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Bridging the Gap: Building a Sustained Approach to Mid-scale Research Infrastructure and Cyberinfrastructure at NSF

October 1, 2018

NATIONAL SCIENCE BOARD

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National Science Board

October 1, 2018

MEMORANDUM FROM THE CHAIR OF THE NATIONAL SCIENCE BOARD

SUBJECT: *NSB Report on Mid-scale Research Infrastructure and Cyberinfrastructure at NSF*

The National Science Board (NSB) is pleased to present its report, *Bridging the Gap: Building a Sustained Approach to Mid-scale Research Infrastructure and Cyberinfrastructure at NSF.* This report contains the findings and recommendations of the Board's Mid-scale Working Group that was created to examine the extent to which an investment gap exists between the cap for the Major Research Instrumentation (MRI) program and the threshold for the Major Research Equipment and Facilities Construction (MREFC) account and to propose recommendations to bridge any discovered gap.

NSB is grateful for the assistance provided by the National Academies of Science, Engineering and Medicine (NASEM) as the NSB worked to create this time-sensitive report .

If you or your staff have any questions on this report, please contact Dr. John J. Veysey II, Executive Officer to the Board, by phone at (703)-292-7000 or via email at jveysey@nsf.gov.

Diane L. Souvaine
Chair

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Acknowledgments

The National Science Board (NSB) appreciates the numerous individuals who contributed to the work of the Board's Mid-scale Working Group. We are particularly indebted to the collaboration with the National Academies of Science, Engineering, and Medicine (NASEM). Dr. Bruce Darling, Executive Officer, NASEM, Dr. Peter Blair, Executive Director, NASEM Division on Engineering and Physical Sciences, Dr. Laura T. DeFeo, Associate Executive Director, Division on Earth and Life Studies, and the Directors of a number of Boards within these Divisions provided the Working Group and its staff support team with numerous reports produced by NASEM's National Research Council and referred the team to key scientists who provided valuable insight into those reports. We extend our deepest gratitude to these individuals who greatly expanded the Board's understanding of the science and engineering communities' views on this important topic. (A list of individuals and reports can be found in the appendix.)

NSF staff members were essential to the drafting of this report. Dr. James Ulvestad, Chief Officer for Research Facilities, deserves special recognition for his invaluable contributions to the Board's understanding of NSF efforts to build mid-scale programs, current challenges, and the wide diversity of programs and awards funded in this budgetary range across the Foundation. The Board's Mid-scale Working Group also spoke with representatives from nearly every directorate across NSF and gained vital perspectives on the infrastructure needs and challenges relevant to their respective disciplines. (A list of individuals can be found in the appendix.)

The Board also extends a special note of appreciation to the dedicated NSF staff who serve the Board as Committee Executive Secretaries. Drs. Carol Bessel, Kathy McCloud, and Linnea Avallone, Executive Secretaries for the Committee on Awards and Facilities, provided numerous reviews as this project developed offering a keen eye to NSF processes that impact past, present, and future mid-scale-level investments.

The National Science Board Office (NSBO) provided essential support to the work of the Mid-scale Working Group. Especially deserving of recognition are: Dr. Elise Lipkowitz, Science Policy Analyst and Dr. Brad Gutierrez, Executive Secretary to the Board, for their staff leadership during the production of this report. Dr. Mateo Munoz, AAAS Science and &Technology Policy Fellow, was instrumental in collecting, analyzing, and organizing the data used in this report. Additionally, Dr. Reba Bandyopadhyay, Science Policy Analyst, and Dr. John Veysey, NSBO Director, supplied numerous reviews, edits, and substantive recommendations.

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Executive Summary

This report responds to U.S. House Appropriations Committee Fiscal Year (FY) 2018 Report language that directs the National Science Board (NSB), in collaboration with the National Academies of Science, Engineering, and Medicine (NASEM), to consider steps to bridge the gap between the NSF's Major Research Instrumentation Program (MRI) and the agency's Major Research Equipment and Facility Construction (MREFC) account and to develop appropriate processes to address this matter through the MREFC account within a restricted funding environment. The timing of this request from Congress is welcome, following NSF's October 2017 Request for Information (RFI) on existing and future needs for research infrastructure projects in the $20 million-$100 million-dollar range. It also comes at a time of increased NSF efforts to strategically prioritize mid-scale research infrastructure as one of the Agency's Big Ideas, as seen in NSF's 2019 Budget Request.

