new instruments or techniques,
- Training technically skilled staff,
- Carrying out basic and collaborative research activities,
- Educating future scientists and engineers,
- Training and assisting users, and
- Maintaining and repairing equipment.

Noting the lack of sufficient attention to the components of the midsize materials research facilities, previous studies have stated that, in particular, the training, hiring, and retention of staff as well as equipment maintenance and repair were often inadequate.[2] More recently, the escalating cost of instrumentation and the associated large cost-sharing requirements of some instrumentation programs have become a major issue. It is also clear that the high cost of facilities necessarily precludes the establishment of cutting-edge facilities at every research university, government laboratory, and industrial company involved in materials research and development. For example, the replacement costs for the equipment now in place at the 500 or so midsize materials facilities are estimated to be $1 billion to $2 billion. The investment required for the replacement of current equipment is far too great to be realized, leading to the conclusion that sharing facilities and resources is increasingly necessary for the future.

Driving this study is a concern that significant opportunities over a wide cross section of scientific disciplines might be missed if the resources offered by small and midsize user facilities are not fully exploited. The capabilities offered by midsize facilities are generally more wide ranging and much more expensive than are those encountered in a single investigator's laboratory; the sharing of resources has therefore become a necessity. Yet along with the rapidly increasing capabilities of instruments such as electron-beam writers and electron microscopes has come an escalation of the cost of acquisition and maintenance, to the point that smaller facilities typical of individual institutions can no longer afford their purchase and upkeep.

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[2] Most notably, National Research Council, *Condensed Matter and Materials Physics: Basic Research for Tomorrow's Technology*, Washington, D.C.: National Academy Press, 1999, p. 25; and National Science Board (NSB), *Science and Engineering Infrastructure for the 21st Century*, Arlington, Va.: National Science Foundation, 2003, p. 3. The NSB report focuses on the challenges associated with "chronic underinvestment," however, and the present report focuses on the opportunities for optimizing the current investment.

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FINDINGS AND OBSERVATIONS

Today, making scientific advances requires access to sophisticated facilities and instrumentation. The role of such facilities in materials synthesis, fabrication, characterization, and measurement is steadily increasing. In fact, these facilities are essential to the scientific infrastructure of the nation. It is well recognized that efficient and cost-effective utilization of sophisticated and expensive instrumentation is best achieved by making the instrumentation widely available. Shared experimental facilities have thus become an increasingly important part of materials research and development (R&D), and it is increasingly difficult to carry out forefront interdisciplinary materials research without access to at least some of the capabilities of such facilities. There are significant opportunities for accelerating scientific advances in materials and nanotechnology research by invigorating such facilities and allocating their resources to best effect.[3] Accordingly, the committee reemphasizes the importance of midsize facilities.

The growth of interdisciplinary research, the emphasis on research focused on developing new devices and structures, and the impetus toward nanoscience and engineering are also fueling a growing demand for facilities with more sophisticated instrumentation, such as high-resolution secondary ion mass spectrometers and atomic resolution transmission electron microscopes (TEMs). This trend is especially evident in the nanosciences, given that characterization of the structural and electronic properties of materials is dependent on the routine and ready availability of tools such as atomic force microscopy and analytic transmission electron microscopy. Furthermore, as materials with greater complexity are being developed, there is a growing need within the materials community for multiple types of characterization methods. Indeed, much of the intellectual challenge and technological impact comes from investigating and designing materials that are multifunctional. These issues are an inevitable outgrowth of interdisciplinary approaches to materials research.

Concurrently, the costs of instrumentation, service contracts, and staffing have increased substantially in recent years. It is unlikely that this trend will abate, which puts growing emphasis on the need for more effective management of instrumentation facilities. Furthermore, not only has existing instrumentation increased in cost, but capabilities have also expanded, further raising the cost of instrumentation. With the possible exception of general-purpose scientific com-

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[3] The National Science and Technology Council's Research Business Models Subcommittee has recognized these opportunities and is currently investigating new approaches for interdisciplinary collaboration and for more stable support of research facilities and instrumentation.

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putation, the expansion in instrumentation capabilities has always been accompanied by substantial price increases.

Exemplifying these price increases, the TEMs of the 1970s lacked any analytical capabilities and were about $1 per volt (i.e., typically $100,000); those in the 1980s often had energy dispersive spectroscopy (EDS) capabilities (about $250,000); and those available today have field-emission electron sources and capabilities for electron energy loss spectroscopy (EELS), atomic resolution, and scanning transmission electron microscopy (STEM) (about $2 million to $3 million). The next generation of TEMs will likely incorporate some form of lens aberration correction. These new tools bring significant advances in resolution by correcting spherical aberration in the column, providing electron beams of precisely controlled shape and confined energies to minimize chromatic aberrations. Similar increases in capability have occurred in instrumentation for secondary ion mass spectrometry (SIMS), nuclear magnetic resonance (NMR), and equivalent sophisticated techniques.

In addition to access to costly instruments, specialty environments such as clean rooms, hazard-containment laboratories, water purification systems, chemical usage, and so on may be key attractors at shared user facilities. Such embedded infrastructure may be as costly as the instrumentation and therefore is only affordable at shared facilities. Midsize facilities often offer access to these advanced R&D environments to commercial collaborators; the partnerships can invigorate local industry and even spawn new ventures. In the face of increasing globalization, midsize facilities associated with such regions of vigorous technological research and development can enable improved competitiveness.

As the cost of interdisciplinary instrumentation and facilities has increased, host institutions have become less able (in some cases, less willing) to afford the proportionate cost sharing, either directly or indirectly through the additional provision of support staff, technical staff, and other infrastructural contributions that are required to support those facilities. This shortcoming has been compounded by the increase in materials research activities in nontraditional areas such as biomaterials and nanobiotechnology. Furthermore, many universities, large and small—especially those that are state-funded—have been under severe budgetary constraints for several years, jeopardizing the provision of permanent staff and technical support for the long-term viability of facilities.

CONCLUSIONS

As a facility reaches a certain size, a number of operations and management issues require the transition from a loose confederation of funding and management sources to a more centralized system that can support the core infrastructure of the facility. In this report, the committee recognizes a similar need for midsize

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facilities that have reached this level of "critical mass." That is, they have sufficient size and complexity, either in instrumentation or in the supporting technical staffing or even building infrastructure, to require that significant attention and resources be spent on supporting these core activities. The committee terms these core activities long-term infrastructure and recognizes that, as required at the larger national facilities, steady funding and stewardship are required to make midsize facilities work more effectively over the long run.

The committee has identified real challenges facing the future viability of small and midsize facilities. Prominent among these challenges are the following:

- Providing and sustaining long-term infrastructure, which includes
  - —Diverse and stable funding,
  - —Stable and secure staffing,
  - —Visibility to the user community,
  - —Sound management and operational practices, and
  - —Maintaining a balanced and effective suite of equipment;
- Networking with other facilities;
- Balancing competing purposes; and
- Cooperating with commercial interests in compliance with federal guidelines for noncompetition.

These challenges must be addressed in an environment of roughly flat federal funding (in constant dollars) as well as declining state and private resources. In this financial environment, there is already evidence of a possible decline in U.S. leadership in materials research and technology. For example, the fraction of foreign students seeking a U.S. education in the physical sciences has fallen,[4] and the proportion of publications in the physical sciences from U.S. institutions is decreasing in the overall international context.[5] The time is right to optimize existing resources in order to exploit latent opportunities in the current facilities system and to be quite systematic and judicious in the development of new facilities.

Midsize facilities in the United States that provide essential instrumentation support to materials research are estimated by the committee to number about 500 separate facilities; their sizes and levels of involvement vary. They represent a

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[4] NSF InfoBrief (NSF 04-326, June 2004): "Graduate Enrollment in Science and Engineering Fields Reaches a New Peak; First-Time Enrollment of Foreign Students Declines." Available online at http://www.nsf.gov/statistics/infbrief/nsf04326/; last accessed June 1, 2005.

[5] M. Heylin, "Science Is Becoming Truly Worldwide," *Chemical and Engineering News*, June 14, 2004, p. 38.

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capital investment of greater than a billion dollars and an annual operating cost over several hundred million dollars. At current funding levels, this investment exceeds the capability of any one federal funding agency to sustain.

This study found the current operational state of a large proportion of midsize facilities, especially those in universities, to be precarious, jeopardizing the future well-being of the materials research enterprise. Initiatives to exploit recent improvements in the capabilities of instrumentation are severely limited because of the associated costs, threatening stagnation of the field. In general, there is not strong support for the long-term infrastructure that a midsize facility requires to continually be successful. To maintain its preeminent international leadership position in science and technology, the United States must address these and related issues.

Midsize facilities fill a key role in the materials research enterprise. Once dominated by tabletop instruments, materials research has blossomed into an endeavor whose threshold for individual investment has risen substantially over the past decades. By centralizing resources (in terms of equipment, staff, and expertise), midsize facilities provide much-needed focal points of innovation and creativity for research, education, and training. Because of the economic benefits of pooled resources and the escalating costs of instrumentation, midsize facilities can deliver unique capabilities to materials researchers that the researchers cannot individually or independently afford to own, maintain, or operate. Finally, the ubiquity of midsize facilities is one of their greatest strengths: as research needs are identified and as researchers coordinate their activities, it is possible to initiate such a facility, although doing so is becoming more difficult. That is, midsize facilities represent sufficiently small levels of investment that they can be (and are) spread widely around the country. Most importantly, this characteristic allows smaller and non-elite research universities to participate and contribute effectively.

The committee's analysis suggests that midsize facilities represent considerable untapped potential. Many such facilities, a large fraction of them established with federal funds, could serve a considerably broader community as well as advance the development of both techniques and instruments if optimized resources were provided for those purposes. Because of the lack of explicit and dedicated programmatic support for the infrastructure that a midsize facility requires, a significant number of existing facilities are struggling to meet a set of increasingly competing and complex demands.

The greatest challenge faced by midsize facilities is in their long-term infrastructure—which includes such mainstays as resident technical staff, support for sustained operations and maintenance, user training and support, education and outreach, and in-house development of new instrumentation and experimental techniques. Responses to the committee's facilities questionnaire indicate that,

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with rare exceptions, facilities managers believe that they have insufficient operations budgets, and concerns about maintenance expenses are universal.

The committee summarizes its analysis with several conclusions:

- *Importance and uniqueness.* Shared experimental facilities in the form of midsize multiuser facilities are a key component in maintaining the nation at the leading edge of materials research, education, and training. Midsize facilities are everywhere in the materials research landscape, and they offer unique capabilities and benefits, especially when compared with current small-scale and large-scale facilities.
- *Need for long-term planning and commitment.* A continuing and fundamental challenge facing a majority of small to midsize facilities is planning, securing, and maintaining the long-term infrastructure necessary for productivity and success.
- *Need for systematic program planning.* The network of midsize facilities can no longer be treated as atomized and as a set of noninteracting units. There is a substantial opportunity for improved efficiency and effectiveness of the existing network, with increased cooperation, coordination, and consolidation among the individual facilities.
- *A network ripe for optimization.* As a special category within the U.S. materials research enterprise, the class of midsize facilities described herein could contribute even more to national, regional, and local research priorities; it could serve even larger numbers of investigators; and it is ripe for optimization as a system. Certain facilities are closer than others are to optimal operations already: midsize facilities with clear stewards for ongoing operations and maintenance, facilities wholly embedded in the fabric of a larger laboratory infrastructure, and facilities well coordinated with other resources in their respective regions are operating effectively.

RECOMMENDATIONS

In order for the United States to develop and sustain a leadership role in materials research, the committee makes the recommendations presented below. The responsibilities should be shared between the research agencies and the community (as proposers, reviewers, managers, host institutions, and users). Clearly, there is a disconnect between what researchers at midsize facilities perceive to be needed for their success and the level of resources currently available. As directed by its charge to consider revenue-neutral options in these fiscally constrained times, the committee identifies reallocation of existing resources in materials research as an option for addressing the needs of midsize facilities.

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The first two recommendations identify pathways for realizing additional economies and for enhancing the effectiveness of the network of midsize facilities. The second pair of recommendations identifies means for strengthening individual facilities by recognizing the long-term commitments necessary for successful operations. The final recommendation emphasizes the importance of follow-up and follow-through via periodic reviews of the investments made in midsize facilities.

Realizing Economies

Recommendation 1: COLLECTIVE STEWARDSHIP
For the United States to maintain national capabilities to perform world-class, forefront scientific research in materials, the Department of Energy, the National Science Foundation, and other federal agencies should foster cooperative, responsible planning among all stakeholders to provide collective stewardship for midsize facilities. That is, midsize facilities require explicit programmatic planning for their support and oversight. Existing successful facilities should continue, and new opportunities should be created through the reallocation of resources.

Recommendation 2: REGIONAL NETWORKING
To improve the effectiveness of the current national investment in midsize facilities, agencies should realize the economies of networking. That is, midsize facilities participating in a regional network should be given priority for expansions of capability and capacity.

- *Teaming among and consolidation of neighboring facilities to form regional resources should be strongly encouraged by the agencies.*
- *Midsize facilities that are successful in this regard should be provided with adequate long-term infrastructure support.*
- *Proposals for new midsize facilities—or for significant changes to existing midsize facilities—should be viewed within the context of the particular region involved; such proposals should develop a strong business case based on measured need within the region and should outline expected relationships with existing resources in the region.*
- *To facilitate networking, midsize facilities should develop an online inventory of resources that would enable users to optimally identify facilities for their use and to allow managers to make referrals.*

Midsize facilities in materials research differ from the large national facilities because of the lack of a programmatic home for any and for all of them. That is,

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the large national user facilities have explicit program agency stewards that oversee their long-term viability. In many cases, investments for capital costs and operating expenses at a midsize facility are made by different programs within a federal agency, by different agencies of the federal government, or even by state, local, or private organizations.

Midsize facilities suffer individually and collectively from the lack of coordinated stewardship: typically, host institutions (usually universities) do not monitor the effectiveness of the facility, federal agency funds provided for the acquisition or construction of new instrumentation are not reviewed for impact, and user communities are not sufficiently informed about alternatives to make judicious choices. Explicit, programmatic planning at the level of the federal agencies should help coordinate and connect midsize facilities with mechanisms for their long-term viability. The steward of a midsize facility should be identified as the party most responsible for the continuing operations and maintenance of that facility. In many cases, this party will be a federal research program; in some instances, it may include a state program or an institutional entity such as a university provost's office or the office of a national laboratory director.

Stewardship should also take into account the regional context. Instrumentation of the sort housed in midsize facilities is a long-term obligation (both in terms of personnel and upkeep) that is not necessarily addressed well in the current network of facilities. Since the nation cannot afford to place midsize materials research facilities and instruments at every possible location and since many institutions have considerably less than a full-time need for them, the development of a system of regional user facilities is an effective way to fully address the diverse needs of midsize facilities.

It is also highly desirable that these facilities be actively engaged in networking with other facilities that have similar capabilities or complementary instrumentation. These relationships will encourage rapid sharing of new methods for use of instrumentation and will facilitate user access to related technologies of increasing importance for interdisciplinary projects. The committee believes that by explicitly planning for the operation and support of a system of coordinated midsize facilities, agencies can realize certain economies to allow the provision of specific incentives and to expand the effectiveness of the system as a whole. Before facilities are approved or significant enhancements to capabilities are awarded, proposals should be evaluated in a regional context by the federal agencies. Likewise, consideration should be given to a more regionally or nationally minded approach to planning for and purchasing instruments, rather than engaging in many individual negotiations.

Making use of the existing facilities would allow regional outreach to proceed more rapidly. Reliable support for long-term infrastructure, for instance, would

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provide incentives and would enable these facilities to take on the important challenges of training and educating the materials scientists and technologists of the future, developing the next generation of instrumentation and analytical techniques, and providing an even larger community of researchers with access to enhanced capabilities for research. The committee offers the hub-and-spoke model as one example of an effective regional network.

Moreover, the committee has observed that most high-quality facilities require some degree of additional support in order to provide stability, to improve the instrumentation, and to fulfill the facilities' educational responsibilities. It is anticipated that a portion of such facilities' operations and maintenance costs will be met by user fees. Thus, the importance of such fees as a line item in funded grants should be recognized by the agencies. Given that these high-quality regional facilities will be expected to address the needs of neighboring institutions, some of the operations and maintenance costs should be provided directly by the research agencies. Similarly, these facilities should be encouraged to develop new techniques and/or instrumentation. Thus, midsize facilities should be planned and operated in a manner that is intermediate between the smallest service centers with single, commercially purchased instruments and large national laboratories such as synchrotron radiation or neutron-scattering facilities.

Many already-existing facilities and instruments could greatly enhance the overall research and educational effectiveness of U.S. universities, 4-year colleges, and community colleges, as well as the productivity of local industry and companies that do not otherwise have access to such capabilities. For instance, regional facilities located in areas of high industrial concentration and activity would be expected to have a larger role in impacting the regional development of technology.

Improving Effectiveness

> *Recommendation 3: LONG-TERM INFRASTRUCTURE*
> *Host institutions and supporting agencies should give high priority to maintaining the long-term viability of midsize facilities, including long-term infrastructure such as resident staff, normal operating costs including maintenance contracts, user training and support, education and outreach, and in-house development of instrumentation and techniques. Midsize facilities that are successful in the context of teaming should be provided with improved support.*

The nation is currently making investments in sophisticated instrumentation without considering the commensurate long-term requirements of operations and maintenance. In a revenue-neutral environment, support for long-term infra-

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structure of successful facilities should be carefully judged within a region against awards for new facilities or significant enhancements to existing capabilities. Facilities organized to provide access and support for sophisticated instrumentation are struggling to identify the necessary resources to provide the dividends on the initial capital investment. The committee recommends that agencies supporting materials research explicitly recognize the needs of midsize facilities programmatically, thereby allowing midsize facilities to be judged fairly against one another on common grounds in competitive peer review. Stewardship mechanisms should reflect the specific needs of midsize facilities; for example, funding should be long term, and oversight should also be longer term and should be better matched to the activities of facilities.

> *Recommendation 4: PROFESSIONAL STAFFING*
> *Midsize facilities require extraordinarily talented and experienced staff. The career paths of these individuals should be respected and cultivated. A midsize facility should include technical and Ph.D.-level professional staff members who are offered opportunities for career development and/or participation in ongoing facility research. Operating plans for midsize facilities should explicitly address this issue.*

Since midsize facilities serve users from different institutions who have a broad range of experience in using instrumentation and techniques, it is vital that the facilities have resident staff to provide user education and support. Professional staff members are also necessary to develop and improve a facility in order to address specialized needs and to take advantage of emerging scientific opportunities.

At the heart of fulfilling their mission is the reliance of midsize facilities on their experienced staff to engage users, operate and maintain instruments, and enhance instrumentation. Accordingly, the committee recommends that the educational efforts of midsize facilities should also emphasize programs that explicitly provide ongoing training and career development for facility support staff.

Follow-up

> *Recommendation 5: PERIODIC REVIEW*
> *Successful performance should be identified and rewarded. Consistent with their long-term responsibilities, sponsors should periodically review midsize facilities to ensure that the facilities' primary objectives are continuing to be met, potential improvements to operations and instrumentation are identified, and continued*

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funding is appropriate. The depth of the reviews should be commensurate with the funding levels.

The operation of a regional facility that effectively meets researchers'—and the nation's—needs requires commitment, thoughtfulness, and effort considerably beyond what is required to maintain instruments for a single investigator or a small number of researchers. Periodic reviews provide opportunities to identify potential improvements to the facility's operations and instrumentation, as well as to assess the adequacy of funding. Finally, situations in which facility operation is no longer appropriate can be identified. Review panels should be composed of experts from both the scientific and the midsize project management domains. Criteria to be considered in such reviews should include the following:

- Instrument maintenance and upkeep;
- Accessibility and openness to users, including mechanisms for new user education, support, and training;
- The quality of educational programs, including professional training and development of staff;
- The development of new techniques or instrumentation;
- Effectiveness in meeting regional needs, including strong links to other facilities (small, midsize, or large) offering similar or complementary capabilities;
- Mechanisms for incorporating suggestions for improvements from the facility's network of users;
- Evidence of sound management plans and practices; and
- A record of cooperation and noncompetition with commercial interests in compliance with federal guidelines and regulations.

The committee recommends that periodic reviews of midsize facilities be used as one of the primary criteria in evaluating whether support for a facility's operations should be continued. One possible outcome of such a review might be an increase in funding for a facility's operations or improvements to its instrumentation. Another could be the transfer of the instrumentation to some other host institution. Consequently, the federal government should retain title to the instrumentation at a regional user facility for at least one major review cycle.

* * * * *

Midsize facilities have played a pivotal and invigorating role in materials research. By providing access to shared tools, training, and resources, these facilities

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have been a cornerstone of research for a broad cross section of the community. Since the days of the first interdisciplinary research laboratories in the 1960s, materials research has blazed a trail in recognizing and responding to the needs of its investigators. It is now time to acknowledge the need for the next phase of transition, from a system of loosely connected independent facilities to a networked effort of coordinated facilities. By leveraging such opportunities, the materials research enterprise will continue to offer a transformative and effective path to the future.

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Appendixes

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A

Statement of Task

The proposed study will review the state of small and mid-sized multi-user facilities within the materials research complex in the United States and will consider methods for optimizing the use of existing resources, including the consideration of structural strategies and actions to provide services more efficiently through the implementation of revenue-neutral solutions. These facilities are recognized as a key feature of materials research, yet there is concern that they are not being optimally developed or utilized and that new opportunities for scientific development are not being properly pursued. Although the study will confine its recommendations to university and national laboratory facilities, it will also examine the operations of materials facilities in the commercial sector and in the international arena.

Specifically, the study's task will incorporate the following elements:

1. Providing a definition of small and mid-sized multi-user facilities and their role in the materials research complex.
2. Collecting data on the usage, costs and structure of smaller facilities and compiling an inventory of small equipment clusters.
3. Examining the current models of facility operation and assessing their cost/effectiveness, considering the appropriate metrics for facility success, and assessing criteria for minimal size.

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4. Exploring alternate methods of instrumentation utilization such as:
   a. Increasing user groups at small facilities to 10-20 independent investigators.
   b. Establishing regional centers by identifying equipment appropriate for consolidation into multi-user shared facilities.
5. Examining opportunities for instrumentation research in the context of facilities, including the impact of these on science and industry and the determination of the optimal location of instrumentation development activities.
6. Assessing the educational role played by small facilities.
7. Exploring the need for long-range support models for these facilities.
8. Assessing the effect, if any, of the policies and structure of the federal research agencies that support smaller facilities.
9. Analyzing the issues from an international perspective.

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B

Committee Meeting Agendas

FIRST MEETING
NATIONAL RESEARCH COUNCIL—WASHINGTON, D.C.
MAY 12-13, 2003

Monday, May 12, 2003

Closed Session

8:30 a.m.	Welcome and Introductions —Robert Sinclair, Chair
9:00	Opening Thoughts
10:30	Committee Composition and Balance Discussion —Donald Shapero, Director, Board on Physics and Astronomy —Robert Sinclair
11:30	Discussion of Study Task and Scope —Robert Sinclair
Noon	Working Lunch

Open Session

1:00 p.m.	Perspectives from the National Science Foundation, Division of Materials Research —Hugh Van Horn, National Science Foundation

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1:30	Perspectives from the Department of Energy, Office of Basic Energy Sciences —Patricia Dehmer, Department of Energy, Office of Basic Energy Sciences
2:00	Smaller Facility Perspectives I —Ani Aprahamian, University of Notre Dame
2:20	Smaller Facility Perspectives II —Uli Dahmen, National Center for Electron Microscopy
2:40	Smaller Facility Perspectives III —John Soures, University of Rochester, Laboratory for Laser Energetics
3:00	Break
3:30	Smaller Facilities—National Institutes of Health, Division of Bioengineering and Physical Science —Richard Leapman, National Institutes of Health, Division of Bioengineering and Physical Science
3:50	University-Based Smaller Facilities —David Smith, Arizona State University
4:10	Commercial and Industrial Smaller Facilities —Charles A. Evans, Jr., Full Wafer Analysis, Inc.
4:30	From Small to Large Facilities —Arthur Bienenstock, Stanford University
5:00	Adjourn

Tuesday, May 13, 2003

8:30 a.m.	Review of Yesterday's Business —Robert Sinclair
9:00	Origins of the Study —J. Murray Gibson, Argonne National Laboratory, Advanced Photon Source, Solid State Sciences Committee
10:00	Break
10:30	Definition of a Smaller Facility —David Clarke, University of California at Santa Barbara
11:15	Site Visit Plans and Protocol —Robert Sinclair
12:00 p.m.	Working Lunch
1:00	Committee Discussions
3:00	Adjourn

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SECOND MEETING
STANFORD UNIVERSITY—STANFORD, CALIFORNIA
OCTOBER 10-12, 2003

Friday, October 10, 2003

Closed Session

6:00 p.m.	Working Dinner
9:00	Adjourn

Saturday, October 11, 2003

Closed Session

8:30 a.m.	Welcome and Meeting Goals —Robert Sinclair
8:45	Review of Site Visits
12:15 p.m.	Working Lunch
1:45	Break
2:00	Smaller Facilities and Smaller Schools —Walter Lowe, Howard University
2:45	Microscopy Technology Center —Judy Murphy, San Joaquin Delta College
3:30	Break
3:45	Personal Perspectives —Helene Schember, Cornell University
4:30	James R. Macdonald Laboratory —Pat Richard, Kansas State University
5:15	Open Discussion
6:00	Adjourn

Sunday, October 12, 2003

Closed Session

8:30 a.m.	Committee Discussion
1:00 p.m.	Adjourn

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THIRD MEETING
NATIONAL RESEARCH COUNCIL—WASHINGTON, D.C.
MAY 21-23, 2004

Friday, May 21, 2004

Closed Session

6:00 p.m.	Working Dinner
9:00	Adjourn

Saturday, May 22, 2004

Closed Session

9:00 a.m.	Goals of the Meeting —Robert Sinclair
9:15	Review of Committee Balance and Composition —Donald Shapero
9:30	Discuss Findings and Recommendations
Noon	Working Lunch
1:00 p.m.	Review Questionnaire Responses
3:00	Writing Group Breakout Sessions
5:30	Adjourn

Sunday, May 23, 2004

Closed Session

9:00 a.m.	Continue Discussions of Final Report
Noon	Working Lunch
1:00 p.m.	Revisit Charge to the Committee
2:00	Final Plans and Homework Assignments
3:00	Adjourn

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C

Description and Analysis of Questionnaires

To better inform its deliberations, the Committee on Smaller Facilities (COSF) determined that a pair of questionnaires should be distributed broadly to the community. One questionnaire solicited feedback from facility managers, the other from facility users. Because of biases introduced by the self-selected population that responded to the questionnaire, the committee does not believe that these results are statistically significant; rather, they are intended to give a flavor of the population. The questionnaires are reproduced in this appendix.