The research community has identified mid-scale research infrastructure as a key enabler of scientific advances on shorter timescales than required for the larger projects funded within the MREFC account. Mid-scale research infrastructure can also provide the foundations for new innovative large facilities, and, in the process, train early-career researchers in the development, design, construction, and effective use of cutting-edge infrastructure. Likewise, cyberinfrastructure is key to solving the challenges of collecting, processing, and distributing the big data so prevalent in today's science and engineering endeavors. Infrastructure investments at the required mid-level can also help maintain the United States' standing among global partners and competitors.

The message of the research infrastructure-intensive science community to NSB during the course of our research was that it did not see a home at NSF for mid-scale research infrastructure projects. While proposal processes for the MRI program and the MREFC account are understood, no such clear path has existed for most mid-scale research infrastructure ($10 million-$70 million).

Evidence supports this community perception. Most NSF awards between $20 million and $70 million go to centers and institutes and to large facility Operations & Maintenance (O&M), with comparatively little investment in mid-scale research infrastructure and cyberinfrastructure. A review of existing programs indicates that specific programs dedicated to mid-scale instrumentation or infrastructure exist in a few divisions, and that those programs support few projects in the $10 million plus range. By contrast, the Foundation's 2017 RFI confirmed broad interest in infrastructure at this scale across all disciplines, identifying $3 billion of high impact ideas in the $20 million-$70 million range. Given this strong community interest, NSB endorses NSF's inclusion of mid-scale research infrastructure as one of its 10 Big Ideas and supports devoting $60 million to mid-scale research infrastructure as proposed in the FY 2019 Budget Request.

Recommendations

The top-level recommendations for this report include:

- NSF should affirm and sustain the mid-scale Big Idea with a long-term *agency-level* commitment to mid-scale research infrastructure.

- NSF should investigate the feasibility of using the MREFC account as one possible funding mechanism

- NSB and NSF should review existing infrastructure oversight and management structures to ensure compatibility with mid-scale range investments.

- NSF, in cooperation with NSB, should develop an evaluation and assessment program to determine the full scope of the demand for mid-scale research infrastructure and ensure NSF's programs and processes address that demand.

In keeping with the idea that NSF must provide a home for all good ideas that promote the progress of science, this report recommends sustaining nascent efforts to bridge the mid-scale research infrastructure gap via new *agency-level* programs that provide opportunities for all NSF research communities to compete for funding. The size of such a programs must also be balanced with other portfolio considerations including the balance among principal investigator grants, center awards, and existing infrastructure support such as that now available for major multi-user research facilities and cyberinfrastructure. This commitment could include using the MREFC account to construct competitively-selected and strategically prioritized *ensembles* of mid-scale research infrastructure awards. Employing the MREFC account to support mid-scale research infrastructure, cyberinfrastructure, and/or upgrades would raise the strategic priority and provide NSB and NSF visibility into infrastructure in the mid-scale cost range. This emphasis on agency-level strategic visibility and portfolio prioritization was also a key component of the recommendations in the NSB's May 2018 *Study of Operations and Maintenance Costs for NSF Facilities*.

Centrally managed mid-scale programs at NSF would require new mechanisms to compare mid-scale research infrastructure opportunities across all fields and to identify the strategic priorities appropriate for agency-level funding. Modifications to NSF's management structures and NSB's oversight structures will be necessary to accommodate the risks associated with an agency-level program and this scale of infrastructure. Additionally, the agency-wide mid-scale research infrastructure program will require careful evaluation and assessment to ensure strategic balance and that initial program efforts lead to the ultimate goal of a sustained mid-scale program.