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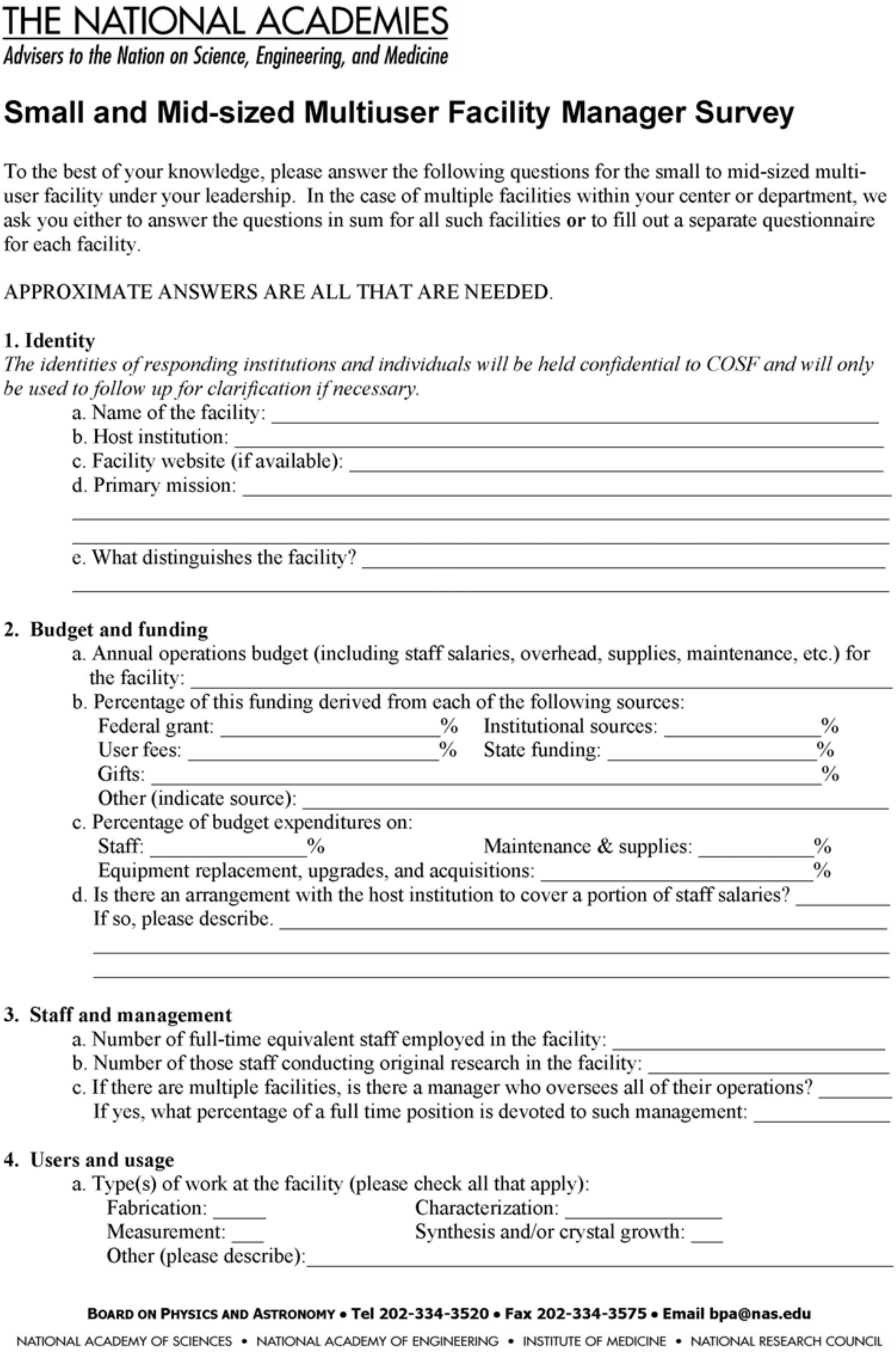

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Small and Mid-sized Multiuser Facility Manager Survey

To the best of your knowledge, please answer the following questions for the small to mid-sized multi-user facility under your leadership. In the case of multiple facilities within your center or department, we ask you either to answer the questions in sum for all such facilities **or** to fill out a separate questionnaire for each facility.

APPROXIMATE ANSWERS ARE ALL THAT ARE NEEDED.

1. Identity

The identities of responding institutions and individuals will be held confidential to COSF and will only be used to follow up for clarification if necessary.

a. Name of the facility: ____________________
b. Host institution: ____________________
c. Facility website (if available): ____________________
d. Primary mission: ____________________
____
____
e. What distinguishes the facility? ____________________
____

2. Budget and funding

a. Annual operations budget (including staff salaries, overhead, supplies, maintenance, etc.) for the facility: ____________________
b. Percentage of this funding derived from each of the following sources:
Federal grant: __________% Institutional sources: __________%
User fees: __________% State funding: __________%
Gifts: ____________________%
Other (indicate source): ____________________
c. Percentage of budget expenditures on:
Staff: __________% Maintenance & supplies: __________%
Equipment replacement, upgrades, and acquisitions: __________%
d. Is there an arrangement with the host institution to cover a portion of staff salaries? ______
If so, please describe. ____________________
____
____

3. Staff and management

a. Number of full-time equivalent staff employed in the facility: __________
b. Number of those staff conducting original research in the facility: __________
c. If there are multiple facilities, is there a manager who oversees all of their operations? ______
If yes, what percentage of a full time position is devoted to such management: ______

4. Users and usage

a. Type(s) of work at the facility (please check all that apply):
Fabrication: _____ Characterization: __________
Measurement: ___ Synthesis and/or crystal growth: ___
Other (please describe): ____________________

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b. What is the breakdown of scientific disciplines of users (physics, chemistry, biology, etc.) and in what percentages?
 Discipline 1: ____
 Discipline 2: ____
 Discipline 3: ____
c. Is the facility oversubscribed or undersubscribed?
 Oversubscribed: ________ By what amount? ______ %
 or Undersubscribed: _____ By what amount? _______%
d. Number of distinct users served annually: ______________________
e. Percentage of users who are:
 Graduate students and post-docs: ___________%
 Government lab staff researchers: ___________%
 Undergraduates: _________________________%
 Commercial/industrial researchers:__________%
f. Percentage of users who are:
 From within the host institution: ____________________________%
 Local, but outside host institution: __________________________%
 Regional (within a day's travel by car): ______________________%
 National/international (overnight stay required): _______________%
g. Percentage of facility usage for each of the following:
 User research (including user training and support): __________%
 Service research (conducted by technical staff): _____________%
 Instrument technology and applications development: ________%
 Other (please describe): ______________________________%
h. Are there facilities with similar capabilities at the host institution? _______________________
i. What formal coordination exists among facilities at the host institution to develop complementary capabilities? ____
____
j. If the facility has a formal users' group, please provide contact information: _______________
____

5. Equipment and capital investment

a. Replacement capitalization cost (at today's prices) for all instruments in the facility: ________
b. Average annual investment in capital equipment (from all sources of funding): ____________
c. What is your most heavily used instrument? ____
d. Most important acquisition planned in the next five years and its estimated cost:
____
____

6. Other comments (optional)

Please provide any additional comments that might be relevant to the committee's task. For instance, you may comment on future needs of your facility or any challenges experienced in operating your facility. We are also particularly interested in thoughts on how to improve the facilities system—increasing usage, effectiveness, impact, etc. Finally, feel free to elaborate on any of the answers provided above.

____
____
____
____

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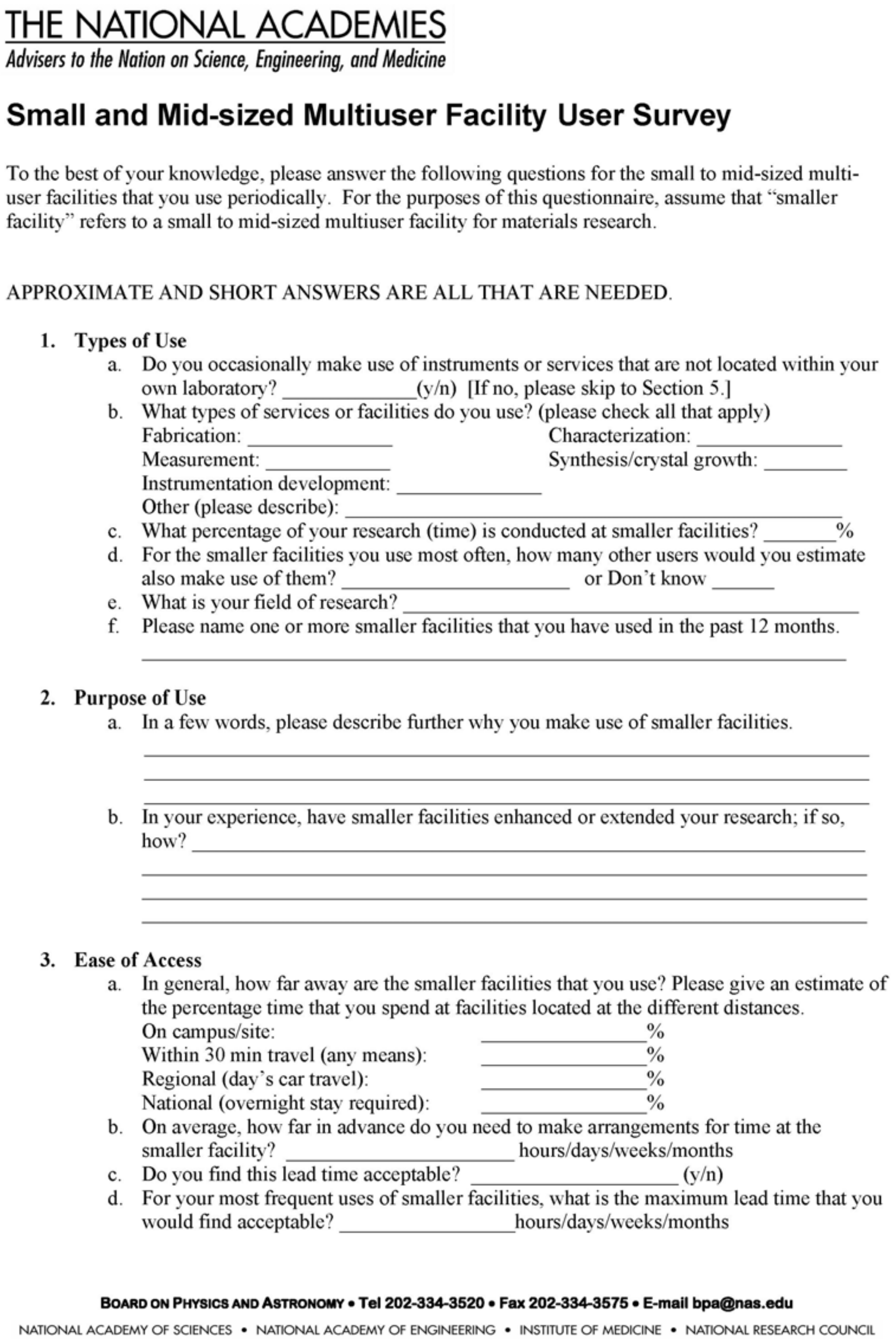

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Small and Mid-sized Multiuser Facility User Survey

To the best of your knowledge, please answer the following questions for the small to mid-sized multiuser facilities that you use periodically. For the purposes of this questionnaire, assume that "smaller facility" refers to a small to mid-sized multiuser facility for materials research.

APPROXIMATE AND SHORT ANSWERS ARE ALL THAT ARE NEEDED.

1. **Types of Use**
   a. Do you occasionally make use of instruments or services that are not located within your own laboratory? ____________(y/n) [If no, please skip to Section 5.]
   b. What types of services or facilities do you use? (please check all that apply)
      Fabrication: ____________ Characterization: ____________
      Measurement: ____________ Synthesis/crystal growth: ________
      Instrumentation development: ____________
      Other (please describe): ________________________________
   c. What percentage of your research (time) is conducted at smaller facilities? _______%
   d. For the smaller facilities you use most often, how many other users would you estimate also make use of them? ________________ or Don't know ______
   e. What is your field of research? ________________________________
   f. Please name one or more smaller facilities that you have used in the past 12 months.
      ____

2. **Purpose of Use**
   a. In a few words, please describe further why you make use of smaller facilities.
      ____
      ____
      ____
   b. In your experience, have smaller facilities enhanced or extended your research; if so, how? ____
      ____
      ____
      ____

3. **Ease of Access**
   a. In general, how far away are the smaller facilities that you use? Please give an estimate of the percentage time that you spend at facilities located at the different distances.
      On campus/site: ______________%
      Within 30 min travel (any means): ______________%
      Regional (day's car travel): ______________%
      National (overnight stay required): ______________%
   b. On average, how far in advance do you need to make arrangements for time at the smaller facility? ________________ hours/days/weeks/months
   c. Do you find this lead time acceptable? ________________ (y/n)
   d. For your most frequent uses of smaller facilities, what is the maximum lead time that you would find acceptable? ______________hours/days/weeks/months

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e. If ideal facilities became available, considering travel, and setup time, how far would you be willing to travel to use them? (in miles or hours) ____________________________

f. If ideal facilities became available, considering the travel expense and user fees, what level of cost would be prohibitive for you to consider their use? (either in terms of total cost, cost per hour, or other measure relevant to you) ____________________________
____

g. To generalize, what is the number one criterion for determining which facility you will use? ____
____
____

4. Quality of Service

a. In general, what percentage of your time using the smaller facility are you operating the instruments yourself, relatively unattended?

b. If you or your students have been trained on equipment at smaller facilities, are you satisfied with the degree of training that was provided? _______________ (y/n)

c. In general, when registering to use a smaller facility, do you speak with a facility manager or technical staff person? ____

d. When you have questions or concerns about the equipment and facilities, to whom do you go for answers?

Facility director: _________	Technical staff person: __________
Colleague: ______________	Another user: __________________

5. Facility Outreach

a. Would you say that you are well aware of the smaller facilities at other institutions (local, regionally, and nationally) that could assist you in your research and/or training needs? _________(y/n)

b. If so, how did you learn about those facilities? _________________________________
____
____

c. What kinds of resources could help you identify such facilities? ___________________
____
____

d. If you have prepared proposals for research funding, have you included requests for access to and use of specific smaller facilities (on site, nearby, in your region, or nationally) in the grant proposal? _____ (y/n) Likewise, when preparing budget estimates for a research proposal, to what extent do you include estimates for user fees to take advantage of specific smaller facilities? ________ (y/n)

Please comment further. ____
____
____

Finally, what level of financial support per year would be necessary to fully enable your research by providing sufficient access to smaller facilities? _$________________

e. In general, are you satisfied with your experiences using smaller facilities? ________ (y/n)

f. In general, have you recommended your colleagues to any smaller facilities? _____ (y/n)

g. Have you ever considered commercial alternatives to smaller facilities? _________(y/n)
Why or why not (too expensive, too slow, too far, etc.)? _________________________
____

h. Have you considered remote operation of and access to smaller facilities to reduce the travel required? _____________ (y/n) Why or why not? _________________________
____

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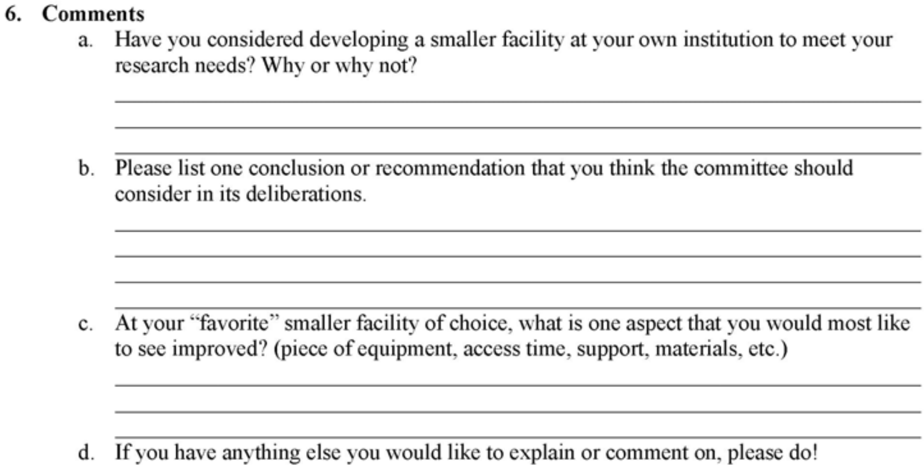

6. Comments

- a. Have you considered developing a smaller facility at your own institution to meet your research needs? Why or why not?
- b. Please list one conclusion or recommendation that you think the committee should consider in its deliberations.
- c. At your "favorite" smaller facility of choice, what is one aspect that you would most like to see improved? (piece of equipment, access time, support, materials, etc.)
- d. If you have anything else you would like to explain or comment on, please do!

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FIGURE C.1 Sites in the continental United States targeted for dissemination of the committee's facilities' and users' questionnaire.

DISTRIBUTION

The questionnaires were distributed to the community (see Figure C.1) by a variety of techniques:

- Direct e-mail to facilities identified by committee members and staff, as indicated below in the list of 275 facilities;
- Electronic posting on the committee's public Web site;
- Paper distribution at the American Physical Society's March 2004 meeting in Montreal, Canada, and the Materials Research Society's April 2004 meeting in San Francisco, California; and
- E-mail solicitation to subscribed members of the American Physical Society's Division of Materials Physics and Division of Condensed Matter Physics.

Following is the list of facilities specifically targeted to receive the facilities' and users' questionnaires by direct e-mail solicitation.

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1. Active Materials Laboratory, University of California at Los Angeles
2. Advanced Analysis Facility, University of Wisconsin at Milwaukee
3. Advanced Coatings and Surface Engineering Laboratory, Colorado School of Mines
4. Advanced Materials Characterization Laboratory, State University of New York at Stony Brook
5. Advanced Materials Processing and Analysis Center, University of Central Florida
6. Advanced Materials Research Center, University of Florida
7. Alabama Microelectronics Science and Technology Center, Auburn University
8. Ames Laboratory, Iowa State University
9. Analytic Instrumentation Facility, North Carolina State University
10. Atomic Resolution Electron Microscopy Center, North Carolina State University
11. Australian Key Centre for Microscopy and Microanalysis, University of Sydney
12. Basic Plasma Science Facility, University of California at Los Angeles
13. Biofilm Research Center, Stanford University
14. Biological and Biomaterials Preparation, Imaging, and Characterization Laboratory, University of Wisconsin at Madison
15. Biological Imaging Resource Center, California Institute of Technology
16. Biological Science Division Core Facilities, University of Chicago
17. Biology Imaging Center, University of California at San Diego
18. Biomolecular Research Facility, University of Virginia Health System
19. Butler Polymer Laboratory, University of Florida
20. California Nanosystems Institute, University of California at Los Angeles
21. Campus Chemical Instrumentation Center, Ohio State University
22. Campus Microscopy and Imaging Facility, Ohio State University
23. Carnegie Mellon Materials Research Science and Engineering Center, Carnegie Mellon University
24. Center for Accelerated Maturation of Materials, Ohio State University
25. Center for Adaptive Optics, University of California at Santa Cruz
26. Center for Advanced Electron Microscopy, Brookhaven National Laboratory
27. Center for Advanced Materials and Nanotechnology, Lehigh University
28. Center for Advanced Materials and Smart Structures, North Carolina State University
29. Center for Advanced Materials Immiscible Polymer Processing, Rutgers University
30. Center for Advanced Materials Processing, Clarkson University

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31. Center for Advanced Materials Research, Brown University
32. Center for Advanced Polymer and Composite Engineering, Ohio State University
33. Center for Advanced Thin Film Technology, State University of New York at Albany
34. Center for Applied Isotope Studies, University of Georgia
35. Center for Biological and Environmental Nanotechnology, Rice University
36. Center for Biologically Inspired Materials and Materials Systems, Duke University
37. Center for Biologically Inspired Nanocomposite Materials, University of California at Santa Barbara
38. Center for Composite Materials, University of Wisconsin at Milwaukee
39. Center for Composite Materials, University of Delaware
40. Center for Composite Materials, University of Southern California
41. Center for Computational Chemistry, University of Georgia
42. Center for Computational Materials Science, Georgia Institute of Technology
43. Center for Electrochemical Science and Engineering, University of Virginia
44. Center for Electron Microscope and Microanalysis, University of Southern California
45. Center for Electronic Materials, Devices and Systems, Texas A&M University
46. Center for Electronic Materials and Devices, San Jose State University
47. Center for Excellence in Nanoelectronics, State University of New York at Albany
48. Center for Functional Nanomaterials, Brookhaven National Laboratory
49. Center for High Resolution Electron Microscopy, Arizona State University
50. Center for High Technology Materials, University of New Mexico
51. Center for High-Resolution Neutron Scatter, National Institute of Standards and Technology
52. Center for Integrated Nanotechnologies, Sandia National Laboratories
53. Center for Interface and Materials Science, University of California at San Diego
54. Center for Magnetic Recording Research, University of California at San Diego
55. Center for Materials Chemistry, University of Houston
56. Center for Materials for Information Technology, University of Alabama
57. Center for Materials Processing, University of Tennessee at Knoxville
58. Center for Materials Research, Ohio State University

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59. Center for Materials Science and Engineering, Massachusetts Institute of Technology
60. Center for Materials Simulation, University of Connecticut
61. Center for Micro Analysis and Reaction Chemistry, University of Utah
62. Center for Micro and Nano Processing, Case Western Reserve University
63. Center for Microelectronic Materials and Structures, Yale University
64. Center for Micro-engineered Materials, University of New Mexico
65. Center for Micromagnetics and Information Storage Technologies, University of Minnesota
66. Center for Molecular and Atomic Studies at Surfaces, Vanderbilt University
67. Center for Nanophase Materials Science, Oak Ridge National Laboratory
68. Center for Nanoscale Materials, Argonne National Laboratory
69. Center for Nanoscale Science, Pennsylvania State University
70. Center for Nanoscale Science and Technology, Rice University
71. Center for Nanoscience and Technology, University of Notre Dame
72. Center for Nanoscopic Materials Design, University of Virginia
73. Center for Nanostructured Materials, Columbia University
74. Center for Nanotechnology, University of Wisconsin at Madison
75. Center for NMR Spectroscopy, Washington State University
76. Center for Polymer Science and Engineering, Lehigh University
77. Center for Polymer Studies, Boston University
78. Center for Research at the Bio/Nano Interface, University of Florida
79. Center for Response-Driven Polymeric Films, University of Southern Mississippi
80. Center for Self-Assembled Nanostructures and Devices, Virginia Polytechnic Institute and State University
81. Center for Semiconductor Physics in Nanostructures, University of Arkansas and University of Oklahoma
82. Center for Sensor Materials, Michigan State University
83. Center for Solid State Electronics Research, Arizona State University
84. Center for Structural Biology, Vanderbilt University
85. Center for Surface Analysis of Materials, Case Western Reserve University
86. Center for the Science and Engineering of Materials, California Institute of Technology
87. Center for Thermal Spray Research, State University of New York at Stony Brook
88. Center for Ultrafast Optical Science, University of Michigan
89. Center of Excellence in Polymer Science and Engineering, Illinois Institute of Technology
90. Center on Hierarchical Structures, Case Western Reserve University

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91. Center on Polymeric Interfaces and Macromolecular Assemblies, Stanford University
92. Central Analytical Facility, University of Alabama
93. Ceramic Materials Laboratory, Princeton University
94. Certificate Program in Microscopy, San Joaquin Delta College
95. Chemistry Magnetic Resonance Facility; X-ray Crystallography Facility, University of California at San Diego
96. Chicago Materials Research Center, University of Chicago
97. Colorado Advanced Materials Institute, Colorado School of Mines
98. Complex Carbohydrate Research Center, University of Georgia
99. Composite Materials and Structures Center, Michigan State University
100. Composites Education and Research Center, Georgia Institute of Technology
101. Compound Semiconductor Device Laboratory, Simon Fraser University
102. Compound Semiconductor Laboratory, University of Southern California
103. Computing Recharge Facility, University of California at San Diego
104. Cornell Center for Materials Research, Cornell University
105. Cornell High-Energy Synchrotron Source, Cornell University
106. Data Storage Systems Center, Carnegie Mellon University
107. Department of Chemical Engineering and Materials Science, University of Minnesota
108. Department of Chemistry, State University of New York at Binghamton
109. Department of Chemistry, Syracuse University
110. Department of Chemistry, University of Rochester
111. Department of Materials Science and Engineering, Lehigh University
112. Department of Materials Science and Engineering, University of Pittsburgh
113. Department of Mechanical Engineering, University of California at San Diego
114. E-Beam Facility, University of California at San Diego
115. Electron Microprobe Laboratory, Yale University
116. Electron Microscope and X-Ray Diffraction Facilities, Michigan State University
117. Electron Microscope Facility, University of California at San Diego
118. Electron Microscope Unit, University of New South Wales
119. Electron Microscopy and Microanalysis, University of Oxford
120. Electron Microscopy Center, University of South Carolina
121. Electron Microscopy Center, Washington State University
122. Electron Microscopy Center; Center for Nanoscience and Nanotechnology, Georgia Institute of Technology
123. Electron Microscopy Facility, University of Texas at Austin

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124. Electron Spin Resonance, University of California at San Diego
125. Electronic Materials Synthesis and Plasma Processing Laboratory, University of California at Los Angeles
126. Electronic-Photonic Materials Group, University of Toronto
127. Engineering Research Center for Advanced Electronic Materials Processing, North Carolina State University
128. Ferroelectric Liquid Crystal Materials Research Center, University of Colorado at Boulder
129. Fluid Dynamics Research Center, Illinois Institute of Technology
130. Free-Electron Laser Center, Vanderbilt University
131. Free-Electron Laser Laboratory, Duke University
132. Garcia Materials Research Science and Engineering Center-Polymers at Engineered Interfaces, State University of New York at Stony Brook
133. Geophysical Laboratory, Carnegie Institution
134. Goldwater Materials Visualization Facility, Arizona State University
135. Harvard Materials Research Science and Engineering Center, Harvard University
136. Hatch Magnetic Resonance Research Center, Columbia University
137. Helium Recharge Facility, University of California at San Diego
138. High Density Electronics Center, University of Arkansas
139. High Field Magnetic Resonance Imaging Center, Brookhaven National Laboratory
140. Highly Filled Materials Institute, Stevens Institute of Technology
141. Institute for Biological Research and Technology, University of South Carolina
142. Institute for Materials Research, State University of New York at Binghamton
143. Institute for Systems Research, University of Maryland
144. Institute of Materials Science, University of Connecticut
145. Institute of Nanoscience and Engineering, University of Pittsburgh
146. Integrated Microelectronics Laboratory, Brigham Young University
147. Integrated Technologies Laboratory, University of California at San Diego
148. Interdisciplinary Center for Biotechnology Research, University of Florida
149. Ion Beam Laboratory, State University of New York at Albany
150. Jack Maddox Laboratory, Texas Tech University
151. Johns Hopkins Materials Research Science and Engineering Center, Johns Hopkins University
152. Keck Bioimaging Laboratory, Arizona State University
153. Keck Center for the Design of Nanoscale Materials for Molecular Recognition, Howard University

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154. Laboratory for Electronic Materials and Device Technology, University of Alabama
155. Laboratory for Micro and Nanotechnology, Paul Scherrer Institute
156. Laboratory for Nanometer Scale Engineering, Boston University
157. Laboratory for Nanostructured Materials Research, Rutgers University
158. Laboratory for Plasma Processing of Materials, University of Maryland at College Park
159. Laboratory for Research on the Structure of Matter, University of Pennsylvania
160. Laboratory for Surface Studies, University of Wisconsin at Milwaukee
161. Life Sciences Electron Microscopy Facility, Arizona State University
162. Lizzadro Magnetic Resonance Research Center, University of Notre Dame
163. Long Island Laboratory for Crystal Growth, State University of New York at Stony Brook
164. Los Alamos Center for Materials Science, Los Alamos National Laboratory
165. Magnetic Resonance Imaging and Spectroscopy Facility, University of Chicago
166. Major Analytical Instrumentation Center, University of Florida
167. Maryland Infrared Free Electron Laser, University of Maryland at College Park
168. Mass Spectrometry Facility, University of Notre Dame
169. Mass Spectrometry Resource Center, California Institute of Technology
170. Mass Spectrometry Resource for Biology and Medicine, Boston University School of Medicine
171. Materials Analysis User Center, Oak Ridge National Laboratory
172. Materials and Process Simulation Center, California Institute of Technology
173. Materials Characterization Facility, University of Houston
174. Materials Characterization Laboratory, State University of New York at Stony Brook
175. Materials Research Center, University of Missouri-Rolla
176. Materials Research Laboratory, University of California at Santa Barbara
177. Materials Science Division, Oak Ridge National Laboratory
178. Max Planck Institute for Metals Research, Stuttgart
179. Medical School Electron Microscope Facility, University of Wisconsin at Madison
180. Metals-Processing Laboratory Users Program, Oak Ridge National Laboratory
181. Michigan Ion Beam Laboratory for Surface Modification and Analysis, University of Michigan
182. Micro Fabrication Laboratory, University of Missouri at Columbia

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183. Microelectromechanical Systems (MEMS) Laboratory, Carnegie Mellon University
184. Microelectromechanical Systems (MEMS) Laboratory, University of California at Los Angeles
185. Microelectronics and Nanotechnology Research Laboratory, Purdue University
186. Microelectronics Fabrication Laboratory, Carleton University
187. Microelectronics Research Center, Georgia Institute of Technology
188. Microelectronics Research Center, Iowa State University
189. Microelectronics Research Center, New Jersey Institute of Technology
190. Microelectronics Research Center, University of Texas at Austin
191. Microfabrication Facility, University of California at Davis
192. Microfabrication Facility, University of Pennsylvania
193. Microfabrication Laboratory, Case Western Reserve University
194. Microfabritech, University of Florida
195. Micromachine and Nanofabrication Facility, University of Alberta
196. Micromanufacturing Laboratory, University of California at Los Angeles
197. Microscopy and Imaging Resource, University of Wisconsin at Madison
198. Microscopy Resource, University of Wisconsin at Madison
199. Microstructure Laboratory, University of Wuerzburg
200. Microsystems Laboratory, University of California at Los Angeles
201. Microtechnology Laboratory, University of Louisville
202. Microtechnology-Based Energy, Chemical and Biological Systems, Oregon State University
203. Microwave Processing Laboratory for Advanced Materials, University of Maryland at College Park
204. Molecular Biosensor and Imaging Center, Carnegie Mellon University
205. Molecular Foundry, Lawrence Berkeley National Laboratory
206. Molecular Materials Research Center, California Institute of Technology
207. Molecular Resource Center, University of Tennessee at Knoxville
208. Nanoelectronics Laboratory, University of Cincinnati
209. Nanoelectronics Research Facility, University of California at Los Angeles
210. Nanofab, University of Texas at Arlington
211. Nanofabrication Facility, Carnegie Mellon University
212. Nanoscale Solid and Molecular Structures Laboratory, Colorado School of Mines
213. Nanoscience and Technology Center, University of Central Florida
214. Nanostructures Laboratory, Massachusetts Institute of Technology
215. Nanostructures Laboratory, Princeton University
216. Nanotech, University of California at Santa Barbara

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217. NanoTech Institute, University of Texas at Dallas
218. National Center for Microgravity Research, Case Western Reserve University
219. National Center for Microscopy and Imaging Research, University of California at San Diego
220. National High Magnetic Field Laboratory, Florida State University
221. National Magnetic Resonance Facility, University of Wisconsin at Madison
222. National Nanofabrication User Network (NNUN), Howard University
223. National Nanofabrication User Network (NNUN), Pennsylvania State University
224. National Resource for Automated Molecular Microscopy, Scripps Research Institute
225. New Jersey Center for Biomaterials, Rutgers University, New Jersey Institute of Technology, University of Medicine and Dentistry of New Jersey
226. New Jersey Institute of Technology, University of Medicine and Dentistry of New Jersey
227. New York Structural Biology Center, Consortium of New York Universities
228. North Carolina Center for Nanoscale Materials, University of North Carolina
229. Northwestern University Materials Research Science and Engineering Center, Northwestern University
230. NSF Center for Low-Cost, High-Speed Polymer Composites, Michigan State University
231. NSF Center for Molecular and Microstructure of Composites, Case Western Reserve University
232. Nuclear Radiation Center, Washington State University
233. Optical Analysis Facility, University of Alabama
234. Optoelectronics Technology Center, University of California at Santa Barbara
235. Particle Beam Physics Laboratory, University of California at Los Angeles
236. Pittsburgh NMR Center for Biomedical Research, Carnegie Mellon University
237. Plasma Applications Laboratory, University of Texas at Dallas
238. Princeton Center for Complex Materials, Princeton University
239. Quantitative Microscopy Laboratory, University of California at San Diego
240. Radiation Center, Oregon State University
241. Resource Center for Advanced Characterization and Metrology, State University of New York at Albany
242. Resource for Biomedical and Bio-organic Mass Spectrometry, Washington University

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243. Resource for the Visualization of Biological Complexity, N.Y. State Department of Health; Wadsworth Center
244. Scanning Transmission Electron Microscope, Brookhaven National Laboratory
245. School of Engineering, Alfred University
246. Sealy Center for Structural Biology, University of Texas at Galveston
247. Shared Materials Instrumentation Facility, Duke University
248. Shared Research Equipment User Center, Oak Ridge National Laboratory
249. Silicon Wafer Engineering and Defect Science Center, North Carolina State University
250. Silvio O Conte National Center for Polymer Research, University of Massachusetts at Amherst
251. Solid State Electronics Laboratory, University of Michigan
252. Southwestern Biomedical Magnetic Resonance Facility, University of Texas Southwestern Medical Center
253. Supercomputing Institute, University of Minnesota
254. Surface Analysis Facility, University of Notre Dame
255. Surface Analysis Facility, University of Texas at Austin
256. Surface Analysis Laboratory, University of Alabama
257. Surface Science Center, University of Virginia
258. Synchrotron Radiation Center, University of Wisconsin at Madison
259. Texas Center for Superconductivity and Advanced Materials, University of Houston
260. The Photonics Center, Boston University
261. Thermal Analysis Center, University of Minnesota
262. Thermal Processing Technology Center, Illinois Institute of Technology
263. Three-Dimensional Electron Microscopy of Cells, University of Colorado
264. Three-Dimensional Electron Microscopy of Macromolecules, Baylor Medical College
265. University of Maryland Materials Research Science and Engineering Center, University of Maryland at College Park
266. University of Massachusetts Materials Research Science and Engineering Center, University of Massachusetts at Amherst
267. University of Minnesota Materials Research Science and Engineering Center, University of Minnesota
268. University of Nebraska Materials Research Science and Engineering Center, University of Nebraska at Lincoln
269. University of Wisconsin Materials Research Science and Engineering Center, University of Wisconsin at Madison
270. USC Nanocenter, University of South Carolina

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271. Vanderbilt Institute for Nanoscale Science and Engineering, Vanderbilt University
272. W.M. Keck Center for Microelectronics, Syracuse University
273. W.M. Keck Laboratory for Biological Imaging, University of Wisconsin at Madison
274. X-Ray Crystallography Center, Caltech
275. X-Ray Physics Facility, Columbia University

RESPONSES

Responses to the facility users' and facility managers' questionnaires were received by e-mail, postal mail, and fax and were entered into a small database for organization and primitive analysis. The following 10 facility users and 65 facility managers responded to the committee's questionnaires:

1. Campus Microscopy and Imaging Facility, Ohio State University
2. Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory
3. Center for Advanced Imaging and Micromanipulation, University of Pennsylvania, Laboratory for Research on the Structure of Matter
4. Center for Advanced Materials Research, Central Electron Microscope Facility, Brown University
5. Center for Advanced Materials Research, Central Microelectronics Facility, Brown University
6. Center for Advanced Microgravity Materials Processing, Northeastern University
7. Center for Composite Materials, University of Delaware
8. Center for Imaging and Mesoscale Structures, Harvard University
9. Center for Materials Research and Analysis, Central Facility for Crystallography, University of Nebraska at Lincoln
10. Center for Materials Research and Analysis, Central Facility for Electron Microscopy, University of Nebraska at Lincoln
11. Center for Materials Research and Analysis, Central Facility for Materials Preparation, University of Nebraska at Lincoln
12. Center for Materials Research and Analysis, Central Facility for Metallurgical and Mechanical Characterization, University of Nebraska at Lincoln
13. Center for Materials Research and Analysis, Central Facility for X-Ray Materials Characterization, University of Nebraska at Lincoln
14. Center for Materials Research and Analysis, Scanning Probe Microscopy, University of Nebraska at Lincoln

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15. Center for Materials Science and Engineering Shared Experimental Facilities, Massachusetts Institute of Technology
16. Center for Microanalysis of Materials, Frederick Seitz Materials Research Laboratory, University of Illinois at Urbana-Champaign
17. Center for Nanoscale Systems, Cornell University
18. Center for Response-Driven Polymeric Films, University of Southern Mississippi
19. Center for Solid State Electronics Research, Arizona State University
20. Center for Thermal Spray Research, State University of New York at Stony Brook
21. Chicago Materials Research Center, University of Chicago
22. Colorado Advanced Materials Institute, Colorado School of Mines
23. Columbia Materials Research Science and Engineering Center Shared Instrument Facility, Columbia University
24. Composite Materials and Structures Center, Michigan State University
25. Cornell Center for Materials Research Shared Experimental Facilities, Cornell University
26. Cornell High-Energy Synchrotron Source, Cornell University
27. Department of Chemical Engineering and Materials Science, University of California at Irvine
28. Department of Chemistry, Texas A&M University
29. Department of Materials Science, Washington State University
30. Department of Materials Science and Engineering, State University of New York at Stony Brook
31. Department of Physics, Colgate University
32. Department of Physics, University of Delaware
33. Department of Physics and Astronomy, Rice University
34. Electron Microscope Unit, University of New South Wales, Australia
35. Electron Microscopy Center, Materials Science Division, Argonne National Laboratory
36. Ferroelectric Liquid Crystal Materials Research Center, Shared X-Ray Diffraction Facility, University of Colorado at Boulder
37. High Temperature Materials Laboratory, Oak Ridge National Laboratory
38. Institute of Technology Characterization Facility, University of Minnesota
39. Intense Pulsed Neutron Source, Argonne National Laboratory
40. Interfacial and Nanoscale Science Facility, Environmental Molecular Sciences Laboratory, Pacific Northwest National Laboratory
41. J.B. Cohen X-ray Diffraction Facility, Northwestern University
42. J. Earle and Mary Roberts Materials Characterization Laboratory, Carnegie Mellon University

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43. Johns Hopkins Materials Research Science and Engineering Center, Johns Hopkins University
44. Keck Microfabrication Facility, Michigan State University
45. Lizzadro Magnetic Resonance Research Center, University of Notre Dame
46. Major Analytic Instrumentation Center, University of Florida
47. Materials Characterization Facility, University of Central Florida
48. Materials Characterization Laboratory of the Materials Research Institute, Pennsylvania State University
49. Microfabrication Laboratory, University of California at Berkeley
50. Microfabrication Laboratory, University of Pennsylvania, School of Electrical Engineering
51. Materials Research Science and Engineering Center, University of Maryland at College Park
52. Nanoscale Surface Characterization Facility, Washington State University
53. Nanostructures Laboratory, Massachusetts Institute of Technology
54. Nanotechnology User Facility at the Center for Nanotechnology, University of Washington at Seattle
55. National Center for Electron Microscopy, Lawrence Berkeley National Laboratory
56. National ESCA and Surface Analysis Center for Biomedical Problems, University of Washington at Seattle
57. National High Magnetic Field Facility, Florida State University, Los Alamos National Laboratory, University of Florida
58. National Magnetic Resonance Facility, University of Wisconsin at Madison
59. New York Structural Biology Center, Consortium of New York Universities
60. NIST Center for High Resolution Neutron Scattering, National Institute of Standards and Technology
61. Northwestern University Atomic and Nanoscale Characterization Experimental Center, Northwestern University
62. Optical Analysis Facility, University of Alabama
63. Oregon State University Radiation Center, Oregon State University
64. Pennsylvania Regional Nanotechnology Facility, Laboratory for Research on the Structure of Materials, University of Pennsylvania
65. Princeton Center for Complex Materials Shared Experimental Facilities Imaging and Analysis Center, Princeton University
66. Quantum Design Physical Property Measurement System, University of Pennsylvania
67. Rensselaer Nanotechnology Center, Rensselaer Polytechnic Institute
68. Scanning Transmission Electron Microscope User Facility, Brookhaven National Laboratory

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69. Shared Equipment Authority, Rice University
70. Shared Experimental Facilities of the University of Massachusetts Materials Research Science and Engineering Center, University of Massachusetts at Amherst
71. Shared Materials Instrumentation Facility, Duke University
72. Shared Research Equipment User Center (SHaRE), Oak Ridge National Laboratory
73. Stanford Nanofabrication Facility, Stanford University
74. Texas Materials Institute, University of Texas at Austin
75. University of Wisconsin Materials Science Center, University of Wisconsin at Madison

ANALYSIS

Quantitative analysis of the responses to the facility managers' questionnaire is inappropriate, of course, because of sample bias and size, but several figures (Figures C.2 through C.6) are presented here to provide information, based on responses to the facilities questionnaire, regarding sources of support for and distribution of annual operating budgets, numbers of users and makeup of the user base, and full-time-equivalent staff supporting midsize facilities.

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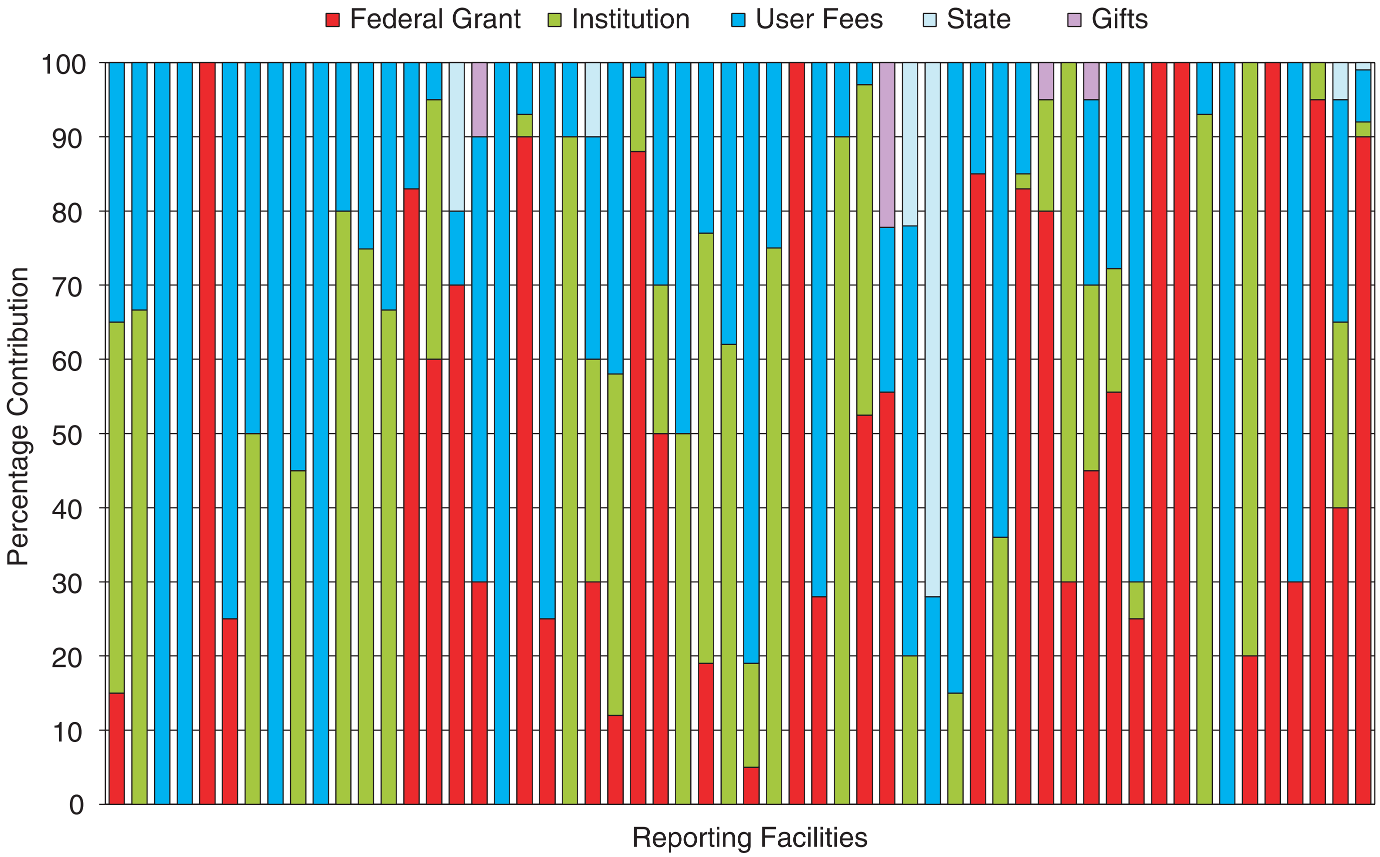

FIGURE C.2 Comparison of sources of support for individual facilities' annual operating budgets. The dominant sources of support are from federal research programs (35 percent) and user fees (35 percent), followed by contributions from the host institutions (27 percent). Data based on responses to the committee's survey.

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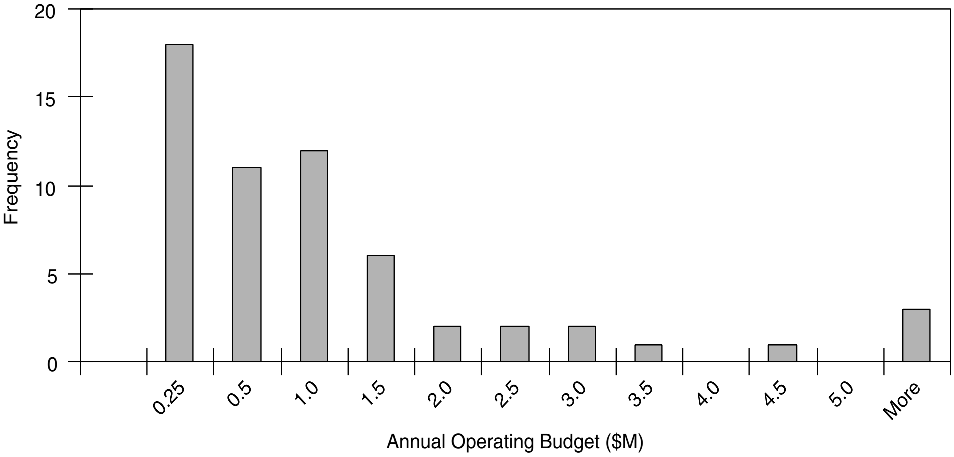

FIGURE C.3 Distribution of midsize facility annual operating budgets. Data based on responses to the committee's survey.

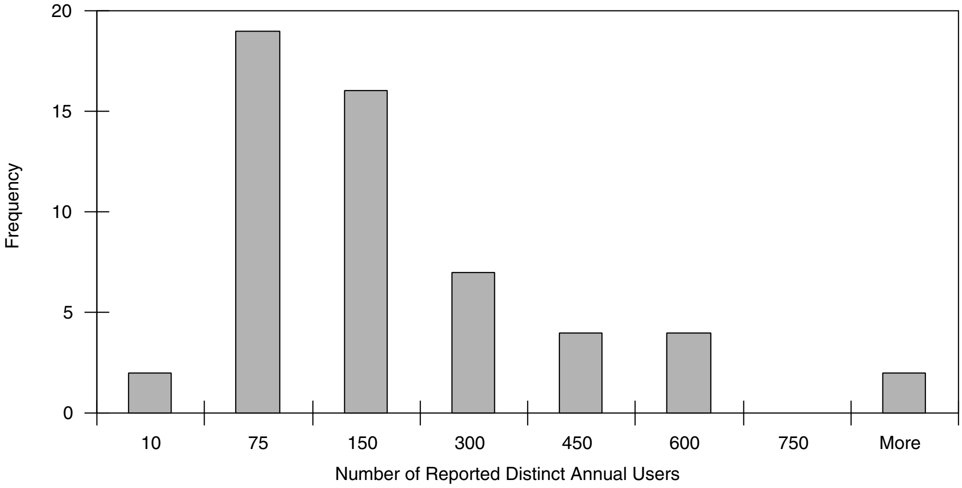

FIGURE C.4 Spectrum of reported number of distinct annual users for midsize facilities. The reporting facilities were used by a total of more than 9,800 persons, with an average of 180 annual users (median 100). Data based on responses to the committee's survey.

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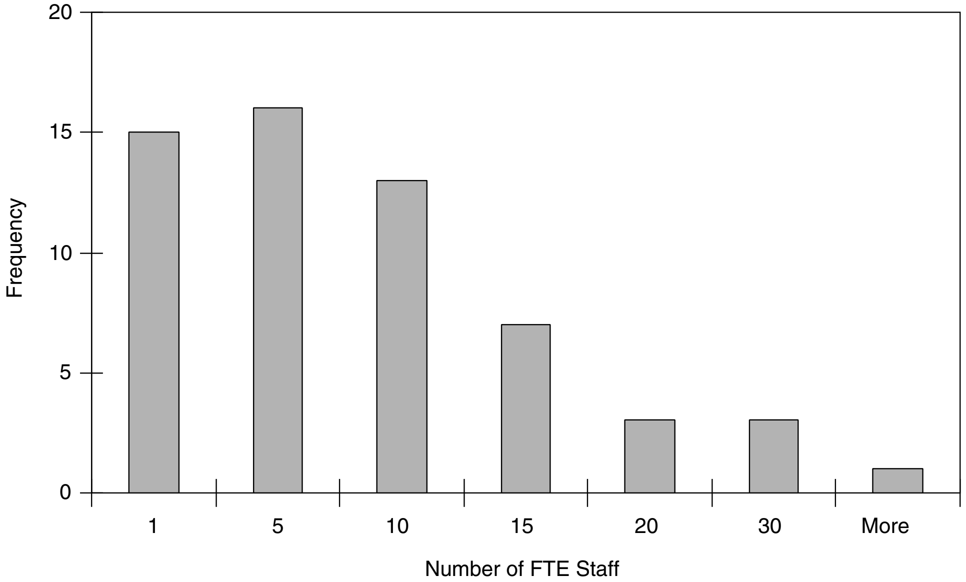

FIGURE C.5 Distribution of the number of full-time-equivalent (FTE) staff supporting midsize facilities. Each bar represents the number of facilities that have the indicated number of FTE staff or fewer; for instance, the leftmost bar indicates that about 15 facilities have one staff member or fewer. Data based on responses to the committee's survey.