Introduction

For over 60 years, NSF has made investing in research infrastructure an essential component of its activities to support the U.S. Science & Engineering (S&E) enterprise. NSF-supported research infrastructure has provided U.S. scientists with shared resources to study phenomena large (ecosystems, earth systems) and small (cells, nanoparticles, neutrinos), to sample and take measurements locally and globally, to compute, and to store, share, and analyze data. NSF investments in research ships, field stations, telescopes, particle accelerators, materials fabrication labs, state-of-the-art microscopes, social science surveys, and cyberinfrastructure have fostered breakthroughs. New tools have helped to generate research questions and train the next generation of scientists and engineers. Overall, these infrastructure investments have been central to NSF's commitments to research and education.

NSF's approach to investing in research infrastructure has evolved since it carved out from discipline-focused budgets its first awards for radio astronomy, computing, reactor, and biological field facilities in the 1950s. In the intervening years, NSF has increasingly supported research infrastructure through dedicated mechanisms – including the Academic Research Infrastructure (ARI), Major Research Instrumentation (MRI) program, and the Major Research Equipment and Facilities Construction (MREFC) account. These mechanisms have given certain types of research infrastructure a visible home and clearly identified funding profiles. The latter is important, given that the returns from infrastructure investments often require a longer time horizon than research grants.

Previous Board reports, most recently in 2011, have addressed mid-scale research infrastructure. The infusion of American Reinvestment and Recovery Act funds and the prospect of continued budget growth led the Board to conclude in 2011 that NSF's longstanding approach of leaving decisions regarding investment in mid-scale research infrastructure to the divisions remained the right approach. However, a constrained budget environment in the intervening years has forced choices that have left the 2011 vision partially unfulfilled. As the Board's recent report on large facility O&M highlighted, increased proposal pressure, division/directorate budgets that have not kept pace with operational needs, and the pressures that O&M mortgages for new large facilities now place on divisions and directorates, are stressing the divisions' capacity to fund the full range of research and research infrastructure needs. Additionally, relatively flat division budgets, coupled with the volatility of the annual budget cycle, have challenged long-range planning and incentivized choices that maximize flexibility. Investments, such as mid-scale research infrastructure, that may require large upfront commitments on short timescales, and/or funding for design, construction/acquisition, and operations, have been de-emphasized. As a result, many division-level mid-scale research infrastructure programs – including those set up since the Board's 2011 report – have tended to fund smaller infrastructure projects.

NSF's renewed effort to fund mid-scale research infrastructure as part of its 10 Big Ideas occurs at a time of increasing need in all S&E fields for infrastructure in the mid-scale range. Cyberinfrastructure is no exception. Although the Office of Advanced Cyberinfrastructure (OAC) in the Directorate for Computer and Information Sciences and Engineering (CISE) funds cyberinfrastructure for CISE and other NSF directorates, the preponderance of these awards (over 97%) are below $5 million, whereas needs with funding requirements in the $10 million to $70 million are forecast to grow as the promises of big data and machine learning are realized. Some individual instrument costs now exceed the upper limit of NSF's MRI program, even as scientists report the need for clusters or networks of instruments.

Additionally, the past few years have seen robust investments in mid-scale research infrastructure by other countries – both those that invest only in the mid-scale range and those that fund the full spectrum of research infrastructure. As the NSB heard during its discussions with both internal and external stakeholders, strategic investments by other countries in instrumentation and state-of-the-art multi-user facilities are already enabling them to attract U.S. talent to work abroad.

In the FY 2018 Appropriations bill, the House Appropriations Committee tasked NSB to address this issue with the following statement:

> "*The Committee is supportive of recent actions to lower the MREFC threshold but encourages the National Science Board to consider further changes that would bridge the gap between the Major Research Instrumentation program and the MREFC account while also developing processes appropriate for mid-scale infrastructure, cyberinfrastructure, and instrument upgrades to be funded through the MREFC account. The Board shall, in collaboration with the National Academies, examine these requirements and report to the Committee within 180 days after enactment of this Act regarding its recommendations on how to address this matter within the confines of a restricted funding environment.*"

The Board notes that this Congressionally-mandated report on mid-scale research infrastructure complements the NSB's May 2018 report on *Operations and Maintenance (O&M) Costs for NSF Facilities*. Together, the two reports provide a portrait of the challenges and opportunities associated with balancing a portfolio that includes research infrastructure at various price points.