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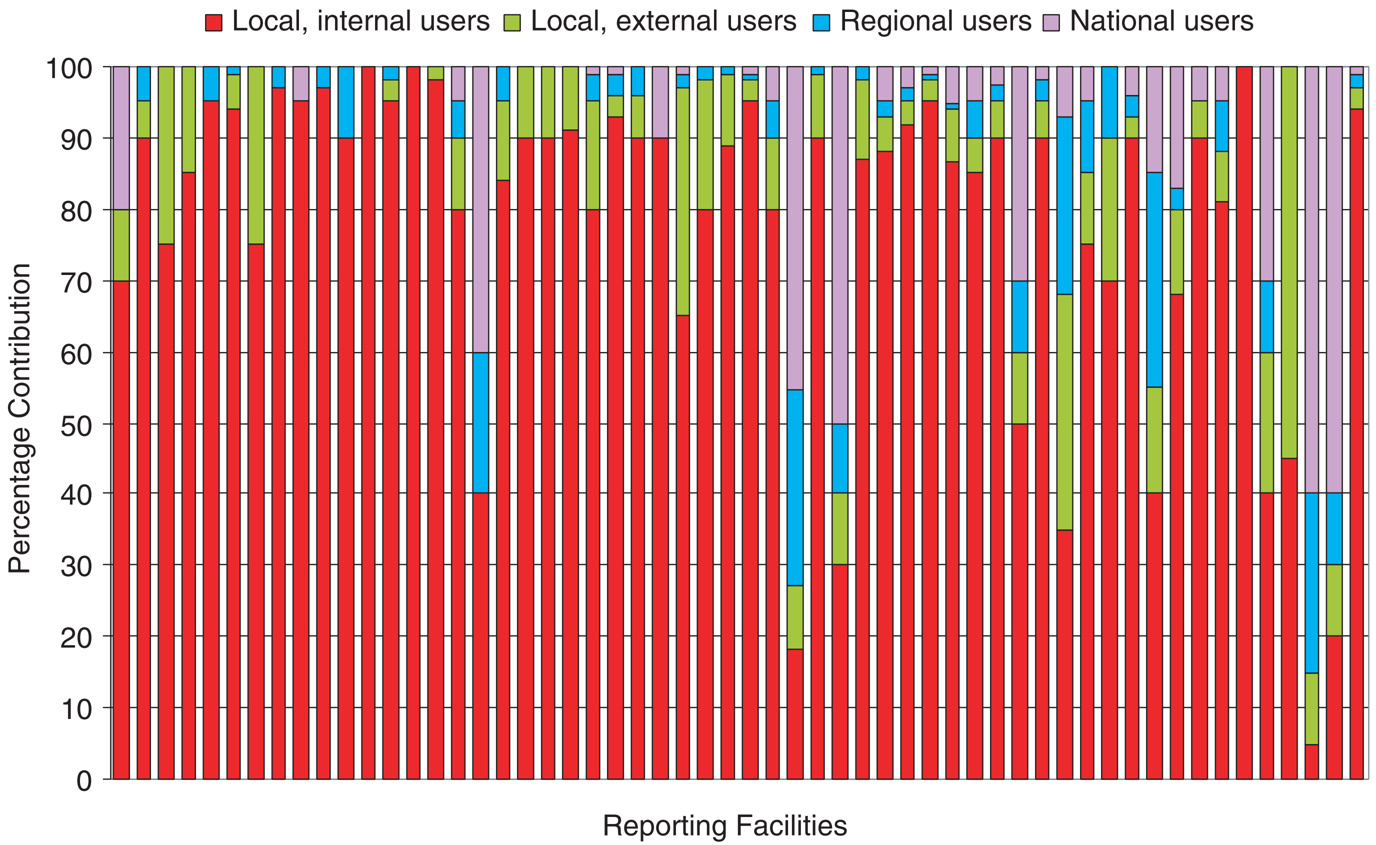

FIGURE C.6 Makeup of the user base for midsize facilities. On average, 77 percent of users are from within the same institution, an additional 10 percent are from the immediate local area, and 5 percent are regionally based (within 1 day's travel). Finally, about 8 percent of midsize facility users have traveled from another region of the United States to use the facility.

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D

Committee's Interim Report

The committee's interim report of March 24, 2004, follows. Appendixes A through E of the interim report are reproduced after the letter.

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

March 24, 2004

Dr. Hugh Van Horn
Program Director
Division of Materials Research
National Science Foundation
4201 Wilson Boulevard
Arlington, VA 22201

and

Dr. Patricia Dehmer
Associate Director
Office of Basic Energy Sciences
SC-10/Germantown Building
U.S. Department of Energy
1000 Independence Avenue, S.W.
Washington, DC 20585-1290

Dear Dr. Van Horn and Dr. Dehmer:

I write to you as chair of the National Research Council's Committee on Smaller Facilities (COSF) to report on the progress of the committee's deliberations to date. Established by the National Research Council (NRC) with financial support from the National Science Foundation and the Department of Energy, COSF is reviewing the current state of small and mid-sized multiuser facilities for materials research in the United States. Its task is to recommend methods for optimizing the operation and use of existing resources and to consider strategies and actions needed to ensure such facilities' efficient and successful future operation. Information on COSF's charge and its activities to date is appended to this report and elaborated on as needed in the text. This interim report identifies the key topics that the committee will explore in greater detail to develop the findings and recommendations for its final report, to be released in the second half of 2004.

Although they play a major, recognized role in materials research in this country, small and mid-sized multiuser facilities for materials research (referred to here simply as smaller facilities) are widely regarded as not being optimally developed or utilized. The 1999 NRC report *Condensed Matter and Materials Physics: Basic Research for Tomorrow's Technology* found that a greater burden now falls on small research centers in universities and government laboratories and that it is appropriate to strengthen this part of the nation's research infrastructure. Smaller facilities appear to face many issues in common, yet a study has never focused specifically on them. There was thus a recognized need to collect data on and study these facilities to help in determining effective ways to use existing resources more efficiently.

The primary concerns driving this study are the scientific opportunities in a wide cross section of disciplines that might be missed because of these issues and perceived problems. Furthermore, the developments in instrumentation that take place in smaller facilities underpin critical tools for industry; these facilities also have an important role in the education of future industrial scientists and engineers. The charge given to the committee, developed by the Solid State Sciences Committee of the NRC's Board on Physics and Astronomy in coordination with the sponsors, is given in Appendix A. To be most effective, the study is aimed for an audience that includes both federal program agencies and the wider materials research community.

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As a consequence of the widely varied nature of smaller facilities for materials research in the United States, COSF has a broad membership composed of expert individuals with university, national laboratory, and industrial backgrounds. COSF includes facility users, facility managers and directors, and a wide range of materials and non-materials experts. The members of the committee and their affiliations are listed in Appendix B.

Committee Activities

The full committee first met in May 2003 and then in October 2003. At the first meeting, presentations were made by senior personnel with experience in operating user facilities in both university and government laboratory settings. The committee also heard from various agencies currently providing extensive support for instrument acquisition and facility operation. The major outcomes of this meeting were the committee's formulation of a preliminary definition of smaller facilities, its establishment of the study's general areas of investigation, and the articulation of a plan for carrying out a series of facility site visits over the summer of 2003.

During summer 2003, subgroups of the committee, generally consisting of two to three committee members plus an NRC staff officer, visited various user facilities around the country. The purpose of these visits was primarily to gather some firsthand experience relating to planning, operation, and maintenance of typical smaller facilities; another important function of the visits was to hear directly from users and to learn about the commonalities across and differences between smaller facilities and other types of facilities. To minimize the time commitment involved, and to ensure maximum effectiveness, it was decided to target geographical areas that had clusters of similar facilities. However, the number of sites to be visited was limited by schedule and resources such that it was not possible to cover the full breadth of the United States. Sensitive to the need to obtain information about the resources, needs, and perspectives of other geographical areas, the committee agreed to invite additional testimony at future meetings and to develop a suitable questionnaire for distribution to a broad range of smaller facilities' managers and users.

The committee's five separate site visit trips concentrated on the approximate geographical areas of Boston, upstate New York, Illinois, the San Francisco Bay Area, and the Pacific Northwest. A total of 47 facilities were visited (see Appendix C). To ensure that broadly similar information was obtained from each facility, a site visit checklist (Appendix D) was used as a guideline to facilitate discussion during the site visits.

The full committee convened again in October 2003 to share the experiences and impressions gained by its various subgroups. Several presentations were made relating to the operation and organization of smaller facilities and the need for staff training. Extensive discussions followed relating to the development of a vision for the committee's study, a working definition of a smaller facility, the characteristics of successful facilities and their best practices, current and future issues relating to facility operation, and future committee activities. The committee also developed facility manager and user questionnaires (Appendix E) designed to gather general information to better inform the committee about the breadth of its purview; the questionnaires were not designed to be statistical data-gathering instruments. In order to obtain a standard set of data, these questionnaires were also circulated to the smaller facilities that committee members had visited over the summer.

The Importance of Smaller Facilities

In the modern era, scientific advances require access to sophisticated facilities and instrumentation, and the role of such facilities in materials synthesis, fabrication, characterization, and measurement is steadily increasing. In fact, these facilities are essential to the scientific infrastructure of the United States. There are significant opportunities for accelerating scientific advances in materials and nanotechnology research by invigorating such facilities and allocating their resources to best effect. Accordingly, COSF re-emphasizes the importance of smaller facilities.

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In its final report the committee will address a number of the important roles that smaller facilities play in materials research, several of which represent significant opportunities for smaller facilities for the future. It is widely recognized that user facilities can and should play a major educational role, especially when located at universities, since they are able to help link researchers across campuses, institutions, and even regions. Teaming between institutions—large and small—could be encouraged by providing additional incentives and benefits. Similarly, stronger links between universities and national laboratories (including cross-agency links, which would combine strengths of NSF and DOE) could be enhanced. A strategy for reinvigoration of instrumentation development within the United States could incorporate a significant role for smaller facilities. Moreover, given the growing recognition that many innovations will occur at the intersection of the sciences (physical, chemical, biological, and medical), cross-fertilization of ideas across the traditional disciplines will become an ever more important function of smaller facilities. Finally, user facilities could serve to initiate and enable research experiences above and beyond K-12 education levels, to include community colleges and smaller schools.

Vision for the Study

A need for regional facilities is now being more widely acknowledged, but the locations of such facilities have to be carefully considered, taking into account areas of high concentration of science and industry as well as clearly identified user communities (perhaps as a result of self-initiated proposals). Conversely, there are educational and inspirational benefits to locating some facilities at smaller schools that have not traditionally had access to such resources. To provide capabilities that satisfy local, regional, and national needs in advanced materials research, a strategic plan for the development and operation of smaller user facilities is required that also recognizes the escalating costs of instrumentation. The committee will address such a strategic plan in its final report.

Identifying the instruments in existence and on the horizon that fall in the price range of a smaller facility is an essential aspect of the committee's study. In addition, the likely demand and future outlook for novel instrumentation have to be assessed. This information should become more apparent once responses to the facility surveys have been collected.

By identifying the essential ingredients of successful facilities, the committee can recommend approaches that will lead to greater efficiency and effectiveness within the U.S. materials research enterprise, consistent with the limitations of finite resources. Likewise, learning about and clarifying the challenges that smaller facilities face are essential steps toward developing approaches that can be mapped and implemented—at the national level as appropriate—to tackle their problems.

Working Definition of a Smaller Facility

For the purposes of this study, the committee proposes the following working definition of a smaller facility in materials research:

A smaller facility is a facility that owns and operates one or more pieces of equipment at an institution and is characterized by the following criteria:

- Facilitates scientific and/or technological research for multiple users;
- Has a resident staff to assist, train, and/or serve users;
- Provides services on local, regional, or national scales;
- Is open to all qualified users subject to generally agreed-upon rules of access; and
- Has a replacement capitalization cost of between approximately $1 million and $50 million and an annual operating budget (including staff salaries, overhead, supplies, routine maintenance and upgrades, and so on) in the range from about $100,000 up to $20 million (2004 dollars).

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This definition is a preliminary guideline: the committee recognizes that not all smaller facilities will meet all elements of this definition. Indeed, a number of the facilities it visited over the summer of 2003 would not qualify as smaller facilities for materials research, and yet they provided valuable and relevant information. The basis for this definition and the taxonomy of smaller facilities will be further elaborated in the committee's final report.

The committee believes that smaller facilities also distinguish themselves in other ways. A smaller facility often meets one or more of the following additional criteria:

- Provides a unique or special service that is not generally available at an individual investigator's laboratory;
- Fulfills a particular scientific niche/role in the research enterprise;
- Has a clear mission that addresses a well-defined or emerging need for a well-defined community;
- Plays a leading role in education, workforce training, and workforce development;
- Facilitates instrument/technology development and/or training;
- Promotes synergy and communication among its users and with others;
- Fosters cross-disciplinary and cross-sector interactions, including scientific, medical, and engineering endeavors; and
- Represents a means for coordinating scientific endeavors among other facilities or institutions with complementary capabilities.

As a result of its continuing study, the committee may modify its definition to reflect other considerations yet to be identified.

Characteristics of Successful Smaller Facilities

Based on evidence gathered in their site visits and on the committee members' own experiences, it became clear that successful smaller facilities share a number of characteristics. Many of the following characteristics were observed to be key ingredients in the more successful facilities.

Successful user facilities generally contained equipment that facilitates both routine and state-of-the-art research, and they incorporated a mix of permanent scientific and technical staff. In some cases, operation of the facility also advanced the technology (instrumentation and/or techniques and/or applications). Open and reasonable access to the user community was commonly provided; successful facilities also focused on sending users back to their home institutions with high-quality, useful data. Critical self-assessment was common, and a mechanism to take account of feedback from users was important. Successful operation was enabled by stable, long-term funding source(s), with local institutional support, and it was often enhanced by having an enthusiastic and broad user base, as well as effective and energetic management.

Challenges Facing Smaller Facilities

The committee has identified a number of issues that can have a significant impact on both the establishment and the operation of a smaller user facility. These issues affect not only the ability of a smaller facility to operate optimally but also such facilities' ability to work in concert. These challenges are summarized briefly here and will be discussed at greater length in the committee's final report as the subject of specific recommendations.

Two competing trends are apparent in the materials research enterprise. The capabilities of new instrumentation are advancing at a remarkable rate and they enable—and indeed are essential to—significant advances in materials research and development. Both the capital costs and the cost of support and maintenance for these instruments are escalating to the point that individual institutions experience

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severe difficulty in providing equipment to their user base. It is challenging for smaller facilities to be responsive to both of these trends.

Funding sources for existing facilities are highly diverse, ranging from local to regional to national agencies, as well as the private sector. Cost-sharing for the acquisition of expensive instrumentation is usually a standard requirement, but the amount required seems highly variable. Meeting the imposed cost-sharing obligation often represents a major obstacle for smaller institutions. It is difficult, in light of this variability, to specify the most desirable models or to recommend the best funding practices. However, by providing suitable incentives, it may be possible to encourage institutions to team together as partners, and this action might go a long way toward overcoming what are widely perceived to be serious funding gaps and the loss or denial of opportunities to participate in ground-breaking materials research.

Staffing at both technical and scientific levels is a basic requirement for successful facility operation over the long term, but the sources of staff funding are diverse and variable. Staff support often depends to a large extent on the financial commitment of the home institution to the facility and on the size of the local user base. Stable and long-term support for staff, allowing a viable and worthwhile career path, is essential.

Operation and management practices can have a major impact on whether a facility’s users accumulate meaningful and reliable data. Mechanisms for ensuring convenient access to user facility resources for internal, and especially external, user communities are a major concern. If properly taken into account, user feedback can contribute to maximizing a facility’s usefulness, and possibly also assist in extending its lifetime. Facility self-assessment is perceived as a necessity, but some additional mechanism for providing oversight on behalf of the user community also has to be developed. The overall health of the smaller-facility enterprise within the United States could benefit from a well-established set of policies at the national level regarding management, funding, and goals.

There are no clear-cut answers to the need for further instrumentation development itself within the realm of operations of a user facility. Conversely, novel types of applications are invariably developed, and these should be transmitted in a timely fashion to other facility users. Teaming between scientific institutions and industrial partners is likely to become increasingly mutually beneficial and complex. The nature and extent of partnerships with industry may depend both on the services being rendered and on the scale of the industrial partner.

Materials synthesis and/or preparation of samples can be a serious obstacle to research, especially for users obliged to travel elsewhere to utilize smaller facilities. In some cases, making these capabilities available onsite at the user facility location could be helpful. Thus, the most successful institutions or team centers for materials research may need to encompass modern facilities for fabrication, synthesis, characterization, and materials property testing.

Smaller facilities often serve a variety of competing purposes. The balance between instrumentation development and routine operation, both nationally and in individual facilities, is one example. Likewise, the balance between training students (where equipment breakage is an inevitable part of the learning process) and maintaining a state-of-the-art facility, where only staff and highly trained users are allowed access (to protect the fragile equipment), is another. The balance between these somewhat conflicting goals can affect both the management of and the ability to obtain funding for a facility.

A final challenge relates to the perceptions of proposal reviewers, review panels, and the funding agencies when considering requests for instrumentation acquisition. Proposals for "workhorse" instruments for routine characterization are not as well received as those requesting "racehorse" types, yet both types are equally important for the national infrastructure in materials research.

Future Plans

In addition to dissemination of this interim report in the spring of 2004, the committee will be conducting a series of town-hall meetings, coinciding with annual meetings of the major related scientific societies (e.g., the March American Physical Society Meeting and the Spring Materials Research Society

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Meeting). The purpose of these open meetings will be to provide opportunities for discussion of this report and to gather feedback from the community. The facility manager and facility user questionnaires will be distributed at both town meetings to solicit responses from the broader community; additionally, the questionnaires are being distributed by committee members to their colleagues and by NRC staff to the targeted sets of smaller facilities such as the NSF Materials Research Science and Engineering Centers and the DOE Nanoscale Science Research Centers. The committee recognizes the need to engage both facility managers and users as well as potential users of future smaller facilities. The committee will then reconvene as a whole late this spring to prepare the draft of its final report.

I trust that this letter provides you with a sense of where the COSF deliberations are going and look forward to transmitting a full report to you in the second half of 2004.

Sincerely yours,

/s/ Robert Sinclair, *Chair*
Committee on Smaller Facilities

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APPENDIX A

Charge to the Committee

The proposed study will review the state of small and mid-sized multi-user facilities within the materials research complex in the United States and will consider methods for optimizing the use of existing resources, including the consideration of structural strategies and actions to provide services more efficiently through the implementation of revenue-neutral solutions. These facilities are recognized as a key feature of materials research, yet there is concern that they are not being optimally developed or utilized and that new opportunities for scientific development are not being properly pursued. Although the study will confine its recommendations to university and national laboratory facilities, it will also examine the operations of materials facilities in the commercial sector and in the international arena.

Specifically, the study's task will incorporate the following elements:

1. Providing a definition of small and mid-sized multi-user facilities and their role in the materials research complex.
2. Collecting data on the usage, costs and structure of smaller facilities and compiling an inventory of small equipment clusters.
3. Examining the current models of facility operation and assessing their cost/effectiveness, considering the appropriate metrics for facility success, and assessing criteria for minimal size.
4. Exploring alternate methods of instrumentation utilization such as:
    a. Increasing user groups at small facilities to 10-20 independent investigators.
    b. Establishing regional centers by identifying equipment appropriate for consolidation into multi-user shared facilities.
5. Examining opportunities for instrumentation research in the context of facilities, including the impact of these on science and industry and the determination of the optimal location of instrumentation development activities.
6. Assessing the educational role played by small facilities.
7. Exploring the need for long-range support models for these facilities.
8. Assessing the effect, if any, of the policies and structure of the federal research agencies that support smaller facilities.
9. Analyzing the issues from an international perspective.

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APPENDIX B

Committee Roster

Robert Sinclair, Chair
Professor of Materials Science and Engineering
Stanford University
Peterson Building, Room 550L
Stanford, CA 94305

Ani Aprahamian
Professor of Physics
University of Notre Dame
Nieuwland Science Hall 183
University of Notre Dame
Notre Dame, IN 46556-5670

Arthur I. Bienenstock
Professor of Applied Physics and of Materials
Science and Engineering, Vice Provost and
Dean of Research and Graduate Policy
Stanford University
Stanford, CA 94305-2061

John P. Bradley
Director, Institute of Geophysics
and Planetary Physics
Lawrence Livermore National Laboratory
7000 East Avenue
L-413
Livermore, CA 94550

David R. Clarke
Professor of Materials
University of California at Santa Barbara
Materials Department
College of Engineering
Santa Barbara, CA 93106

Walter P. Lowe
Professor of Physics
Howard University
2355 Sixth Street, NW
Washington, DC 20059

Frances M. Ross
Manager, Nanoscale Materials Analysis Department
IBM T.J. Watson Research Labs
PO Box 218
Room 29-003, 1101 Kitchawan Road
Yorktown Heights, NY 10598

David J. Smith
Regents' Professor of Physics and Astronomy
Director, Center for Solid State Science
Arizona State University
Center for Solid State Science
Arizona State University
Tempe, AZ 85287-1704

John M. Soures
Manager, National Laser Users' Facility
University of Rochester
Laboratory for Laser Energetics
250 E. River Road
Rochester, NY 14623

Leonard Spicer
University Distinguished Service Professor of
Biochemistry and Radiology
Duke University
Department of Biochemistry
Duke University Medical Center
Durham, NC 27710

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James W. Davenport
Senior Physicist and Associate Director, Center for Data Intensive Computing
Brookhaven National Laboratory
Building 463B
Upton, NY 11973-5000

Francis J. DiSalvo
John A. Newman Professor of Physical Science and Director, Cornell Center for Materials Research
Cornell University
Department of Chemistry
Baker Laboratory
Ithaca, NY 14853

Charles A. Evans, Jr.
President
Full Wafer Analysis, Inc.
2326 Walsh Avenue
Santa Clara, CA 95051

Don M. Tennant
Distinguished Scientist
New Jersey Nanotechnology Consortium and Lucent Technologies
600-700 Mountain Avenue
Room 4-209B
Murray Hill, NJ 07974

NRC Staff

Board on Physics and Astronomy
National Research Council
Keck Center of the National Academies
500 Fifth Street, NW
Washington, DC 20001
Tel: 202-334-3520

Donald C. Shapero
Director, Board on Physics and Astronomy

Timothy I. Meyer
Program Officer, Board on Physics and Astronomy
E-mail: tmeyer@nas.edu

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APPENDIX C

Site Visit Itineraries

San Francisco Bay Area
Team: C. Evans,* J. Bradley, F. DiSalvo, R. Sinclair, T.I. Meyer

- Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory
- Lick Observatory at Mt. Hamilton
- National Center for Electron Microscopy, Lawrence Berkeley National Laboratory
- Surface Analysis Laboratory, Lawrence Berkeley National Laboratory
- Department of Material Science and Engineering, University of California at Berkeley
- Integrated Materials Laboratory and Microlab, University of California at Berkeley
- Stanford Nanofabrication Facility, Stanford University
- Stanford Nanocharacterization Laboratory, Stanford University
- Stanford Synchrotron Radiation Laboratory, Stanford Linear Accelerator Center
- Accurel Systems, Sunnyvale, California
- Charles Evans and Associaties, Sunnyvale, California

Upstate New York
Team: J. Davenport,* L. Spicer, D. Smith, T.I. Meyer

- Nanobiotechnology Center, Cornell University
- Cornell Center for Materials Research, Cornell University
- Center for Nanoscale Systems, Cornell University
- Facilities Committee of Office of the Vice Provost for Research, Cornell University
- Advanced ESR Technology Center, Cornell University
- Cornell Nanoscale Science and Technology Facility, Cornell University
- Office of the Associate Dean for Research, Rensselaer Polytechnic Institute
- Center for Subsurface Sensing and Imaging Systems, Rensselaer Polytechnic Institute
- Terahertz Science and Technology Center, Rensselaer Polytechnic Institute
- Rensselaer Nanotechnology Center, Rensselaer Polytechnic Institute

Illinois
Team: W. Lowe,* J. Bradley, R. Sinclair, T.I. Meyer

- Materials Research Science and Engineering Center, Northwestern University
- Jerome B. Cohen X-Ray Diffraction Facility, Northwestern University
- Northwestern University Atomic and Nanoscale Characterization Center, Northwestern University
- Nanoscale Science and Engineering Center, Argonne National Laboratory
- Electron Microscopy Center and Materials Science Division, Argonne National Laboratory
- New Brunswick Laboratory, Department of Energy Chicago Operations Office (located on the site of Argonne National Laboratory)
- Office of the Associate Director, Advanced Photon Source, Argonne National Laboratory
- Office of the Director of the Frederick Seitz Materials Research Laboratory, University of Illinois at Urbana-Champaign
- Center for Microanalysis of Materials (at the MRL), University of Illinois at Urbana-Champaign
- Molecular Beam Epitaxy Center (at the MRL), University of Illinois at Urbana-Champaign
- Microfabrication and Crystal Growth (at the MRL), University of Illinois at Urbana-Champaign
- Micro and Nanotechnology Center, University of Illinois at Urbana-Champaign

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- Facilities Committee of the Materials Consortium and Department of Materials Science and Engineering, Purdue University
- Campus-wide Mass Spectrometry Center, Purdue University

Boston
Team: D. Tennant,* F. Ross, J. Soures, D. Shapero

- Center for Materials Science and Engineering, MIT
- Materials Processing Center, MIT
- Microphotonics Center, MIT
- NASA Center for Advanced Microgravity Materials Processing, Northeastern University
- Electronic Materials Research Institute, Northeastern University
- Center for Imaging and Mesoscale Structures, Harvard University
- Office of the Dean of Engineering and Applied Science, Harvard University
- Office of the Director of the Rowland Institute for Science, Harvard University
- Materials Research Science and Engineering Center, Harvard University
- Nanoscale Science and Engineering Center, Harvard University

Pacific Northwest
Team: D. Clarke,* A. Aprahamian, T.I. Meyer

- Environmental Molecular Science Laboratory, Pacific Northwest National Laboratory
- Applied Process Engineering Laboratory, Richland, Washington
- UW Engineered Biomaterials Center, University of Washington at Seattle
- Center for Nanotechnology, University of Washington at Seattle
- Washington Technology Center, Microfabrication Laboratory
- National ESCA and Surface Analysis Center for Biomedical Problems, University of Washington at Seattle

NOTE: Asterisk (*) denotes site visit team leader.

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APPENDIX D

Site Visit Checklist

- Purpose, philosophy, brief history and anticipated future of facility
- Major equipment inventory (with cost, replacement cost, age, funding source etc.)
- Total budget and charging rates
- Funding sources (host institution, government, industry, other)
- Staff: permanent/non-permanent (faculty, professional, technical, student/intern)
- Annual number of uses per instrument
- Annual number of users per instrument (host, local, distant, international)
- Status of equipment (adequate, up-to-date?)
- For state-of-the-art facility, what additional equipment is needed?
- Is support personnel/funding adequate?
- Most successful aspects of facility (up to five)
- Ways to improve facility, presently non-optimal (up to five)
- Complementary facilities (host, local, distant, international)
- Educational role versus research role
- How does facility meet host, local, distant, international needs?
- How does facility fit into national/international perspective?
- Recommendations to the committee (up to five)

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APPENDIX E

Facility Manager and User Questionnaires

The following two questionnaires (and accompanying cover letter) have been prepared by the committee to gather information about the spectrum of smaller facilities within the United States and to solicit input from the broader community. The first questionnaire is aimed at facility managers and the second is aimed at users (and potential users) of smaller facilities. The questionnaires will be made available at the town meetings held in the spring; the American Physical Society meeting in March 2004 will draw persons from material, condensed matter, and chemical physics and the Materials Research Society meeting in April 2004 will include persons from materials science and engineering. To help broaden the distribution and questionnaire response rate, the questionnaires have also been sent to specific facilities such as the NSF Materials Research and Engineering Centers and the DOE Nanoscale Science Research Centers. Because of the usual sensitivity of survey results on population subsample response rates, the committee does not plan to make any sweeping generalizations based upon the information returned. The dissemination of these questionnaires has only begun; plans for broader distribution will continue to evolve.

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Dear Colleague,

The Committee on Smaller Facilities (COSF) was established by the National Research Council (NRC) with the support of both the National Science Foundation and Department of Energy to make recommendations about the challenges and opportunities that small and medium-sized multi-user facilities face in materials research.

A questionnaire is attached for your response that is designed to gather data on existing smaller facilities. The data will only be used in aggregate or in ways that do not reveal the identity of the responding institutions or individuals. We only ask for identification in case the committee wishes to follow up for clarification.

Please send your responses to the NRC via

E-mail: smallerfac@nas.edu
Fax: 202-334-3575
Mail: Committee on Smaller Facilities
Board on Physics and Astronomy
Keck 922W
500 5th St., NW
Washington, DC 20001

Finally, if you are aware of colleagues who would be interested in accessing this request for input, please have them contact the NRC at smallerfac@nas.edu or direct them to the committee's website, located at http://www7.nationalacademies.org/bpa/projects_COSF_committee.html.

We would appreciate receiving your responses in about two weeks.

Thank you for your assistance in this endeavor. We recognize the demands on your time and appreciate the information you and your staff are able to provide.

Sincerely,

Robert Sinclair, *Chair*
Committee on Smaller Facilities

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Small and Mid-sized Multi-user Facility Manager Survey

To the best of your knowledge, please answer the following questions for the small to mid-sized multi-user facility under your leadership. In the case of multiple facilities within your center or department, we ask you either to answer the questions in sum for all such facilities **or** to fill out a separate questionnaire for each facility.

APPROXIMATE ANSWERS ARE ALL THAT ARE NEEDED.

1. Identity

The identities of responding institutions and individuals will be held confidential to COSF and will only be used to follow up for clarification if necessary.

a. Name of the facility: ____
b. Host institution: ____
c. Facility website (if available): ____
d. Primary mission: ____
____
____
e. What distinguishes the facility? ____
____
____

2. Budget and funding

a. Annual operations budget (including staff salaries, overhead, supplies, maintenance, etc.) for the facility: ____
b. Percentage of this funding derived from each of the following sources:
Federal grant: ______________________% Institutional sources: _______________%
User fees: _________________________% State funding: ____________________%
Gifts: ____%
Other (indicate source): ____
c. Percentage of budget expenditures on:
Staff: _______________% Maintenance & supplies: ___________%
Equipment replacement, upgrades, and acquisitions: ___________________________%
d. Is there an arrangement with the host institution to cover a portion of staff salaries? _________
If so, please describe. ____
____
____

3. Staff and management

a. Number of full-time equivalent staff employed in the facility: ___________________________
b. Number of those staff conducting original research in the facility: ________________________
c. If there are multiple facilities, is there a manager who oversees all of their operations? _______
If yes, what percentage of a full time position is devoted to such management: _____________

4. Users and usage

a. Type(s) of work at the facility (please check all that apply):
Fabrication: _____ Characterization: _______________
Measurement: ___ Synthesis and/or crystal growth: ___
Other (please describe):____

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b. What is the breakdown of scientific disciplines of users (physics, chemistry, biology, etc.) and in what percentages?
Discipline 1: ____
Discipline 2: ____
Discipline 3: ____
c. Is the facility oversubscribed or undersubscribed?
Oversubscribed: ________ By what amount? ______ %
or Undersubscribed: _____ By what amount? _______%
d. Number of distinct users served annually: ______________________
e. Percentage of users who are:
Graduate students and post-docs: ___________%
Government lab staff researchers: ___________%
Undergraduates: _________________________%
Commercial/industrial researchers:__________%
f. Percentage of users who are:
From within the host institution: ____________________________%
Local, but outside host institution: __________________________%
Regional (within a day's travel by car): ______________________%
National/international (overnight stay required): _______________%
g. Percentage of facility usage for each of the following:
User research (including user training and support): __________%
Service research (conducted by technical staff): _____________%
Instrument technology and applications development: ________%
Other (please describe): _______________________________%
h. Are there facilities with similar capabilities at the host institution? _______________________
i. What formal coordination exists among facilities at the host institution to develop complementary capabilities? ____
____
j. If the facility has a formal users' group, please provide contact information: _______________
____

5. Equipment and capital investment
a. Replacement capitalization cost (at today's prices) for all instruments in the facility: ________
b. Average annual investment in capital equipment (from all sources of funding): ____________
c. What is your most heavily used instrument? ____
d. Most important acquisition planned in the next five years and its estimated cost:
____
____

6. Other comments (optional)

Please provide any additional comments that might be relevant to the committee's task. For instance, you may comment on future needs of your facility or any challenges experienced in operating your facility. We are also particularly interested in thoughts on how to improve the facilities system—increasing usage, effectiveness, impact, etc. Finally, feel free to elaborate on any of the answers provided above.

____
____
____
____
____
____

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Small and Mid-sized Multi-user Facility User Survey

To the best of your knowledge, please answer the following questions for the small to mid-sized multi-user facilities that you use periodically. For the purposes of this questionnaire, assume that “smaller facility” refers to a small to mid-sized multi-user facility for materials research.

APPROXIMATE AND SHORT ANSWERS ARE ALL THAT ARE NEEDED.

1. **Types of Use**
   a. Do you occasionally make use of instruments or services that are not located within your own laboratory? _____________(y/n) [If no, please skip to Section 5.]
   b. What types of services or facilities do you use? (please check all that apply)
   Fabrication: ______________ Characterization: ______________
   Measurement: ____________ Synthesis/crystal growth: ________
   Instrumentation development: ______________
   Other (please describe): ____
   c. What percentage of your research (time) is conducted at smaller facilities? _______%
   d. For the smaller facilities you use most often, how many other users would you estimate also make use of them? ______________________ or Don’t know ______
   e. What is your field of research? ____
   f. Please name one or more smaller facilities that you have used in the past 12 months.
   ____

2. **Purpose of Use**
   a. In a few words, please describe further why you make use of smaller facilities.
   ____
   ____
   ____
   b. In your experience, have smaller facilities enhanced or extended your research; if so, how? ____
   ____
   ____
   ____

3. **Ease of Access**
   a. In general, how far away are the smaller facilities that you use? Please give an estimate of the percentage time that you spend at facilities located at the different distances.
   On campus/site: ________________%
   Within 30 min travel (any means): ________________%
   Regional (day’s car travel): ________________%
   National (overnight stay required): ________________%
   b. On average, how far in advance do you need to make arrangements for time at the smaller facility? ______________________ hours/days/weeks/months
   c. Do you find this lead time acceptable? ____________________ (y/n)
   d. For your most frequent uses of smaller facilities, what is the maximum lead time that you would find acceptable? _________________hours/days/weeks/months

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e. If ideal facilities became available, considering travel, and setup time, how far would you be willing to travel to use them? (in miles or hours) ____________________________
f. If ideal facilities became available, considering the travel expense and user fees, what level of cost would be prohibitive for you to consider their use? (either in terms of total cost, cost per hour, or other measure relevant to you) ____________________________
____
g. To generalize, what is the number one criterion for determining which facility you will use? ____
____
____

4. **Quality of Service**
a. In general, what percentage of your time using the smaller facility are you operating the instruments yourself, relatively unattended?
b. If you or your students have been trained on equipment at smaller facilities, are you satisfied with the degree of training that was provided? _______________ (y/n)
c. In general, when registering to use a smaller facility, do you speak with a facility manager or technical staff person? ____
d. When you have questions or concerns about the equipment and facilities, to whom do you go for answers?
Facility director: _________ Technical staff person: __________
Colleague: ______________ Another user: __________________

5. **Facility Outreach**
a. Would you say that you are well aware of the smaller facilities at other institutions (local, regionally, and nationally) that could assist you in your research and/or training needs? _________(y/n)
b. If so, how did you learn about those facilities? _________________________________
____
____
c. What kinds of resources could help you identify such facilities? ___________________
____
____
d. If you have prepared proposals for research funding, have you included requests for access to and use of specific smaller facilities (on site, nearby, in your region, or nationally) in the grant proposal? _____ (y/n) Likewise, when preparing budget estimates for a research proposal, to what extent do you include estimates for user fees to take advantage of specific smaller facilities? ________ (y/n)
Please comment further. ____
____
____
Finally, what level of financial support per year would be necessary to fully enable your research by providing sufficient access to smaller facilities? _$________________
e. In general, are you satisfied with your experiences using smaller facilities? _______ (y/n)
f. In general, have you recommended your colleagues to any smaller facilities? _____ (y/n)
g. Have you ever considered commercial alternatives to smaller facilities? _________(y/n)
Why or why not (too expensive, too slow, too far, etc.)? _________________________
____
h. Have you considered remote operation of and access to smaller facilities to reduce the travel required? _____________ (y/n) Why or why not? ________________________
____

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6. **Comments**
   a. Have you considered developing a smaller facility at your own institution to meet your research needs? Why or why not?

      ____
      ____
      ____

   b. Please list one conclusion or recommendation that you think the committee should consider in its deliberations.

      ____
      ____
      ____
      ____

   c. At your "favorite" smaller facility of choice, what is one aspect that you would most like to see improved? (piece of equipment, access time, support, materials, etc.)

      ____
      ____
      ____

   d. If you have anything else you would like to explain or comment on, please do!

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E

Report of a Site Visit Team

INTRODUCTION

The Boston Area Site Visit was conducted by three members of the Committee on Smaller Facilities (COSF)—Donald Tennant (Lucent), Frances Ross (IBM), and John Soures (University of Rochester)—and facilitated by the Board on Physics and Astronomy's director, Donald Shapero.

As in most of the regional visits, the trip was arranged such that a number of facilities and centers could be accessed in a 2- to 3-day period, and therefore much of the time was devoted to interviews and tours rather than point-to-point travel. The Boston area trip therefore permitted visits to three institutions, which represented many more research centers, all within a 2+ day stay. The trip was conducted from July 30 to August 1, 2003. Trip reports were filed for internal committee use from each of the area groups, and summary reviews were conducted by the group leaders at the COSF meeting at the Stanford University campus in October 2003.

The host institutions for the Boston area included the Massachusetts Institute of Technology (MIT) and Northeastern University on July 31 and Harvard University on August 1. All three institutions were generous with their time and made access to staff and facilities amply available to the committee. The specific individuals and research organizations visited included:

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- Massachusetts Institute of Technology
  —*Center for Materials Science and Engineering*, Michael Rubner, Director
  —*Materials Processing Center*, Lionel Kimerling, Director
  —*Microphotonics Center*, George Kenney, Associate Director
- Northeastern University
  —*NASA Center for Advanced Microgravity Materials Processing*, Albert Sacco, Jr., Director
  —*Electronic Materials Research Institute*, Donald Heiman, Principal Investigator (PI) and Professor of Physics
- Harvard University
  —*Center for Imaging and Mesoscale Structures (CIMS)*, Bill Appleton, Director
  —Venkatesh Narayanamurti, Dean of Engineering and Applied Sciences
  —*Rowland Institute of Science*, Frans Spaepen, Director
  —*Materials Research Science and Engineering Center*, David Weitz, Director
  —*Nanoscale Science and Engineering Center (NSEC)*, Robert Westervelt, Principal Investigator (PI) and Director

OBSERVATIONS

Massachusetts Institute of Technology

Forum The site visit team met most of the time with the leadership of the Center for Materials Science and Engineering (CMSE) and the Materials Processing Center (MPC), had tours of the CMSE facilities, and conducted impromptu interviews with staff.

Facility Mission/Purpose The mission of the MIT CMSE is to foster collaborative interdisciplinary research and education in the fundamental science of materials and in the engineering of materials for specific applications. CMSE promotes collaborations among MIT faculty as well as between MIT research faculty and researchers at other universities, industry, government, and nonprofit laboratories. Collaborations are encouraged through several mechanisms including: Interdisciplinary Research Groups (IRGs), Initiative Projects, Shared Experimental Facilities (SEFs), and Outreach Programs. The CMSE SEFs include electron microscopy, analytical, x-ray diffraction, and crystal growth facilities; these facilities are operated for both internal (MIT) and external users.

Background/Origins/History The MIT CMSE is one of 29 existing Materials Research Science and Engineering Centers (MRSEC) sponsored by the National Science Foundation (NSF). MIT has been part of the MRSEC program since 1994.

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The CMSE has benefited from the creation of a "virtual center"—the MIT MPC—in 1980.

The MPC is an umbrella organization that focuses on creating shared structures and partnerships. Within MPC, MIT has created the Microphotonics Center, whose function is to provide for the creation of new materials, structures, and architectures to enable the evolution of photonics from single, discrete devices to integrated photonic systems.

The MIT CMSE was recently renewed by NSF for a period of 6 years. The Center supports an interdisciplinary research program with emphasis on micro- and nanostructured materials in the areas of photonics, polymer assemblies, and semiconductor and magnetic structures. The CMSE has also developed a strong educational program, with graduate, undergraduate, and K-12 elements.

Shared Experimental Facilities Operations The cost structure for the shared facilities was discussed. Issues such as maintenance, salaries, administration, equipment, and materials were explored. Funding discussions followed, including the budget portions that are supplied by NSF-sponsored MRSEC core funding, user fees, cost sharing, and so on. Specifics were discussed in order to help identify typical practices when compared with other institutions.

The site visit team learned that there are eight full-time support staff to operate the four SEFs. The staff titles range from Project Technician to Principal Research Scientist. There are two staff assigned to each of the primary SEF elements: Materials Analysis, Crystal Growth and Preparation, Electron Microscopy, and X-ray Diffraction. The shared facilities are most often operated by the individual users after hands-on training by the facility staff.

The group discussed planning for operations, maintenance, and upgrades. Users sign up to use the facilities on an as-needed basis. Facility maintenance, upgrades, and so on are coordinated with the major users. The management of the SEFs is apparently given a high priority with the CMSE. A high-level senior research scientist oversees the operation of the SEFs. Faculty user groups are established as required, to guide the selection of capital equipment and to assess the facilities' performance. Postdoctoral associates are often incorporated in the facility organization to introduce and develop new instrumentation.

Instrumentation and Services Provided The CMSE SEFs provide state-of-the-art capabilities in a timely manner in four primary areas:

- *Materials Analysis:* Atomic force microscope, X-ray photoemission spectrometer, scanning Auger microprobe, ultraviolet-visible-near infrared spectrophotometers, spectrofluorimeter, two differential scanning calorimeters,

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dynamic mechanical rheology analysis, Fourier transform infrared spectrometer, micro-Raman spectrometer, stress measurement system, thermal co-evaporator, and profilometer.
- *Crystal Growth and Preparation:* Three floating-zone furnaces, six furnaces for top-seeded solution growth, cutting and polishing apparatus, differential thermal analyzer/thermogravimetric analyzer, and two Superconducting Quantum Interference Device (SQUID) magnetometers.
- *Electron Microscopy:* 250 kV field-emission scanning transmission electron microscopes (STEMs), three 200 kV TEMs, field emission gun SEM, environmental SEM with x-ray analysis, specimen preparation, and image analysis equipment.
- *X-ray Diffraction:* Four rotating anode x-ray generators, two sealed-tube x-ray generators, a small-angle x-ray scattering diffractometer, four circle diffractometer, automated crystal analysis system, precession and Laue cameras, pole figure, glancing angle and high-temperature attachments.

Annual use of the SEFs averages 600 to 750 individuals. Approximately 72 percent of the users are MIT internal. The majority of the external users have an academic affiliation. Only about 1 percent are industrial users. Almost all the users are local/regional. Since September 2002, over 600 individuals have used the SEFs, including students and postdoctoral associates of 100 MIT faculty in 23 academic departments and centers, students and staff of 17 faculty from other academic/research institutions, and the staff of 6 senior-level industrial managers.

Education is one of the most important functions of the SEFs. The educational function is exercised in many ways: hands-on operational training provided to users (faculty, staff, and students), minicourses open to the MIT and external academic communities, and the interchange and intermingling provided by the interaction of the multifaceted user community.

Northeastern University

NASA Center for Advanced Microgravity Materials Processing

Forum Discussion and tour of laboratories by the director Albert Sacco, Jr., brief introduction to some research (shown by a postdoctoral associate).

Facility Mission/Purpose The aim of the Center for Advanced Microgravity Materials Processing (CAMMP) is to collaborate with industry to develop materials or processes of use both to the company and to NASA (mostly by ground-based experiments, a few in space).

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Background/Origins/History This is an unusual facility in that it is funded jointly by NASA (60 percent) and by the university (40 percent). It has been going since 1997. It develops its user base by aggressive solicitation (company visits) and by personal contacts of the director. However, only about 60 percent of proposals are accepted.

Shared Experimental Facilities (SEF) Operations CAMMP has little formal management structure; it is mostly run by its founder/director. To become a user, the company pays a membership fee, but after this there are no user fees. So this is really a consortium of industries and the university. It appeared that the membership fee depends on the scope of the collaboration. The biggest user is a commercial chemical company; others included U.S. and European universities. These university collaborators must have industrial links to use CAMMP. The industrial partners fund one or two postdoctoral associates or graduate students, usually for 3 years. If the industrial partner drops the project, Northeastern University (NE) pays for the remainder of the student's term, allowing the student to continue with related research. There are no per hour fees; the belief is that the faculty could not afford them, and instead faculty often supply other value or resources to the operation. Major equipment includes: SEM (used 25 hr/week), x-ray diffraction (XRD) (35 hr/week), GADDS (general area detector diffraction system, an unusual capability, 5 hr/week), atomic force microscope, focused-ion beam, mass spectrometer, Fourier transform infrared spectrometer, particle-size analysis. The only equipment desired is a TEM (currently they go to an industrial partner's central laboratory); the director believes that the current size is about right. CAMMP uses service contracts and buys new to avoid maintenance costs; lower-use equipment is given to NE faculty.

In contrast to MIT, CAMMP SEFs have no technical staff, and technical support is done by postdoctoral associates on extended terms (called research assistants), who stay 5 to 10 years and are often coauthors. There are typically 8 faculty involved, 8 students (3 postdoctoral) from NE, 8 from outside universities, 1 finance administrator, and the director.

Instrumentation and Services Provided The CAMMP facility is smaller and less conventionally funded and therefore more than most reflects the philosophy of the director: The director has informal collaborative arrangements for equipment. He believes that user fees serve no purpose, because in small universities faculty are too poor to pay them. Instead, "ideas are currency, not money." Apart from the funded graduate students, the center hosts 3 to 4 honors students per year, many school teachers, and does some evening classes on techniques (NE is strong on evening classes).

Electronic Materials Research Institute

Forum Group discussion with about 15 people, including the Dean of the university, PI (Donald Heiman), other faculty members, a few users, and some of the technical staff, followed by a brief tour of the outside of clean rooms and the SEM/XRD laboratory.

Facility Mission/Purpose This facility is under development and currently has no physical location. Its aim is to bring all shared equipment together into one location, run it, provide matching funds when groups of faculty apply for equipment, determine overall needs, and solicit donors.

Background/Origins/History The Electronic Materials Research Institute (EMRI) started in 2002 with a modest seed grant from the university to hire and invest in equipment; 15 faculty are involved now, with planned increase to 20 to 25. It was hard to get numbers for the projected final size and budget. The dean has a vision for this center that he compared to the plans for biotechnology (his specialty). According to him, NE is very healthy with its student programs and plenty of government (National Institutes of Health) and industrial (biotechnology) support. It has already (in 1973) set up a biological and chemical effort, the Barnett Institute, with a $100 million building, two endowed chairs, 20 faculty, an endowment, ample research funds, and a notable patent income, and would like to make the same size of effort in materials. As was done with the biotechnology area, he wants industry to define the equipment and curriculum; the biology faculty have a track record in getting funding, and the dean expects EMRI to actually generate revenue.

Shared Experimental Facilities (SEF) Operations An instrumentation committee, with a member from each department and one of the technical staff, considers user feedback and equipment on campus and at other area research institutions.

Users are to include those in the areas of biology, pharmacology, materials, physics, and so on. User fees are nominal but are structured as hourly and yearly; revenue is generated from educational activities.

The EMRI staff is currently 15, but the number is very fluid, and presumably very few of these (secretary, some students) are funded by EMRI itself. The technicians are still funded directly by the university.

Teaching activities include student training, plus classes in techniques and pre-college courses. Research training is projected into broad areas, which include photonic materials, fuel cells, theory, metamaterials (left-handed materials), pharmacology/biotechnology; the special feature of EMRI seems to be the biological connection.

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Instrumentation and Services Provided This facility seems still very much under development. But much was already present in NE: SQUID, near-field scanning optical microscope (NSOM), TEM, AFM, XRD, microelectromechanical systems (MEMS) fabrication, and a computing facility. Their first success as EMRI was in obtaining SEM and NSOM. Their next requests will be for TEM, nuclear magnetic resonance (NMR), and MEMS capabilities. They expect to add more equipment by applying for Nanoscale Interdisciplinary Research Team and NSEC funding.

Harvard University

Forum The site team visit to Harvard was primarily hosted by the CIMS and two major NSF centers, MRSEC and NSEC. Tours were conducted among several locations, since the new building to house most of the shared facilities is still in the planning stages. The director of the Rowland Institute at Harvard, Frans Spaepen, also briefly described the activities of the Rowland Institute, which was recently acquired by Harvard.

Facility Mission/Purpose The CIMS mission is to manage the shared facilities, partially fund visiting scientists, provide small grants to seed research projects, and provide staff assistants. Current research missions include synthesis of nanoscale structures, fabrication of mesoscale devices, advanced imaging and characterization services, and development of new fabrication and imaging methods. The participants draw from five different departments.

Background/Origins/History CIMS is a facility that supports the research activities of two major NSF centers at Harvard, MRSEC and NSEC, in addition to individual research grants and the undergraduate research mission. The center had a proposal pending as a node in the NSF-funded National Nanotechnology Infrastructure Network which has since been successful. While the current equipment is distributed among several locations, a new building and clean room being built by Harvard will eventually house most of the shared facilities. This is an investment on the order of $100 million. The merging of the shared facilities also allows cost share of operational expenses, including support staff. The site visit team also heard briefly about the Rowland Institute but did not visit those facilities.

Shared Experimental Facilities (SEF) Operations About 30 faculty are participating in the CIMS activities. Thirteen technical staff (20 eventually) support the suite of instruments, with 3 postdoctoral associates and 4 visiting scientists. About half of the operation budget comes from the dean from the division budget, the rest from fees and grant cost shares. Since this is a new undertaking, this formula is

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expected to change as more user fees and grants accrue. The construction costs and new faculty are funded by the Harvard endowment.

Harvard has recently brought the physical sciences faculty and the division of engineering and applied science together under one dean. This seems to be a high-level effort to maximize the interaction of the various faculty. CIMS has a non-faculty director plus a faculty scientific director. Great attention has been paid to developing specialized space in an effort provide good tool performance. The university has jump-started the programs with new faculty hires and is refurbishing temporary space in advance of the completion of facility construction.

Harvard offers both short courses and credit courses in some of the technical areas being fostered by CIMS. Undergraduate, not just graduate students, have access to these world-class research facilities. An applied physics course (credit) was also offered in which 19 professors gave tutorial lectures on their research fields.

Attracting and retaining high-quality support staff is a high priority. While support staff are hired on soft money, they can be given rolling 3-year contracts. This adds stability, but requires the university to assume the cost if a grant is discontinued or a funding shortfall is experienced. To encourage and attract high-quality staff scientists, contributions are recognized as authorships in publications.

Instrumentation and Services Provided The CIMS facilities were distributed and incomplete but growing in capability rapidly, and with plans to form a centralized user facility in a new building. The instruments merged analysis and fabrication capabilities in one organization. Materials research instruments include TEM, SEM, ultra-high-vacuum-STM, Rutherford backscattering, XRD, ion accelerators, and fabrication instruments such as electron-beam lithography, FIB, optical pattern generator, furnaces, deposition, and etching tools.

FINDINGS, BEST PRACTICES, AND DISCUSSION POINTS

Following is a cumulative list reflecting the observations of the site visit team based on all of the Boston area site visits.

On the Importance of Shared Facilities

- The innovation is at the intersection of the sciences, and central instrumentation facilities attract individuals and foster cooperation, sharing, and collaboration.
- Shared facilities such as the MIT CMSE provide an essential service to MIT researchers, faculty, and students as well as to external users engaged in

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materials science research and engineering activities. They provide educational as well as research value for the materials science community.

- SEFs provide opportunities for sharing experiences and knowledge among a large group of users with diverse backgrounds.
- Off-campus fabrication facilities are less desirable than off-campus characterization facilities.
- Much of the value of smaller facilities is nonmonetary—enabling faculty to mix and changing the mind set from independent, competing research programs to joint efforts—as well as monetary: providing a focus for large donations (e.g., buildings) and for institutional commitment.
- Regarding how to make facilities more visible: If smaller facilities were more visible, would they get funded and maintained more readily? The team discussed how to emphasize to NSF reviewers the value, monetary and nonmonetary, of such facilities in awarding other grants.

On Management/Philosophy

- There is a new recognition that universities take responsibility for investing in research facilities (are these the new libraries of undergraduate education, as one member of faculty put it?).
- To build a significant facility, high-level support (president, provost, dean) for facilities is essential.
- For shared facilities to work, there needs to be recognition of a service component in everyone's participation.
- There are efficiencies that industry can teach the universities with regard to interaction among staff, but there are important differences—for example, NSF must take a much longer view.
- While the sharing of experimental facilities is key to keeping down the overall cost of materials science research activities, it is evident that such sharing is most effective when the shared facilities are not too distant from the users (local or regional) and when the facility schedule allows for relatively quick turnaround and scheduling (<1-2 weeks).
- MRSEC is vitally important to convincing a university to invest. It is a longstanding example of shared central facilities in the materials area.
- Some facilities have only basic equipment (that seems to be the philosophy of the MIT MRSEC shared-equipment facility), and the complex pieces seen by the team (the ultra-high-vacuum STM at MIT) required hiring a postdoctoral associate or technician to run; it was not clear how the concept of users versus collaborators would apply if there are only a few experiments each year.

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- Successful facilities frequently passed on low-use equipment to faculty or took over the running of heavily used equipment; a bureaucracy that allows such flexibility appears to be a good practice.
- Another question was how much instrument development should be part of the mix. A component of instrument development (as at the Harvard CIMS) is probably appropriate, as there is little other funding avenue for it and it makes use of the skilled technical staff (and makes their jobs more interesting, too).
- Several people made the comment that multiple clean rooms are needed because of materials incompatibility, so similar equipment even in nearby facilities is necessary. And too much emphasis on a few large centers prevents students from getting hands-on experience.
- There seemed to be no uniform way to report income and expenditures of a facility. For example, depreciation is usually ignored (see the section below) and if the university provides secretarial or accounting help, how much is this worth?

On Funding Sources and Gaps

- The shared experimental facilities face challenges in several areas, including equipment renewal. Due to NSF's budget limitations and grant limitations, equipment costing in excess of $500,000 is nearly impossible to include in the MRSEC grant budget. The single-item cost of state-of-the-art instrumentation for these facilities ranges from $100,000 to over $1 million per major system. Some of the equipment on the center inventory is over 10 years old and will be in need of replacement or renewal in the immediate future.
- The discussion of user fees raised lively discussion. Most facilities only expect to raise 25 percent of their running costs through user fees. The typically $250,000 raised per year is useful in buying consumables, but did not appear to be the make-or-break factor in running a facility. An argument for fees was that they lead to extra efficiency on the part of users. Arguments against are that it is hard on a low-budget faculty, especially in less-well-funded schools, and it is philosophically wrong because it hinders the educational value of the institution. High user fees discourage wide use of facilities. Some facility users and managers think that a facility should be free, but most think that user fees demonstrate that instruments and services have value. It seemed important that users have input and form a consensus and buy in with respect to the usage, fees, priorities, and so on. Many small users feel that large users are receiving subsidized use of facilities.

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- Should a university-funded user facility be considered part of the cost share when applying for a grant? There were several ideas about how this should be calculated, but most facility users and managers agreed that it should be, or at least that the concept of cost sharing should be made more flexible. As an example of the high cost of the building facilities required to carry out such work, the MIT SEFs occupy a total of 9,200 ft^2 of space. The facility managers estimated that the cost of building such space is higher than \$2,500/ft^2. Future upgrades and improvements may therefore require significant expenditures in building construction and renewal—an area not normally covered by grant funding.
- Several faculty noted that the MRSEC has been flat funded for many years and that the budget fraction earmarked for infrastructure has shrunk over the years and has become too small to foster renewal even with normal cost shares. This, some believed, reflects the review panel weight placed on the IRG proposals and the added budget required for K-12 outreach.
- There is some sentiment among faculty that many funding agency program managers are flexible in the management of centers, but that the review panel expectations are more rigid. Therefore any changes (e.g., in budget allowances) in guidelines need to be clearly announced to the reviewers.
- On this trip, the site visit team visited well-endowed universities, and the donation of a \$100 million building seemed almost required to get a major new facility going! Most facilities have a business plan for accepting donations. The team noted that donors really seem to like facilities but are reluctant to donate equipment.
- It seemed clear that the operation of the SEFs is dependent on strong support from the university and on subsidies from the primary (NSF) grant. If the actual cost of operations had to be charged to all the users, either the shared experimental facilities would not be able to operate or the scope of work of the center would have to be significantly curtailed.

On Professional Staffing

- Since the facilities are highly specialized, significant experience and a high level of specialized education are required to adequately operate the SEFs. On the other hand, due to the small size of the facilities, there is sometimes little opportunity for personal growth and advancement. Departure or retirement of key individuals remains a major concern for smooth continuing operations.
- Everyone the team visited agreed that technical support staff are key to the facility success. The team saw either successful facilities or those that had

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only just started. MIT permits its technicians to move around, learn more skills, and be coauthors or presenters. Moving around only works in large facilities, but one possibly more universal improvement that the team discussed was establishing a fund to get staff to conferences or classes. There was wide support for the idea that there should be a modest budgetary component for professional growth and the training of support staff in MRSEC, NSEC, and other facilities.

- There were surprisingly many staff at the postdoctoral level rather than people with specific training as technicians. In one case (CAMMP), it was impossible to find a technician for one piece of equipment and a long-term postdoctoral associate was hired instead. Such people are motivated by the work environment, or maybe like research but prefer not to have the responsibility of directing their own research. If the supply of such postdoctoral associates is good, perhaps the lack of technician training schools and lack of career paths are not such a problem.
- Job security can be important to retaining highly skilled staff. Harvard guaranteed 3 years' employment even if the NSF grant were to be terminated, giving technical staff some job security. This is a way that a university can facilitate the quality of shared facilities.

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F

Selected Federal Programs That Support Midsize Facilities

DIVISION OF MATERIALS RESEARCH AT THE NATIONAL SCIENCE FOUNDATION

The Division of Materials Research (DMR) at the National Science Foundation (NSF) has a broad suite of programs designed to support and enable promising research. Several programs are directly relevant to the challenges and opportunities discussed in this report; the committee offers here a brief description of each, based substantially on and adapted from the online material cited. A key observation is that many of these programs require the applicants to include a detailed description of the instrument operation-and-maintenance plan, and even a statement about how it will be supported. However, none of the programs provides a formal mechanism for NSF follow-up and follow-through after the award has expired.

On average, about 12 percent of the DMR annual budget supports capital equipment purchases, or about $30,000 per year in FY 2003 constant dollars. This support is often provided through the Major Research Instrumentation (MRI) program or the Instrumentation for Materials Research (IMR) program.[1]

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[1] This section is based on materials supplied by the program office of the Division of Materials Research, National Science Foundation, January 2005.

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Major Research Instrumentation

The MRI program[2] is an NSF-wide program that seeks to improve the quality and expand the scope of research and research training in science and engineering. It encourages the development and acquisition of research instrumentation for shared inter- and/or intrainstitutional use and in concert with private-sector partners.

The MRI program has five goals:

- Support the acquisition, through purchase, upgrade, or development, of major state-of-the-art instrumentation for research, research training, and integrated research and education activities at institutions;
- Improve access to and increase the use of modern research and research training instrumentation by scientists, engineers, and graduate and undergraduate students;
- Enable academic departments or cross-departmental units to create well-equipped learning environments that integrate research with education;
- Foster the development of the next generation of instrumentation for research and research training; and
- Promote partnerships between academic researchers and private sector instrument developers.

The MRI program assists institutions in the acquisition or development of major research instrumentation that is, in general, too costly to support through other NSF programs. With the change in NSF cost-sharing requirements, the maintenance and technical support associated with these instruments are no longer directly funded. Proposals may be submitted for a single instrument, a large system of instruments, or multiple instruments that share a common or specific research focus. NSF supports the development of the next generation of research instrumentation by encouraging institutions to submit proposals that target instrument development. Individual investigators and teams of researchers are encouraged to apply for instrument development support.

DMR usually captures about 10 percent of the funds awarded annually (see Table F.1); the total MRI program has increased to more than $100 million in the 2004 solicitation. The overall proposal success rate for the FY 2003 MRI competition was approximately 40 percent. Awards for instrumentation ranged from

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[2] This section is based on materials from the Major Research Instrumentation (MRI) Program Solicitation: Instrument Development and Acquisition, NSF 05-515. Available online at http://www.nsf.gov/pubs/2005/nsf05515/nsf05515.htm; last accessed June 1, 2005.

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Midsize Facilities: Infrastructure for Materials Research
http://www.nap.edu/catalog/11336.html

TABLE F.1 History of Major Research Instrumentation Awards Within the Division of Materials Research, 1998-2003

Fiscal Year	Total Award Amount ($)	Number of Competitive Awards	Annual Median (current $)	Annual Mean (current $)
2003	12,081,218	31	172,000	234,975
2002	9,903,643	34	127,008	165,690
2001	10,575,436	37	125,155	154,244
2000	6,548,646	19	150,000	177,462
1999	4,926,129	21	132,149	144,131
1998	2,864,990	13	155,793	214,844

NOTES: Because of different cost-sharing levels over time and per institution, these awards are moderately leveraged to acquire equipment. In each year, several single awards were for $1 million or more, although on average, 80 percent of the awards are for $500,000 or less.

$100,000 to $2 million. Proposals requesting less than $100,000 were considered only from non-Ph.D.-granting institutions and from the mathematical sciences or the social, behavioral, and economic sciences at any eligible institution. Proposers may request an award period of up to 3 years for acquisition and up to 5 years for development of instrumentation. Within DMR, about 90 percent on average of the MRI award is used directly for capital equipment purchases.

Instrumentation for Materials Research

The DMR-specific IMR program[3] supports the acquisition and/or development of research instruments that will provide new capability and/or advance current capability to (1) discover fundamental phenomena in materials; (2) synthesize, process, and/or characterize the composition, structure, properties, and performance of materials; and (3) improve the quality, expand the scope, and foster and enable the integration of research and education in research-intensive environments.

Based on a minimum acquisition cost of $100,000 less the required cost-sharing percentage (exactly 30 percent for Ph.D.-granting institutions and 0 percent otherwise), the minimum award in the IMR program is $70,000 for Ph.D.-granting institutions and $50,000 for non-Ph.D.-granting institutions. Because instrumentation development was recognized as a priority area in 2002, cost-sharing for

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[3] This section is based on materials from the Instrumentation for Materials Research (IMR) Program Solicitation, NSF 04-503. Available online at http://www.nsf.gov/pubs/2004/nsf04503/nsf04503.htm; last accessed June 1, 2005.

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Midsize Facilities: Infrastructure for Materials Research
http://www.nap.edu/catalog/11336.html

TABLE F.2 History of Instrumentation for Materials Research Awards in the Division of Materials Research, 1998-2003

Fiscal Year	Number of Competitive Awards	Annual Median (current $)	Annual Mean (current $)	Mean Duration (years)
2003	44	147,000	143,074	1.32
2002	45	93,212	110,512	1.66
2001	47	96,708	108,478	1.61
2000	51	91,145	102,608	1.55
1999	41	105,000	128,212	1.58
1998	38	78,619	81,525	1.66

NOTE: About 80 percent of the average award goes directly toward the capital equipment costs for new instrumentation.

instrument development projects is in general no longer required. The typical award duration is 1 to 3 years. Each year, 35 to 40 new awards are made, competing for a total of about $7 million (see Table F.2).

Instrumentation proposals must discuss arrangements for acquisition, maintenance, operation, use plans, and shared use of the instrument, including:

- Overall acquisition plan;
- Biographical sketch of the person(s) who will have overall responsibility for maintenance and operation, and a brief statement of qualifications;
- Description of the physical facility, including floor plans or other appropriate information, where the equipment will be located;
- Statement of why the equipment is severable or nonseverable from the physical facility;
- Plans for the allocation of time on the instrument and the criteria used for allocation;
- Estimate of the fraction of time the instrument will be used by the various local and other potential users;
- Detailed plan of how use charges will be assessed (if applicable);
- Annual budget for operation and maintenance of the proposed equipment, indicating source of funds; and
- Brief description of other support services available for this instrument, and the annual budget for their operation, maintenance, and administration.

NSF applies additional review criteria for the IMR program: essential need for the instrument; impact on infrastructure; the ability of the applicants to operate and maintain the instrument; appropriateness of development plans (as applicable); and relevance to research and education.

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Instrumentation for Materials Research-Mid-Scale Instrumentation Projects

Responding to broad needs identified in a report by the National Science Board,[4] DMR launched the Instrumentation for Materials Research-Mid-Scale Instrumentation Projects (IMR-MIP) program[5] in 2004. The program is designed to support equipment such as beamline instrumentation and high-field magnets with awards between $2 million and $20 million.

Two types of proposals are solicited: (1) conceptual and engineering design and (2) construction. The design award enables the proposer to do the necessary engineering design of the instrument. A construction proposal may be submitted only after a satisfactory engineering design of the instrument has been completed and has been approved by both the facility at which the instrument will be situated and by NSF. The program does not provide operating funds for any of the projects it supports through this solicitation. Operational costs must be supported either by the facility at which the instrument is located or through some other source. DMR expected to have $3.5 million available to support this activity in FY 2004 for 3 to 4 awards, and to increase this level of support in future years, depending on the availability of funds.

The IMR-MIP program accepts proposals from university researchers for the design and construction of midscale tools for materials research—including equipment for materials characterization or preparation, such as detectors, beam lines, new high-field magnets, or preparation environments—at user facilities supported by NSF or other sources, including the Department of Energy (DOE) and the National Institute of Standards and Technology (NIST). For example, these could include proposals for beam-line instrumentation at the Spallation Neutron Source (SNS).

Use by the scientific team that constructs such an instrument is limited to 25 percent of the total time available on that instrument; at least 75 percent is made available to the facility for allocation to other users through the facility's normal peer review process. To ensure that the facility is willing to entertain such a project, the principal investigators (PIs) for a proposal must attach to the proposal a letter from the facility director stipulating that if the PIs subsequently are successful in obtaining construction funding, the facility will allow construction and will staff and operate the equipment on completion of construction through the operations phase.

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[4] National Science Board, *Science and Engineering Infrastructure for the 21st Century: The Role of the National Science Foundation,* NSB 02-190, Arlington, Va.: National Science Foundation, 2003.

[5] This section is based on materials from the Instrumentation for Materials Research-Major Instrumentation Projects (IMR-MIP) Program Solicitation, NSF 03-604. Available online at http://www.nsf.gov/pubs/2003/nsf03604/nsf03604.htm; last accessed June 1, 2005.

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Of note is that NSF proposes the use of additional review criteria that mirror DOE's large facility project approval process using so-called "critical decisions."

Materials Research Science and Engineering Centers

The NSF Materials Research Science and Engineering Center (MRSEC) program[6] was started in 1994. The new program combined elements of the Materials Research Laboratory (MRL) and Materials Research Group (MRG) programs while placing additional emphasis on the integration of research and education and the development of partnerships. The MRLs represent one of the first center-based activities at NSF. They were initiated in 1972 when the Interdisciplinary Laboratories, created in 1960 by the Advanced Research Projects Agency of DOD, were transferred to NSF and the NSF DMR was created. The MRG program was started in 1985 to foster interdisciplinary research in smaller group environments. By 1993, just before the MRSEC program was created, NSF supported 10 MRLs and 18 MRGs.

The purpose of the MRSEC program is to undertake materials research of a scope and complexity that would not be feasible under traditional funding of individual research projects. NSF support is intended to reinforce the base of individual investigator and small group research by providing the flexibility to address topics requiring an approach of broad scope and duration. To the extent consistent with the size of the center, MRSECs incorporate the following activities:

- Programs to stimulate interdisciplinary education and the development of human resources (including support for underrepresented groups) through cooperation and collaboration;
- Active cooperation with industry and other academic institutions to stimulate and facilitate knowledge transfer among the participants and strengthen the links between university-based research and its applications; and
- Support for shared experimental facilities, properly staffed, equipped, and maintained, and broadly accessible to users. MRSECs may encompass one or more interdisciplinary research groups (IRGs). Each IRG involves several faculty members and associated researchers, addressing a major topic or area in which sustained support for interactive effort is critical to progress.

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[6] This section is adapted from Materials Research Science and Engineering Centers (MRSEC) Program Solicitation, NSF 04-580. Available online at http://www.nsf.gov/pubsys/ods/getpub.cfm?nsf04580; last accessed June 1, 2005.

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The MRSEC program encompasses 27 different centers with annual support of about $52 million. Awards range from a minimum of $1 million to a maximum of $5 million with a limit of two such awards per institution. Each award is initially for 6 years; renewed NSF support is possible through competitive review in the sixth year of the award. In FY 2002, 3 new MRSECs were added, another 10 existing MRSECs successfully renewed their support, and 2 existing MRSECs were phased out in open competition.

The average support for any of the 758 faculty-level participants supported within the MRSEC program in 2003 was approximately $70,000 per year, including support for students, postdoctoral associates, and some equipment, and in some cases summer salary support. It should be noted that two-thirds of all MRSEC faculty do not receive salary support at all.

Partnerships for Research and Education in Materials

DMR launched the Partnerships for Research and Education in Materials program[7] in 2003 "to enhance diversity in materials research education by stimulating the development of long-term collaborative research and education partnerships between minority institutions and DMR-supported groups, centers, and facilities." Awards of up to $750,000 for 5 years are granted to the minority institution. The PREM proposals are evaluated on the following criteria:

- Are the goals and mission of the partnership clearly defined and achievable?
- Is the role of the DMR-supported group, center, or facility clearly stated?
- Is the planned research and education program sound and feasible?
- Is the management plan sound? Does the organizational chart contain the appropriate participants?
- Is the plan for internal assessment of the impact, dissemination of results, and progress of the project reasonable?

In 2004, from 30 proposals, 4 were selected.

International Materials Institutes

Continued progress in materials research depends increasingly on collaborative efforts among chemists, physicists, biologists, mathematicians, and engineers,

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[7] This section is based on materials from the Partnerships for Research and Education in Materials (PREM) Program Solicitation, NSF 03-564. Available online at http://www.nsf.gov/pubs/2003/nsf03564/nsf03564.htm; last accessed June 1, 2005.

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as well as closer coordination among funding agencies and effective partnerships involving universities, industry, national laboratories, and international organizations. Because of the rapidly growing interdependence of regional priorities, partnerships are important not only at the national level but also from a global perspective. With this in mind, NSF has co-sponsored a series of international workshops in materials research designed to stimulate enhanced collaborations among materials researchers and create networks linking the participating countries.

The International Materials Institutes (IMI) program[8] aims to enhance international collaboration between U.S. researchers and educators and their counterparts worldwide. The institutes advance fundamental materials research by coordinating international research and education projects involving condensed matters and materials physics, solid state and materials chemistry, and the design, synthesis, characterization, and processing of materials to meet global and regional needs. The institutes must be university-based and provide a research environment that will attract leading scientists and engineers. A critically important aspect of an international materials institute is its potential impact on advancing materials research on an international scale and developing an internationally competitive generation of materials researchers. This feature helps distinguish an international materials institute from other types of materials research centers that NSF supports.

Each international materials institute must address two long-term goals: (1) creating elements of a global materials research network designed to coordinate and support the rapidly growing interdependence of materials research priorities and related activities carried out in all regions of the world and (2) developing a new generation of students, postdoctoral scholars, and materials researchers and educators with enhanced international leadership capabilities.

In the 2004 call for proposals, a total of $2.2 million was expected to be available for up to 4 awards at a level of $0.5 million to $1.0 million per year. Awards were for an initial period of up to 5 years. Funding for the fifth year will be contingent upon the outcome of a comprehensive review during the fourth year. As a result of the first IMI competition held in FY 2002, NSF established three international materials institutes.

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[8] This section is based on materials from the International Materials Institutes (IMI) Program Solicitation: Toward an International Materials Research Network, NSF 03-593. Available online at http://www.nsf.gov/pubs/2003/nsf03593/nsf03593.htm; last accessed June 1, 2005.

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THE BIOLOGICAL SCIENCES DIRECTORATE AT THE NATIONAL SCIENCE FOUNDATION

The Division of Biological Infrastructure (DBI) in NSF's Biological Sciences Directorate (BIO) supports two programs that are related to the discussions in this report, the Multi-User Equipment and Instrumentation Resources for Biological Sciences (MUE) program and the Instrument Development for Biological Research (IDBR) program. The annual contribution from these two programs is about $10 million, spread across more than 100 multiyear awards.

Multi-User Equipment and Instrumentation Resources for Biological Sciences

DBI has maintained an effort that began in the early 1980s to support the purchase of multiuser instrumentation for research in biological sciences, although the program has been suspended and is not currently accepting any new proposals. The MUE program[9] provides support for the purchase of major items of instrumentation that will be shared by a number of investigators with actively funded research projects in areas supported by BIO. The MUE program gives priority to proposals that involve multiple identified users with active NSF support. The program supports:

- The purchase of single items of biological equipment that cost at least $40,000;
- The establishment of instrumentation resources consisting of several items of equipment with a related purpose, or the purchase of additional equipment for such resources; and
- Shared computational resources. Applications for workstations and midrange computing machines dedicated to broad research needs are appropriate as multiuser equipment proposals. Support is not provided for personal computers, personal workstations, or printers.

The MUE program requires that proposals include an assurance that the requested instrumentation will be used by a minimum of three independent investigators. Such proposals may describe the research projects of no more than seven major user groups. It is expected that a majority of the major user groups will have outside, peer-reviewed funding and that some of the major users will have active NSF funding. Additional use of this equipment in educational activities is encour-

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[9] This section is based on materials from the Multi-User Equipment and Instrumentation Resources for Biological Sciences Program Solicitation, NSF 05-534. Available online at http://www.nsf.gov/pubs/2005/nsf05534/nsf05534.htm; last accessed June 1, 2005.

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aged, consistent with the research needs of the proposed projects. The proposed instrumentation must be managed by individuals who are competent to independently operate and use the proposed instrumentation in their individual research. The remaining users may function through collaborations; however, in no case may more than 60 percent of the instrument time be allocated to one research group and its collaborators. The MUE program encourages applications from user groups that include individuals from different departments and institutions.

Proposals are required to indicate how the instrument will be supported and managed. Individuals who will be responsible for the instrument must be identified and a mechanism for assuring access to the instrument by all investigators must be described; expertise in use of the equipment must also be provided. A commitment to financially support the continuing operation and maintenance of the instrument is essential. Finally, a replacement plan for equipment with a predictable useful life or duty cycle must be presented. The budget of the MUE program is approximately $3.5 million per year; 20 to 25 standards grants will be awarded in FY 2006, subject to availability of funding.

Instrument Development for Biological Research

The IDBR program[10] supports the development of new instrumentation that will increase the accuracy, range, or sensitivity of observations for BIO research fields. The program provides support for:

- Development of concept and proof of concept for an entirely novel instrument for biological research;
- Development of new instruments that provide new capabilities for detection, quantification, or observation of biological phenomena, or significantly extend currently achievable sensitivity or resolution;
- Novel or significantly improved instruments for the study of biological systems at all levels of organization from the molecular and cellular to organisms, communities, and ecosystems;
- Improved or novel software for the operation of instruments or the analysis of data or images; and
- Workshops in emerging areas of instrumentation and instrument development relevant to biological research in areas supported by the Directorate for Biological Sciences.

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[10] This section is based on materials from the Instrument Development for Biological Research Program Announcement, NSF 05-536. Available online at http://www.nsf.gov/pubs/2005/nsf05536/nsf05536.htm; last accessed June 1, 2005.

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There are no specific limits on the amount of funding that may be requested. The budget should be commensurate with the proposed instrument development research activity. It is not required that individual prototype instruments developed under these awards have multiple users; however, the advances in instrumentation that result from these awards must have future utility to a broad set of potential users in biological research.

The IDBR program does not consider proposals for the development or acquisition of specialized items of equipment required for projects that do not aim to develop novel or significantly improved instrumentation for general use. Typical awards are in the range of $150,000 to $250,000 total annual cost for a period of 24 to 36 months, not including the cost of any requested equipment. Renewal proposals, i.e., those requesting continued support of an ongoing project supported through a previous IDBR award, are accepted. Although it is not required that instruments developed under these awards have multiple users, the IDBR program expects that the advances that result from its awards will lead to improved instrumentation that is of use to a broad set of potential users and is likely to lead to significant advances in biological research.

DEPARTMENT OF ENERGY

As part of its mission, DOE's Office of Basic Energy Sciences (BES) plans, constructs, and operates major scientific user facilities to serve researchers from universities, national laboratories, and industry.[11] These facilities enable the acquisition of new knowledge that often cannot be obtained by any other means. In the last year, over 9,500 scientists conducted experiments at BES user facilities. Thousands of other researchers collaborate with these users and analyze the data from the experiments at the facilities to publish new scientific findings in peer-reviewed journals.

BES—where materials research is supported—does not have a set of specific programs to support generic smaller facilities and instrumentation. However, from first principles, the number of "national user facilities" that are supported is small and almost all are based at the national laboratories. By ticking off the facilities on one's fingers, one can count four electron beam microcharacterization centers, five nanoscale science research centers, four neutron sources, the four light sources (not small facilities), and five other specialized centers. The total number of "national" user facilities supported in this way by BES is thus 18, plus the 4 light sources.

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[11] A more detailed description of the BES national user facilities is available online at http://www.sc.doe.gov/bes/BESfacilities.htm; last accessed June 1, 2005.

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Electron-Beam Centers

The four electron-beam microcharacterization centers[12] supported by DOE differ from the major user facilities such as the synchrotron radiation light sources or the neutron sources in that they do not have distinct operating budgets; they are supported as part of the Materials Science Division research budget. Each can be regarded as a suite of instruments aimed at using electron beams to characterize materials with high resolution, both structurally and chemically.

Three of the centers grew out of electron-beam microcharacterization groups whose original function was to support the materials research groups in their institutions, and to a greater or lesser extent users from these groups are still a very significant part of their customers. The exception was the National Center for Electron Microscopy at Lawrence Berkeley National Laboratory, which was intended as a national center from the beginning, primarily to develop high-resolution electron microscopy. In all of the centers, there is, however, still a very clear pattern of engaging in collaborative research with users.

The electron-beam centers account for an annual investment by DOE of about $5.8 million.

Nanoscale Science and Research Centers

As part of DOE's participation in the National Nanotechnology Initiative, five Nanoscale Science and Research Centers (NSRCs)[13] are being constructed. With planned operating budgets between $15 million and $20 million each, these centers are at the large end of the spectrum of smaller facilities. However, they represent a $100 million investment by DOE in annual operating costs and therefore bear mentioning.

These user facilities will provide world-class resources for the synthesis, processing, fabrication, and analysis of materials at the nanoscale. Each center will be housed in a new building located near one or more existing BES user facilities. Research thrusts and instrument suites for the centers have been determined in

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[12] Basic Energy Sciences Advisory Committee, *Report of the Basic Energy Sciences Advisory Committee Subpanel Review of the Electron Beam Microcharacterization Centers: Past, Present, and Future*, DOE/SC-0019, Germantown, Md.: Department of Energy, February 2000. Available online at http://www.sc.doe.gov/bes/besac/e-beam%20report.pdf; last accessed June 1, 2005.

[13] Office of Science, *Nanoscale Science, Engineering, and Technology in DOE's Office of Basic Energy Sciences: Research Directions and Nanoscale Science Research Centers*, Germantown, Md.: Department of Energy, February 2003. Available online at http://www.sc.doe.gov/bes/NSET_NSRC_brochure_FEB03.pdf; last accessed June 1, 2005.

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consultation with the nanoscale research community, largely through workshops that have drawn nearly 2,000 participants from industry, universities, and national laboratories.

User programs are being initiated at the NSRCs to give the research community immediate access to their emerging capabilities. Access will be through submission of proposals for peer review. As the centers evolve and mature over the next few years, BES will continue to rely on the research community for guidance.

TEAM Project

Pioneering developments of aberration-correcting electron optics have created the unprecedented opportunity to directly observe the atomic-scale order, electronic structure, and dynamics of individual nanoscale structures by advanced transmission electron microscopy. It is foreseeable that aberration-corrected electron microscopes exhibiting deep subangstrom resolution with single atom sensitivity and an increased time and energy resolution can be constructed within the next few years. The substantial expense of developing and maintaining such aberration-corrected electron microscopes is beyond the capability of individual investigators or even university centers. DOE's electron-beam microcharacterization centers propose to lead the development of advanced aberration-corrected electron microscopes in user facilities and provide the necessary infrastructure to make this instrumentation broadly available to the scientific user community.

For the past several years, five DOE-supported electron beam microscopy efforts, located at Argonne National Laboratory, Brookhaven National Laboratory, Lawrence Berkeley National Laboratory, Oak Ridge National Laboratory, and Frederick Seitz Materials Research Laboratory, have pursued the development of a next-generation Transmission Electron Aberration-corrected Microscope (TEAM).[14] The project was presented to BES in October 2002 and to an external review panel in February 2003. TEAM is guided by a scientific advisory committee.

DEPARTMENT OF DEFENSE

The Department of Defense, primarily through the research offices of the service branches and ARPA/DARPA, has been one of the largest supporters of materials research over the last 40 years. Since the purpose of this study is to address midsize facilities, the discussion here is restricted to the DOD funding to

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[14] Information on the TEAM project can be found online at http://ncem.lbl.gov/team3.htm; last accessed June 1, 2005.

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this topic. Generally the DOD components have not funded infrastructure/facilities, with some notable exceptions.

The Advanced Research Projects Agency (ARPA) was the founding agency for the MRL program in the late 1950s and early 1960s. Not only did these laboratories foster collaborative research, but they also provided a suite of central facilities to support the research without the need for an individual investigator to raise funds to set up and support materials analysis and preparation facilities. At some of the universities, such as Cornell, the University of Illinois at Urbana-Champaign, and Stanford, the facilities were quite extensive, covering cryogenic research, MeV particle accelerators, traditional wet chemical analysis, instrumental analysis, optical and electron microscopy, furnaces for materials preparation, and so on. In 1972, there was a transition of the funding to the NSF and DOE.

In approximately 1983, DARPA made a second major investment in facilities by establishing three GaAs foundries for the development of GaAs device manufacturing processes. The first was managed by Rockwell Science Center and was responsible for digital Metal-Oxide-Semiconductor Field Effect Transistor development. When the facility was closed, the technology went to Conexant and then to Skyworks. The second facility was operated by McDonald Douglas in Huntington Beach, California, and focused on junction field effect transistors. The third facility was at AT&T and concentrated on heterojunctions and bipolar transistors. The foundries had specific device goals set by their contract but did provide manufacturing services to the III-V community.

A third facility program was started by DARPA in 1981, called Metal Oxide Silicon Implementation Service (MOSIS). MOSIS is a low-cost prototyping and small-volume production service for very large scale integrated circuit development. Since 1981, MOSIS has fabricated more than 50,000 circuit designs for commercial firms, government agencies, and research and educational institutions around the world. MOSIS provides designers with a single interface to the constantly changing technologies of the semiconductor industry. Mask generation, wafer fabrication, and device packaging are contracted to leading industry vendors. MOSIS provides microelectronics fabrication services to domestic and foreign educational institutions, companies for pilot projects, and government agencies. From 1985 to 1994, funding came from DARPA, the National Security Agency, NSF, and commercial customers. From 1995 to the present, commercial users pay a sufficient user's fee that all costs are covered for the institutional users. MOSIS does not fabricate devices itself but collects the designs from the user, directs them to a mask house, and then has the runs done at one of several foundries. It has access not only to conventional Si foundries but also to SOI-SOS and InP capabilities.

In some cases, DARPA has undertaken research activities mandated by Congress with facilities occasionally involved. Examples are the optoelectronics facilities that were placed at the University of New Mexico, University of Southern California, and Cornell University. Each facility had a contractual set of goals for materials growth and device fabrication. Any services it provided to other institutions were within its contractual purview but fulfilled a secondary purpose. A second congressionally mandated activity was the establishment of a series of materials preparation and analysis centers in Florida.

Defense University Research Instrumentation Program

The Defense University Research Instrumentation Program (DURIP)[15] is designed to improve the capabilities of U.S. institutions of higher education to conduct research and educate scientists and engineers in areas important to national defense, by providing funds for the acquisition of research equipment. A central purpose of DURIP is to provide equipment to enhance research-related education. Proposals must address the impact of the equipment on the institution's ability to educate students, through research, in disciplines important to DOD missions. The FY 2004 call for proposals provided up to $44 million for more than 200 expected awards, with individual grants ranging from $50,000 to $1 million. The previous solicitation made 214 awards worth $43.5 million, averaging about $200,000 each. Cost-sharing is not required.

Multidisciplinary University Research Initiative

The DOD Multidisciplinary University Research Initiative (MURI),[16] one element of the University Research Initiative, is sponsored by the DOD research offices: the Office of Naval Research, the Army Research Office (ARO), and the Air Force Office of Scientific Research. The MURI program supports basic science and/or engineering research at institutions of higher education that is of critical importance to national defense. The program is focused on multidisciplinary research efforts that intersect more than one traditional science and engineering

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[15] This section is based on materials from the Department of Defense Program Announcement, Defense University Research Instrumentation Program (DURIP), Fiscal Year 2006. Available online at http://www.onr.navy.mil/sci_tech/industrial/363/durip.asp; last accessed June 1, 2005.

[16] This section is based on materials from the Office of Naval Research Broad Agency Announcement 05-017, Multidisciplinary University Research Initiative (MURI). Available online at http://www.onr.navy.mil/02/baa/docs/baa_05-017.pdf; last accessed June 1, 2005.

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discipline. Of the 26 topical areas supported, more than half are materials research related.

By supporting multidisciplinary teams, the MURI program is complementary to other DOD basic research programs that support university research through single-investigator awards. The total funding for 5 years available for grants resulting from the FY 2005 program solicitation is estimated at about $135 million, pending out-year appropriations. It is anticipated that the average award will be $1 million per year, with the funding for each award dependent on the scope of the proposed research.

NATIONAL INSTITUTES OF HEALTH

Included in the broad portfolio of the National Institutes of Health (NIH) are several programs that are relevant to a discussion of programmatic support for smaller facilities.

P41 Centers

NIH oversees the largest federally funded research enterprise in the United States. One of the specified grant mechanisms that it supports is the Biomedical Technology Resource Center Program (P41);[17] grants of this type are typically administered through the National Center for Research Resources of the NIH. Designed to provide a multidisciplinary technological infrastructure, the program supports a combination of research, development, collaborative research, service, and information dissemination activities involving a wide range of technologies. These biomedical technology resource centers provide state-of-the-art experimental and computational resources to a wide range of biomedical researchers, particularly those supported by NIH. Each center functions as both a technological and an intellectual resource, with an infrastructure that permits staff scientists to respond rapidly and effectively to emerging biomedical research opportunities. Resource centers provide major, complex, expensive technologies that are difficult for single institutions to acquire and support. While the primary goal of the P41 resource grant is to facilitate sophisticated research and development activities targeting biomedical applications, the multidisciplinary environment of each center stimulates innovation and collaboration among physical scientists, engineers, and

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[17] This section is based on materials from the National Center for Research Resources, *Biomedical Technology Guidelines, 1999*, Bethesda, Md.: National Institutes of Health, 1999. Available online at http://www.ncrr.nih.gov/biotech/btguide2.pdf; last accessed June 1, 2005.

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biomedical scientists. The centers also make their technologies available to a user community of biomedical researchers.

The technological capabilities of a resource center must be state of the art and not broadly available by other means. The projects served by the new technology must be broad in scope and involve a variety of biomedical research areas. The resource is expected to serve investigators in a wide geographical region. Five required components characterize a biomedical technology resource center:

- *Technological research and development.* Research projects conducted at each center involve the development of new technologies, improvement of existing technologies, or discovery of new uses for existing technologies. These investigations are at the cutting edge of the technological field and sometimes involve a degree of calculated risk, with the potential for producing significant gains in the health-related sciences. The R&D projects often are designed to address emerging needs in the biomedical research community.
- *Collaborative research.* The staff, who are experts in the center's technologies, collaborate with outside investigators who specialize in particular biomedical fields and are likely to become routine users of the technologies under development. These collaborations with potential end users help to refine technological tools and methodologies and also identify new applications to biomedical research. Through this feedback process, technologies ultimately may be developed to the point that they are ready for widespread dissemination.
- *Service.* Each center provides outside investigators with access to resources for studies that do not involve collaborations with the center's staff. In these cases, center personnel offer consultation and technical assistance but generally do not share authorship on resulting papers or patents. Nevertheless, resource users are expected to acknowledge use of the center in papers resulting from their projects.
- *Training.* Center personnel offer training in the use of the center's technologies and methods to collaborators, service users, and others in the biomedical community. On a regular basis, the center provides lectures, seminars, and hands-on laboratory experience. It also conducts occasional short courses and workshops, sometimes in conjunction with scientific meetings attended by the user community.
- *Dissemination.* To ensure that developed technologies and tools reach the broadest possible scientific user group, each resource center engages in outreach activities, such as presenting research results at meetings, conducting conferences, and producing newsletters or Web sites. Centers that develop and disseminate software emphasize ensuring that the software is

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> portable, well documented, and user friendly. Each center maintains an up-to-date Web site that provides information about its research activities and technologies.

A budget ceiling of $700,000 per year in direct costs, excluding equipment costs, and a budget ceiling of $500,000 for equipment for the duration of the requested project are placed on P41 grants. Major equipment purchases (more than $500,000 over the course of the project period) often require support from other sources when the Biomedical Technology Resource Center Program is unable to fund the entire request.

In 2002, NIH supported more than 1,260 resource center grants with an overall investment of more than $230 million. There are currently more than 50 specialized biomedical technology resource centers across the country, housed primarily at academic institutions.

Joint Shared Instrumentation Grant Program with NSF

The NSF MUE program and the NIH National Center for Research Resources (NCRR) Shared Instrumentation Grant (SIG) program[18] encourages applications for joint funding for multiuser high-end instruments. For joint funding consideration at least one principal investigator or 40 percent of the major user groups must have active NSF support. Proposals that request a single instrument with a total purchase cost of more than $500,000, and that would normally be eligible for submission to both NIH and NSF, can be submitted to NIH for joint funding with NSF by including the necessary NSF documentation in the NIH proposal. Such proposals are reviewed by a group convened by NIH with NSF participation.

At NIH, the SIG program provides a cost-effective mechanism for groups of NIH-supported investigators to obtain commercially available, technologically sophisticated equipment costing more than $100,000. This program is designed to provide for the acquisition or updating of expensive shared-use instrumentation not generally available through other NIH mechanisms, such as research project, program project, or center grant programs. If the major user group does not require total usage of the instrument, access to the instrument should be made available to other users upon the advice of an internal advisory committee. To promote cost-effectiveness, to encourage optimal sharing among individual inves-

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[18] This section is based on materials from the NCRR Shared Instrumentation Grant (SIG) Program Announcement, PAR-05-028. Available online at http://grants.nih.gov/grants/guide/pa-files/PAR-05-028.html; last accessed June 1, 2005.

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tigators, research groups, and departments, and to foster a collaborative multidisciplinary environment, the instrument should be integrated into a central core facility, whenever possible.

An internal advisory committee must be named to assist the principal investigator in administering the grant and overseeing the responsibility for the instrument. The membership of this committee should be broadly based and include members without a conflict of interest who can resolve disputes if they arise. The principal investigator and the advisory committee are responsible for the development of guidelines for:

- Maximum utilization of the instrument, including time allocation;
- A detailed plan for the day-to-day management of the instrument; and
- A financial plan for the long-term operation and maintenance of the instrument during the postaward period.

In 2004, the formal cost-sharing mechanism between NSF and NIH expired for this program; however, the SIG program still allows principal investigators to apply to both agencies for support for a large instrument provided that prior arrangements and notifications have been made.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Sample Return Laboratory Instrument and Data Analysis Program

NASA has recently created a new program that seeks to advance the state of the art in analytical instrumentation and methods. The program awarded its first grants totaling $3.1 million in FY 2002, followed by $7.4 million in FY 2003, $6.8 million in FY 2004, $6.7 million in FY 2005, and an estimated $6.1 million will be awarded in FY 2006. The motivation behind the Sample Return Laboratory Instrument and Data Analysis Program[19] is to maximize the scientific return from the samples provided by current and future Discovery-class sample return missions like Genesis (solar wind sample) and Stardust (comet dust). As in an R&A program, individual peer-reviewed proposals are selected for funding. Typical proposals seek to develop new analytical instrumentation or combinations of analytical instruments. Other proposals seek to enhance the capabilities of existing in-

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[19] Information on the NASA Sample Return Laboratory Instrument and Data Analysis Program can be found online at http://nspires.nasaprs.com/external/viewrepositorydocument/92/B.6_Sample_Ret._Lab._&_DA.pdf; last accessed June 1, 2005.

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strumentation. The target user base may vary significantly. In some cases, it makes sense to develop instrumentation and techniques that will be used by only a small number of investigators at a single institution. In other cases, the high cost of the instrument and its associated support structure may allow the development of only a limited number of such facilities that must be shared by the entire community. Cost sharing and evidence of a long-term institutional commitment are viewed as important elements of the program.

NATIONAL NANOTECHNOLOGY INITIATIVE

An important element of the future for materials research is the emphasis on nanotechnology. Although the initiative is still unfolding, and new programs and avenues for investment are still being developed, it represents such a significant national priority that it deserves discussion here.

The National Nanotechnology Initiative (NNI)[20] originated in President Clinton's FY 2001 budget request that included a $225 million (83 percent) increase in the federal government's investment in nanotechnology research and development. The Bush administration has continued to make the NNI a top science and technology priority since then. The initiative supports long-term nanoscale research and development leading to potential breakthroughs in areas such as materials and manufacturing, nanoelectronics, medicine and health care, environment, energy, chemicals, biotechnology, agriculture, information technology, and national security. The initiative, which nearly doubled the nanoscale R&D investment over FY 2000, supports a broad range of scientific disciplines including material sciences, physics, chemistry, and biology and creates new opportunities for interdisciplinary research.

Agencies participating in the NNI include NSF, DOD, DOE, NIH, NASA, and the Department of Commerce's NIST. Roughly 70 percent of the new funding proposed under the NNI will go to university-based research to help meet the growing demand for workers with nanoscale science and engineering skills.

A key component of the implementation plan for the NNI is a coordinated strategy for the development of 10 centers and networks of excellence. DOE's NSRCs mentioned above are one avenue for this investment, and the NSF's NNIN (below) is another.

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[20] Information on the National Nanotechnology Initiative can be found online at http://www.nano.gov/html/about/funding.html and http://www.ostp.gov/html/budget/2006/One-Pagers/FY06NationalNanotechnologyInitiative1-pager.pdf; last accessed June 1, 2005.

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National Nanotechnology Infrastructure Network

As part of the NNI, the National Nanotechnology Infrastructure Network (NNIN)[21] was formed in early 2004 through an NSF-sponsored competition. NNIN is an integrated partnership of 13 user facilities providing broad opportunities for nanoscience and nanotechnology research. The network provides extensive support in nanoscale fabrication, synthesis, characterization, modeling, design, computation, and hands-on training.

To the extent that NNIN represents a nationally coordinated scheme for pooling resources and leveraging individual contributions, the committee considered it as an example in its deliberations. NNIN is still in the initial stages of development (the award was officially made in March 2004), however; plans for the implementation of the winning proposal are discussed here.

Scope of the NNIN

The network, through complementary strengths, will provide on-site and remote external-user access to advanced top-down processing and bottom-up synthesis and self-assembly, comprehensive integration capabilities for multistep processes, state-of-the-art characterization for hard and soft materials, the development of tools and techniques, and a comprehensive Web and computation infrastructure. The network will allow straightforward user access that enables a diversity of projects efficiently and at low cost. NNIN facilities will be operated as open, hands-on user facilities, available to all qualified users.

The computation and Web-based infrastructure will provide a centralized resource for organizing and distributing the rapidly growing knowledge base at the foundation of nanoscience and engineering. Education, human development, outreach, and societal and ethical studies components are thoroughly integrated throughout the network. The goals are to spread the benefits of nanotechnology to new disciplines, to educate a dynamic workforce in advanced technology, and to become a teaching resource in nanotechnology for people of all ages and educational backgrounds. Network-based education and information tools and comprehensive local hands-on activities will be developed to achieve these objectives. NNIN will also support an infrastructure and research environment to promote consideration of the societal and ethical consequences of nanotechnology, cover-

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[21] Information on the National Nanotechnology Infrastructure Network can be found online at http://www.nnin.org and http://www.nnin.org/doc%5Cnninbrochuresmall.pdf; last accessed June 1, 2005.

ing economic, political, educational, environmental, health, legal, security, and cultural implications.

Key Elements

NNIN is distinguished from the previous National Nanofabrication Users Network in its scope and size; the new network consists of 13 different participating institutions encompassing all aspects of nanoscience and technology, whereas the former had only 6 participants and focused exclusively on fabrication. Similarly, NNIN is different from the older Microelectromechanical Systems Exchange program because it is more focused on science and technology research as opposed to process engineering and service.

Two elements of the network are relevant to the work of this committee: (1) the emphasis on developing the "nodes" of the network as fully outfitted, extremely capable user centers to leverage the activities of any one research and (2) the effort to nationally link and coordinate activities at the diverse array of centers hosting the network. In truth, the network is viewed by NSF more as a distributed large facility (indeed, "networks" in general are moving toward the Major Research Equipment and Facilities Construction account line) than as a set of individual autonomous entities that collaborate on self-steering. The standards usage and access policies for the nodes, once developed and released, should serve as good models for user- and service-oriented facilities, since the network is intended to be of service to the nation.

Nanoscale Science and Engineering Centers

Recently, NSF established the Nanoscale Science and Engineering Centers (NSEC)[22] program across all directorates as part of the NNI. Eight centers are currently supported under the NSEC program, many of which bridge multiple institutions, at more than $18 million per year. The 2004 NSEC competition added another six such centers.

The NSEC program addresses opportunities that are too complex and multifaceted for individuals or small groups of researchers to tackle on their own. Centers in the program bring together researchers with diverse expertise—in partnership with industry, government laboratories, and/or partners from other

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[22] This section is based on materials from the Nanoscale Science and Engineering Centers (NSEC) Program Solicitation, NSF 03-043. Available online at http://www.nsf.gov/pubs/2003/nsf03043/nsf03043.htm#nsec; last accessed June 1, 2005.

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sectors—to address complex, interdisciplinary challenges in nanoscale science and engineering, and will integrate research with education both internally and through a variety of partnership activities. Each center, whether based at a single institution or distributed across a number of institutions, must have an overarching research and education theme, well-integrated programs, and a coherent and effective management plan. The NSEC program centers as a whole will span the range from exploratory research—focused on discovery—to technology innovation and will involve a broad spectrum of disciplines such as engineering, mathematics and computer science, and the physical, biological, environmental, social and behavioral sciences. The scope of individual centers and the disciplines involved in them will vary.

Each NSEC award is in the range from about $1 million to $4 million per year for 5 years, depending on the scope of the work proposed. NSEC program centers will be eligible to compete for one 5-year renewal. Awards are made as cooperative agreements. Cost sharing at a level equal to 10 percent of the total amount requested from NSF is required. Centers may be based at a single U.S. academic institution or may consist of a lead institution in partnership with one or more partner institutions.

Other

Another facility program in this category is SEMATECH. This group in Austin, Texas, provided a central location for semiconductor equipment manufacturers to develop and test their equipment while the process engineers who used the equipment were sent to SEMATECH from member companies. This arrangement was very successful, and the program did much to strengthen the U.S. position in equipment manufacturing. Funding for this organization was subsequently provided first by the U.S. semiconductor industry and later with international support. Generally, industry contributions have not established facilities for general use but have primarily supported single and groups of investigators. Now SEMATECH has spun off its fabrication and analysis facilities as the Advanced Technology Development Facility.

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G

Summary of National Science Foundation Workshop on Chemical Instrumentation

Following is the executive summary of the final report of the National Science Foundation (NSF) Workshop on Instrumentation, April 16-17, 1999, Arlington, Virginia.[1]

In today's climate of increased competitive funding, concern has arisen as to the future of instrumentation acquisition at most academic institutions. Important considerations such as sources of funding, shared vs. single investigator instrument usage and costs associated with personnel to oversee and maintain equipment have become of paramount interest. Obviously, the needs of smaller research active institutions are diverse and different from those of major research universities and thus policies established for one may adversely affect the other. These issues are clearly of importance to NSF.

The following is a report generated from an NSF Workshop on [Chemical] Instrumentation, which was held on April 16 and 17, 1999, in Arlington, Virginia. The two-day workshop included approximately 60 scientists from academia, government and instrument manufacturers as well as NSF personnel. The workshop format of morning keynote speakers and afternoon panel discussions was designed to 1) establish a forum for discussing instrumentation issues relevant to NSF and academia, and 2) propose strategies for addressing those issues. The general goal of this workshop was to provide advice, through the medium of discussion, to NSF on funding issues related the [Chemical Research Instrumentation and Facilities] CRIF and [Major Research Instrumentation] MRI programs as regards instrumentation development, acquisition, and infrastructure.

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[1] The full report, "Workshop on Instrumentation," is available online at http://www.cchem.berkeley.edu/~mswww/NSF/nsf.html; last accessed June 1, 2005.

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During this two-day workshop, suggestions and recommendations were put forth regarding the status of instrumentation proposal submission, review and funding. Names, addresses, the agenda and listed speakers are provided as an appendix to this document. All recommendations are listed at the end of each of the ensuing sections that provide detailed information on each of the specific panels. The panel recommendations with highest consensus are listed below:

1. The CRIF program should not be discontinued. Rather, it should continue to provide funds for shared use instrumentation at the current or increased level of funding. An REU [Research Experience for Undergraduates]-CRIF program should be investigated as a possible source of equipment funds for smaller schools and/or undergraduate institutions.
2. In certain disciplines, Regional/National Facilities with extended continuity (greater than five years) can play an important role. Such facilities should be funded appropriately with consideration given to travel and housing costs for those individuals visiting and benefiting from collaborations with such facilities.
3. It is important that NSF fund instrument development proposals. Many suggestions are provided within the following sections on how this might be accomplished more effectively. In particular, instrument development proposals should be reviewed separately from shared instrumentation proposals and a unique set of review criteria for the former should be mandated and implemented.
4. Interagency cooperation is very important and should be encouraged in order to fund high end, expensive instrumentation and national research centers.
5. Support for instrumentation for the individual PI [principal investigator] as well as those applying for shared use instruments must be preserved.
6. The requirement for matching funds should be maintained in order to show institutional commitment. However, more creative sources of matching money should be allowed; i.e. capital development for new buildings, service and maintenance costs and industrial funds should be viewed as matching contribution. It was suggested that matching money be required for equipment in excess of $100K rather than $80K) for undergraduate institutions, thus making it easier for these important institutions to train prospective graduate students as well as future employees to local industry.
7. Although Chemistry as a discipline is rapidly becoming much more equipment-intensive, NSF support for instrumentation is holding at approximately 15% of the Chemistry budget. Therefore, it is essential that NSF maintain at least the current level of support for instrumentation (especially instrument development) in Chemistry.
8. Requests for MRI funds should be limited to $2 million/year per institution rather than the current 2 proposals/year per institution restriction. This would eliminate the bias in favor of large-ticket instrument requests; i.e. a dollar value rather than a restricted number of proposals would ensure equity across the different types of instrumentation.

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Throughout the workshop it became apparent that many perceptions by the attendees about programs, funding procedures, review processes and interagency interactions may not be accurate. Therefore, it seems clear that NSF needs to turn its attention to better educating the scientific community about programs and review processes. This educational endeavor needs to be more than citing a web site. It requires that NSF personnel and staff become more visible and interactive at scientific meetings, visits be made to chemistry departments at various institutions and that program announcements be more clearly delineated and written. In particular, clarification as to choice of submission to CRIF vs. the MRI program was especially vague among the participants.

It also seemed apparent that the Chemistry Division should build more communication and closer liaisons with the Biological Division. In this regard funding for instrument proposals which have a significant biological component, but which are still predominately chemistry research in nature, could be shared between the divisions. Much of chemistry research today is [embedded] in the biological sciences and this natural evolution needs to be encouraged and acknowledged.

Recommendations for future workshops of this nature include the following:

1. Educate your participants beforehand; i.e., provide copies of program guidelines that are to be evaluated.
2. Let participants know at least one month prior to the meeting what the issues are that need addressing. Those who are informed a priori will be better prepared to address crucial questions about the issues at hand.
3. Provide a template for the final written report.

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H

Personal Perspectives from Howard K. Birnbaum

CENTERS FOR MICROCHARACTERIZATION: ESSENTIAL AND ENABLING TOOLS FOR MATERIALS RESEARCH

H.K. Birnbaum
Materials Research Laboratory
University of Illinois

In this age of introspective research funding, it is appropriate to question the funding of the microcharacterization centers in the same manner that we question other activities. While the sciences that comprise the field of microcharacterization are widely used by chemists, physicists, materials scientists and engineers, and by researchers in a number of other disciplines, microcharacterization plays an important educational role only in a limited number of fields other than materials science. This somewhat anomalous situation exists, despite the fact that about 31 percent of recent experimental articles published in the materials physics literature and about 45 percent of recent experimental articles published in the materials chemistry literature utilized one or more methods of microcharacterization.

For the purpose of this statement, microcharacterization is defined as the sciences utilized to specify the structure and/or chemistry of solids on a scale appropriate to the measurements or synthesis being carried out. In almost all cases, this characterization is carried out at a size scale that is small (of the order of nanometers) in at least one dimension. Even in the case of surface analysis, while

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the measured area may be relatively large, the third dimension, depth into the surface, is microscopic in dimension. Included within the scope of microcharacterization are the sciences and methods of electron microscopy (transmission electron microscopy [TEM], scanning transmission electron microscopy [STEM], low-energy electron microscopy [LEEM], spin polarized low-energy electron microscopy [SPLEEM], scanning electron microscopy [SEM], reflection high-energy electron diffraction [RHEED], etc.), surface analysis (Auger electron spectroscopy [AES], scanning Auger electron spectroscopy [SAES], ultraviolet photoelectron spectroscopy [UPS], x-ray photoelectron spectroscopy [XPS], secondary ion mass spectrometry [SIMS], scanning tunneling microscopy [STM], atomic force microscopy [AFM], other scanning probe microscopies, etc.), ion beam analyses (Rutherford backscattering [RBS], particle induced x-ray emission [PIXE], channeling, etc.), x-ray and neutron scattering (wide angle x-ray scattering [WAXS], small angle x-ray scattering [SAXS], fluorescence analysis, etc.), and the group of techniques classified as field emission, field ion, and atom probe microscopies. A somewhat broader view of microcharacterization would include techniques such as nanoindentation. The incomplete listing above demonstrates that the field of microcharacterization is a highly dynamic one and one that makes use of a wide range of physical phenomena. These techniques meet the needs of materials scientists to understand the structure and chemistry of complex systems in order to understand the properties that interest them.

In view of the above, it is fair to ask why the field of microcharacterization remains the "Rodney Dangerfield" of the physical sciences. The lack of incorporation of these sciences into the departments of physics and chemistry in the United States stems from a number of factors and differs for the different techniques. X-ray scattering, in its various manifestations, is accepted in these science departments, perhaps due to its quantitative nature, although academic departments rarely hire faculty whose main research interest is in this field. Surface analysis techniques are widely accepted in departments of chemistry as tools to be used but are rarely a part of the teaching curricula. Electron microscopy methods, although they are widely used by the physics and chemistry research communities, are not considered as subjects for inclusion in the curricula. Rarely are faculty whose area of interest lies in electron microscopy included in the faculty of these departments. While the science underlying electron microscopy methods is considerable and is sophisticated, it is only recently that the field has progressed to the stage where quantitative results can be obtained. It is this lack of quantification that probably lies at the core of

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the lack of acceptance as a field of physics. In the case of chemistry departments, this lack of acceptance probably stems from the very recent use of the methods by chemists. Only within the relatively small fields of metallurgy and ceramics have these methods won acceptance and respectability.

The microcharacterization centers are faced with the somewhat daunting prospect of providing access to a wide range of techniques based on sophisticated instrumentation and sciences to a user base that would be greatly hampered by the absence of such access. Yet the fields of science to which these capabilities are provided, and in which they play a crucial role, have only a limited acceptance of microcharacterization science as a valid field of research. In a very real sense, the capabilities provided by the sciences of microcharacterization and by the centers would be appreciated only if they become unavailable.

Microcharacterization centers play two crucial roles in support of Department of Energy (DOE) science. The first is that they provide a primary tool for study of important problems—studies that could not be carried out without access to these techniques. Examples of this role abound and a few are cited below.

- Investigations of grain boundary and interface structures would remain empty exercises in geometry and simulation without the direct observation provided by atomic resolution TEM.
- Multilayer structures and the defect structure of thin films and multilayers (interface dislocations, threading dislocations, microstructure evolution in polycrystalline layers, etc.) would remain in the realm of speculation without the methods of cross-sectional TEM.
- Surface reconstructions and their role in controlling surface chemistry and film growth would not have been discovered or understood without the use of high-resolution TEM, LEEM, and STM techniques.
- The electronic structures of surfaces and of molecules adsorbed onto the surfaces would not have been understood without the use of XPS and UPS methods.
- Atomic site locations of solutes were established using ion channeling.
- The structure of sonochemically synthesized catalysts and solids was established using SEM and TEM methods.
- Determination of the crystallographic dependence of catalytic activity required the use of TEM and STEM based techniques.
- Fracture processes at crack tips would have remained speculation without the use of x-ray topography and in situ TEM methods.
- Elucidation of hydrogen effects on deformation, fracture, and hydride precipitation would not have been possible without in situ environmental cell TEM and SEM methods.

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Midsize Facilities: Infrastructure for Materials Research
http://www.nap.edu/catalog/11336.html

- The chemistry of grain boundaries and interfaces can only be understood with Auger, XPS, UPS, STEM/EDS, and STEM/EELS methods.
- Many aspects of dislocation behavior would remain exercises in the application of elasticity theory without the direct observations of TEM and in situ TEM experiments.
- Medium-range atomic correlations and fluctuations, of great interest in amorphous materials and glasses, can only be studied with TEM and coherent x-ray methods.
- Nanotubes were discovered using TEM and are still best studied with TEM techniques.
- Much of what is known of epitaxial growth results from the use of TEM, LEEM, STM, and x-ray methods.
- Quasicrystals and their unusual symmetries were discovered using TEM methods.
- The structure and chemistry of amorphous grain boundary films in ceramics have been determined using TEM and microchemical TEM based methods.
- Mass transport during oxidation would not be directly measurable without the isotopic sensitivity of the SIMS method.
- Development of self-assembling nanostructure structures and thin films is dependent upon the observations using TEM, SEM, AFM, and STM and on the surface chemical knowledge developed using XPS, UPS, and SAES.
- The atomic structure of domains in ferroelectric relaxor materials has been established using STEM imaging methods.

Microcharacterization science also provides an extremely important tool for the support of other kinds of measurements. In many cases, this secondary role is so important that it can be considered to be enabling in allowing the science to be carried forth. In these cases, the microcharacterization is often carried out as a cooperative effort between colleagues, one of whom is expert in the microcharacterization methods and interpretations. Examples of this type are:

- Correlations between physical properties (magnetic, mechanical, electrical, etc.) and structure (grain shape, preferred orientation, and distribution, particle size, shape and distribution, defect structure, interface structure, etc.) are often critical in understanding the behavior of materials.
- Development of thin film and multilayer growth methods requires

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close interactions between the processing scientist and the structure analysis that is generally based on determination of the chemistry and defect structure of interfaces and of the crystal layers.

- Growth and properties of quantum confinement structures, such as quantum dots and quantum lines, were greatly enabled by the ability to visualize these structures using TEM and STM methods.
- SIMS is essential for the understanding of doping of semiconductors.
- The first observations of dislocations and other lattice defects were carried out with TEM. Development of our understanding of these defects was enabled by TEM methods. Our understanding of micromechanics is based on the understanding of dislocations and defect interactions based on TEM observations.
- Flux lattice behavior in superconductors was established by direct microscopic observations.
- Imaging of discommensurations in charge density waves has been carried out by TEM methods.
- Theories of kinks on dislocations and dislocation kinetics were confirmed by direct observations in the TEM.
- Catalysis cannot be understood at the level of microscopic rate-structure correlations without the use of XPS and UPS techniques.
- Understanding of the dependence of catalytic activity on crystal orientation was made possible by the use of TEM and STEM based microchemical measurements.
- Understanding of the rate-limiting reaction paths in thin film interfacial reactions necessary for developing improved diffusion barriers in fields as diverse as microelectronics and wear protection was made possible with the use of TEM and STEM based microchemical techniques.
- Development of combustion exhaust remediation depended critically on the knowledge of catalytic and support structures developed by TEM methods and on detailed chemical analysis of the catalyst and substrates during poisoning or deactivation.
- The new methods of combinatorial synthesis are dependent upon the ability to characterize the microdots structurally and chemically with TEM, x-ray, XPS, and UPS methods.

The above examples, by no means a complete list, illustrate the important role played by microcharacterization science in materials science, condensed matter physics, and materials chemistry. Considering the portfolio of research at the DOE laboratories, the role of the characterization centers is perhaps greater than in the average research organization. Microcharacterization certainly plays an extremely

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important role in industrial laboratories as evidenced by their large investments in and support of microcharacterization efforts.

As the above clearly establishes, there is very significant science carried out using microcharacterization methods and even more extensively enabled by microcharacterization science. The DOE microcharacterization centers play an essential role in the DOE science and technology portfolio. In many ways they fulfill complementary roles to those played by the large DOE facilities such as the synchrotron and neutron facilities. While both are important to the DOE effort, there are distinct differences in their modes of operation (in addition to the very large differences in their operating budgets). The large facilities provide intensive user time at limited periods during the year. They generally require a proposal approval for access requiring advance planning. In contrast, the microcharacterization centers generally provide frequent access to their instrumentation and generally (but not always) do not require a proposal process for access. Thus, synchrotron users may have access to synchrotron beams 3 to 4 times per year or less while microcharacterization center users often use the instruments on a weekly or more frequent basis. At many of the microcharacterization centers, the researchers make use of multiple techniques for their studies—indeed this is essential in addressing complex materials problems. Their very nature requires that synchrotrons and neutron scattering facilities serve large regional or national clienteles. In contrast, the microcharacterization facilities serve more local communities, although in many cases, they have unique instruments and capabilities that attract users nationally or internationally.

Since time at the large synchrotron and neutron facilities is available only on a very competitive basis, the user community generally consists of scientists who are experts at the scattering methods. In contrast, there is a greater spectrum of users at the microcharacterization facilities. The users range from experts to novices who are being educated in the techniques. In addition, there is a large cadre of users requiring the information from microcharacterization methods and who work in cooperation with the expert users.

It is often argued that scientists active in the fields of microcharacterization are primarily interested in the instruments and their development. This attitude mirrors the lack of appreciation by the traditional sciences of the importance of the sciences of microcharacterization. As in many fields, instruments have become so complex that it is folly to try to construct them in house when they are available commercially. Hence, as the methods become more comprehensive and capable, there is a desire to obtain that

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greater capability to enable the sciences researchers want to carry out. In recent years, the rate of significant advances is such that instruments should be replaced with a frequency of about 10 years. Is this too large an investment? I think not, when the increased capability to answer important questions in the very wide range of science enabled by microcharacterization is taking into account.

Thus in many ways, the large facilities and the microcharacterization centers play complementary roles in the range of DOE facilities. While they serve complementary purposes, it would be difficult to imagine a DOE research environment with either of the two types of facilities missing.

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I

Committee Member and Staff Biographies

COMMITTEE MEMBERS

Robert Sinclair, Chair, Professor of Materials Science and Engineering, Stanford University

Dr. Sinclair received his B.S. and Ph.D. degrees from Cambridge University in materials science. After holding research positions at the University of Newcastle upon Tyne and the University of California, Berkeley, he joined the faculty of Stanford University, Department of Materials Science and Engineering, in 1977. Dr. Sinclair has received a number of awards for his research, including the Robert Lansing Hardy Gold Medal of the Metallurgical Society of the American Institute of Mining, Metallurgical, and Petroleum Engineers, the Eli Franklin Burton Award of the Electron Microscopy Society of America, an Alfred P. Sloan fellowship, and the Marcus E. Grossman Award of the American Society for Metals. He has also received two awards for excellence in undergraduate teaching at Stanford. He is very active in several professional societies and in the organization of symposia and workshops on electron microscopy. He has published approximately 160 refereed technical articles and contributed chapters to six books. Dr. Sinclair's research centers on the application of high-resolution transmission electron microscopy (TEM), including in situ heating, to a wide range of materials problems. TEM provides imaging of materials at the atomic level, therefore providing microstructural information necessary for the understanding of structural, electrical, and magnetic properties of materials. Dr. Sinclair's research has included

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materials of interest both to microelectronics and to magnetic data storage. In December 2002, Dr. Sinclair became the founding director of Stanford's new Nanocharacterization Laboratory as part of the university's Advanced Materials Initiative, which seeks to provide a set of shared research facilities that will provide top-quality instrumentation to faculty in a variety of disciplines. He is currently chair of the Department of Materials Science and Engineering.

Ani Aprahamian, Professor of Physics, University of Notre Dame

Dr. Aprahamian earned her Ph.D. in nuclear physics from Clark University in 1986 and went on to positions at Brookhaven National Laboratory as a National Synchrotron Light Source Fellow and then Lawrence Livermore National Laboratory. She came to the Notre Dame Physics Department in 1989. She is presently the director of the Nuclear Structure Laboratory, one of only three U.S. low-energy nuclear physics laboratories supported by the National Science Foundation (NSF). Dr. Aprahamian has been involved in numerous workshops and conferences, both on and off campus, and has recently become chair of the Holifield Radioactive Ion Beam Facility Users Group. She is an elected fellow of the American Physical Society, a reviewer for the NSF, the Department of Energy (DOE), and the American Institute of Physics. The research effort of the Nuclear Structure Laboratory is built around three accelerators and a broad program in low-energy nuclear physics. Her research centers on nuclear structure and nuclear astrophysics, covering topics such as weak interactions and fundamental symmetries using positron-neutrino scattering and nuclear structure studies involving collective mode resonances and characterizations of single-particle excited states.

Arthur I. Bienenstock, Vice Provost and Dean of Research and Graduate Policy, Stanford University, and Director Emeritus, Stanford Synchrotron Radiation Laboratory

Dr. Bienenstock received his Ph.D. from Harvard University in applied physics in 1962. From 1997 to 2001, while on leave from Stanford, he served as associate director for science of the White House Office of Science and Technology Policy (OSTP). At OSTP, he concentrated on policy and interagency coordination directly related to the health of U.S. basic science, as well as other policy matters that can be informed by basic science. For the 20 years prior to his going to OSTP, Dr. Bienenstock directed the Stanford Synchrotron Radiation Laboratory (SSRL) at the Stanford Linear

Accelerator Center, leading SSRL's transition from a scientific project to a major facility. He has been a faculty member in Stanford's Departments of Applied Physics and Materials Science and Engineering since 1967. He was director of the Geballe Laboratory for Advanced Materials at Stanford from 2002 to 2003. He has published more than 100 scientific papers in the general areas of solid-state physics, amorphous materials, and synchrotron radiation. Dr. Bienenstock has been a member of many distinguished advisory committees, including seven National Research Council (NRC) panels concerning crystallography and materials science and, most recently, the NRC Committee on Physics of the Universe. He has been a member of the Council of the American Physical Society and is a fellow of both the American Physical Society and the American Association for the Advancement of Science.

John P. Bradley, Director, Institute of Geophysics and Planetary Physics at Lawrence Livermore National Laboratory

Dr. Bradley earned a B.S. in chemistry from the University of Canterbury, Christchurch, New Zealand, in 1976 and a Ph.D. in chemistry from Arizona State University in 1982. He then joined the University of Washington's Department of Astronomy, where he developed an interest in interplanetary dust particles. Dr. Bradley became a senior research scientist with McCrone Associates in Chicago and performed microscopy studies of human-made materials and stratospheric dust. Dr. Bradley served as the executive director of MVA, Inc., in Atlanta, Georgia, a privately held company that specializes in materials science consulting and research for industry and the federal government. He was also an adjunct professor of materials science and engineering at the Georgia Institute of Technology. Dr. Bradley helped lead the team that examined the Antarctic Mars meteorite and showed its microstructure to be consistent with that of naturally occurring processes. He moved to the Lawrence Livermore National Laboratory in July 2001 as director of the Institute for Geophysics and Planetary Physics, where he is working on preparation for the return of the first sample from a comet. In addition to setting up sample handling and nanobeam analysis facilities, he is overseeing the construction of a new kind of transmission electron microscope. Dr. Bradley is a member of the American Association for the Advancement of Science and a fellow of the Meteoritical Society and the Microbeam Analysis Society.

David R. Clarke, Professor of Materials, University of California at Santa Barbara

Dr. Clarke was chair of the Materials Department at the University of California, Santa Barbara for 7 years, having received his Ph.D. in physics from Cambridge

University in 1974. Dr. Clarke has had broad research experience both in industrial laboratories, such as the Rockwell International Science Center and the IBM Research Division at Yorktown Heights, as well as in academia. His current research centers on two areas: the development of advanced ceramic materials and the development of techniques such as piezospectroscopy to measure stresses in electronic circuits, composites, and ceramic materials. He recently stepped down as a trustee of the American Ceramic Society, where he served on numerous committees, and he has served on scientific advisory committees for the Center for Material Sciences and Basic Energy Sciences at the Department of Energy. Dr. Clarke has been on several evaluation committees for university departments and colleges and has served on numerous industrial task forces; he served as a member of the Solid State Sciences Committee of the NRC (his term ended in June 2003). Dr. Clarke is an elected member of the National Academy of Engineering.

James W. Davenport, Senior Physicist and Director, Center for Data Intensive Computing, Brookhaven National Laboratory

Dr. Davenport's research interests include solid-state physics and chemistry, electronic structure of atoms, molecules, and solids, as well as first-principles calculations on metals and alloys. As the director of a user-oriented computing center, Dr. Davenport has significant experience from the computing facility world. He has been chair of the American Physical Society's Division of Materials Physics. His professional affiliations include membership in the American Physical Society, American Chemical Society, Materials Research Society, American Association for the Advancement of Science, and New York Academy of Sciences.

Francis J. DiSalvo, John A. Newman Professor of Physical Science, Cornell University

Dr. DiSalvo is director of the Cornell Center for Materials Research, one of 29 such national centers supported by the National Science Foundation. He earned his Ph.D. in applied physics in 1971 from Stanford University. He then joined the research staff at AT&T Bell Laboratories (now Lucent Technologies), where he later headed several research departments. In 1986, Dr. DiSalvo moved to Cornell's Chemistry Department. His research interests are in the synthesis and characterization of inorganic compounds, and he currently specializes in nitrides and intermetallic materials with

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novel crystal structures. Dr. DiSalvo is a fellow of the American Physical Society (APS) and of the American Association for the Advancement of Science and has received the APS International New Materials Prize. He is also a member of the American Chemical Society, the Materials Research Society, and the National Academy of Sciences. Dr. DiSalvo is a past member of the NRC's National Materials Advisory Board and served on the NRC's Solid State Sciences Committee (his term ended in June 2004).

Charles A. Evans, Jr., President, Full Wafer Analysis, Inc.

Dr. Evans is president of Full Wafer Analysis, Inc., the company that he started recently after retiring from Charles Evans and Associates, which he founded in 1978. Charles Evans and Associates specializes in materials analysis using microanalytical techniques such as secondary ion mass spectrometry, Rutherford backscattering spectrometry, and Auger electron spectroscopy. Before starting his own company, Dr. Evans held other positions as an analytical chemist, including that of professor of chemistry. He is a member of the American Chemical Society, the American Society of Mass Spectrometry, and the Microbeam Analytical Society. Dr. Evans earned both his B.A. (1964) and Ph.D. (1968) in chemistry at Cornell University.

Walter P. Lowe, Professor of Physics, Howard University

Dr. Lowe received his Ph.D. in condensed-matter physics from Stanford University in 1983. He became a professor of physics at Howard University and is now director of the Howard University Beltsville Research Laboratory and director of the joint Michigan-Howard-Lucent Technologies Collaborative Access Team (MHATT-CAT), a three-institution collaboration on one of the synchrotron beam lines at the Advanced Photon Source at Argonne National Laboratories. His primary research interests are in the use of high-brightness synchrotron and x-ray sources to study novel materials. The MHATT-CAT group, under his direction, produced one of the first sequences of real-time images of structural changes taking place on the atomic scale.

Frances M. Ross, Manager, Nanoscale Materials Analysis Department,
IBM T.J. Watson Research Center

Dr. Ross received her B.A. in physics and Ph.D. in materials science from Cambridge University in 1985 and 1989, respectively. She joined AT&T Bell Laboratories in 1990 as a postdoctoral member of the technical staff, where she made

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use of in situ electron microscopy techniques to study silicon oxidation and the properties of dislocations in SiGe devices. From 1992 to 1997, she worked as a staff scientist at the National Center for Electron Microscopy, Lawrence Berkeley National Laboratory, where she used in situ microscopy to observe anodic etching of silicon and the motion of domain walls in ferroelectrics, as well as coordinating users of the High Resolution and In Situ facilities. In 1997, Dr. Ross joined IBM as a research staff member and in 2000 became manager of the Nanoscale Materials Analysis Department. She is currently studying growth processes in semiconductors, and silicides and at liquid/solid interfaces using ultra-high-vacuum and liquid-cell microscopy. In 1999 she received the United Kingdom's Institute of Physics (IOP) Charles Vernon Boys Medal for her contributions to real-time visualization of materials growth and processing, and in 2000 she was named Outstanding Young Investigator by the Materials Research Society. She is a fellow of the APS and the IOP, an author or co-author of more than 40 journal articles, and holds 3 patents.

David J. Smith, Regents' Professor of Physics and Astronomy, Arizona State University

Dr. Smith is currently director of the John M. Cowley Center for High Resolution Electron Microscopy at Arizona State University. He received his Ph.D. in physics from the University of Melbourne, Australia, in 1978, and his D.Sc. from the same institution in 1988. He served as the director of the Cambridge University High Resolution Electron Microscope from 1980 to 1984 and director of the NSF National User Facility for High Resolution Electron Microscopy at Arizona State from 1991 to 1996. His long-term research interests have centered on the development and applications of atomic-resolution electron microscopy, with recent applications directed toward magnetic materials and semiconductors. Dr. Smith is the author or co-author of 15 book chapters and more than 400 refereed journal publications. He is a fellow of the American Physical Society and the U.K. Institute of Physics, and he has received several awards for teaching, including the Burlington Northern Faculty Achievement Award.

John M. Soures, Manager, National Laser Users' Facility, University of Rochester

Dr. Soures received his Ph.D. in mechanical and aerospace sciences from the University of Rochester in 1970. He has served as a consultant for the

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Lawrence Livermore National Laboratory and Eastman Kodak Company and other national laboratories. He holds three patents on laser control systems. Dr. Soures has been a member of the DOE's Fusion Energy Sciences Advisory Committee and has worked with the University of Rochester's Laboratory for Laser Energetics as a budget advisory group member, a panelist on the science policy group, and as a coordinator for the external users group, before assuming his current role as the manager for the National Laser Users' Facility in 1996. He has been a reviewer for both NSF and DOE and a referee for numerous scientific journals. He is a fellow of the American Physical Society and received the 1993 Award for Excellence in Plasma Physics Research. Dr. Soures's research interests are in inertial confinement fusion using high-power, well-focused lasers.

Leonard D. Spicer, University Distinguished Service Professor and Professor of Biochemistry and Radiology, Duke University

Dr. Spicer is founding director of the university-wide high-resolution Nuclear Magnetic Resonance Spectroscopy Center at Duke University. He received his Ph.D. in chemistry from Yale University in 1968 and served as associate graduate school dean at the University of Utah for several years. He has been chair of Duke's Academic Council, as well as serving on numerous university advisory boards, including the Committee on Resources and the Academic Priorities Committee. Dr. Spicer currently chairs the User's Advisory Committee and serves on the Science Advisory Committee for the William R. Wiley Environmental Molecular Science Laboratory operated by the Pacific Northwest Laboratory of the Department of Energy. He has also served on a number of National Institutes of Health, NSF, and DOE review panels. He is a fellow of the American Association for the Advancement of Science and has received the Duke University Award for Merit. Dr. Spicer has published more than 100 research papers in the areas of physical chemistry, biochemistry, and biophysics. His research is focused on structural biology and molecular dynamics associated with biological function in protein assemblies and biomacromolecular machines.

Donald M. Tennant, Distinguished Member of the Technical Staff, New Jersey Nanotechnology Consortium and Lucent Technologies

Dr. Tennant is a 25-year veteran of the Research Division of Bell Laboratories. He is a Distinguished Member of Technical Staff and the acting technical manager for the Advanced Lithography Group of the New Jersey Nanotechnology Consortium (NJNC). The NJNC is a Lucent-owned LLC formed in 2002 after the spin-off of Lucent's Microelectronics Business (now Agere Systems). The NJNC was formed

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within the Bell Labs research division to engage commercial enterprises as well as universities, federal research agencies, and national laboratories in nanotechnology research and solutions. He has built and managed electron-beam lithography facilities at both the Holmdel and Murray Hill, New Jersey, locations. He has been chair of the Gordon Research Conference on Nanofabrication, was the 1996 conference chair of the International Conference on Electron, Ion, and Photon Beam Technology and Nanofabrication and is its permanent financial trustee. Dr. Tennant is widely recognized for his broad materials fabrication expertise. He was one of six selected U.S. representatives to the first U.S.-Korea joint Nanofabrication Workshop in 2002. He is the current chairman-elect of the Nanometer Science and Technology Division of the American Vacuum Society. He has served on several DOE review panels for nanoscale research centers. Dr. Tennant's research expertise is in the area of materials fabrication, focusing on the use of electron-beam lithography in applications as diverse as molecular electronics, optoelectronics, nanotransistors, and microfocusing Fresnel optics for x-ray applications. He has authored or co-authored more than 190 articles in these fields and has been awarded 8 patents. He has had many years of experience dealing with the problems of operating a relatively expensive facility, getting sufficient support, and working with users.

NRC STAFF

Donald C. Shapero, Director, Board on Physics and Astronomy

Dr. Shapero received a B.S. degree from the Massachusetts Institute of Technology (MIT) in 1964 and a Ph.D. from MIT in 1970. His thesis addressed the asymptotic behavior of relativistic quantum field theories. After receiving the Ph.D., he became a Thomas J. Watson Postdoctoral Fellow at IBM. He subsequently became an assistant professor at American University, later moving to Catholic University and then joining the staff of the National Research Council in 1975. Dr. Shapero took a leave of absence from the NRC in 1978 to serve as the first executive director of the Energy Research Advisory Board at the Department of Energy. He returned to the NRC in 1979 to serve as special assistant to the president of the National Academy of Sciences. In 1982, he started the NRC's Board on Physics and Astronomy (BPA). As BPA director, he has played a key role in many NRC studies, including the two most recent surveys of physics and the two most recent surveys of astronomy and astrophysics. He is a member of the American Physical Society, the American Astronomical Society, and the International Astronomical Union. He has published research articles in refereed journals in high-energy physics, condensed-matter physics, and environmental science.

Timothy I. Meyer, Senior Program Officer, Board on Physics and Astronomy

Dr. Meyer is a program officer at the NRC's Board on Physics and Astronomy. He received a Notable Achievement Award from the NRC's Division on Engineering and Physical Sciences in 2003 and a Distinguished Service Award from the National Academies in 2004. Dr. Meyer joined the NRC staff in 2002 after earning his Ph.D. in experimental particle physics from Stanford University. His doctoral thesis concerned the time evolution of the B meson in the BaBar experiment at the Stanford Linear Accelerator Center. His work also focused on radiation monitoring and protection of silicon-based particle detectors. During his time at Stanford, Dr. Meyer received both the Paul Kirkpatrick and the Centennial Teaching awards for his work as an instructor of undergraduates. He is a member of the American Physical Society, the American Association for the Advancement of Science, the Materials Research Society, and Phi Beta Kappa.

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