In this report, the term "**mid-scale**" denotes those projects in the dollar range between the current statutory upper limit of the MRI program, $6 million or $9 million, and the current lower limit of MREFC account eligibility at $70 million.[1] **Research infrastructure** refers to any combination of facilities, equipment, instrumentation, computational hardware and software, and the human capital needed for associated support. This definition includes upgrades to NSF's existing large research facilities. Mid-scale research infrastructure means different things to different disciplines. It can include individual instruments, suites of instruments, multi-user facilities, cyberinfrastructure, or infrastructure for data storage and preservation. Mid-scale research infrastructure also varies substantially in price point and risk profile, ranging from equipment that is procured "off the shelf" to state-of-the art custom tools. Some, but not all, mid-scale research infrastructure includes associated concept and design (C&D) and/or operations and maintenance (O&M) costs. This report divides mid-scale research infrastructure into three categories that currently have somewhat different profiles and avenues for funding at NSF: cyberinfrastructure (including data storage and curation investments), mid-scale-sized infrastructure investments that directly enhance or upgrade existing NSF large facilities, and discrete mid-scale research infrastructure (instrument/suites of instruments and multi-user facilities that are mid-scale in size and exist apart from large facilities).

In preparing this report, the Board spoke with NSF Senior Leadership, Division Directors and Program Officers from NSF Divisions, Directors of the MRI program and Large Facilities Office, and 18 National

[1] In accordance with the America COMPETES Act of 2007, Title VII, sec. 7036 para. a and c(1), the cap for the total cost of an MRI award is based on the annual NSF appropriation for the program. With the required 30% cost share from funded institutions, the cap is $6 million if the appropriation is below $125 million and $9 million if the appropriation is more than $125 million.

Academies-affiliated scientists representing a broad range of NSF-funded fields. In addition, the Board reviewed National Academies of Science, Engineering, and Medicine, NSF Advisory Committee, and other reports that addressed mid-scale research infrastructure. It also conducted analyses of NSF award size and of existing mid-scale research infrastructure solicitations and programs and examined the results of NSF's 2017 RFI on mid-scale research infrastructure.

The Board's investigations have led it to conclude that to continue to be internationally competitive at the frontiers of science and engineering, many researchers will require access to and experience with research infrastructure that falls above the MRI upper limit but below what is currently funded by MREFC.

Eliminating the agency's existing mid-scale research infrastructure gap is thus a key part of ensuring that NSF is positioned to best support each field it serves while making the mix of investments needed for global excellence. In keeping with the fundamental principle that a broad range of good science and engineering ideas should be welcomed at NSF, it is incumbent on NSB and NSF leadership to ensure that the Foundation has the appropriate programs and structures to meet the portfolio needs of its different disciplines. While the exact balance of investments in single investigator grants, centers, and infrastructure at all scales needed for global excellence will vary by division, NSF's funding and programmatic structures should be designed to support the differing requirements for excellence in different fields.

Findings

The NSB has taken a number of steps to better understand the research infrastructure gap between the MRI program and the MREFC account. To develop its recommendations, the Board used quantitative and qualitative data on NSF's recent investments in the mid-scale funding range, data on NSF's existing programs/solicitations for mid-scale research infrastructure, data on the extent of community demand for mid-scale research infrastructure and sought community and NSF leadership perspectives on the challenges and opportunities for NSF in funding mid-scale research infrastructure. The findings from these complementary lines of inquiry support NSF's new, agency-level focus on supporting mid-scale research infrastructure.

For this report all NSF awards made from FY 2008 through July 2018[2] were examined. NSF support does not exhibit a mid-scale funding gap in a strictly budgetary sense. NSF has funded awards at all scales, with, as expected, fewer awards as award size increases. Between FY 2008 and July 2018, roughly 68% of NSF's total award dollars supported investments with a total award size below $10 million, 16% supported investments in the $10 million to $70 million mid-scale range, and the remaining 16% went to awards larger than $70 million.

[2] This time window covers the period for which the most current and reliable data are available. It also coincides with the period of American Recovery and Reinvestment Act (ARRA) funds. ARRA's impacts on our findings are negligible; only five of the awards in the range between $10 million and $70 million dollars had ARRA funds and no award with ARRA funds had a total award size that exceeded $15 million dollars.

Figures 1-3 provide snapshots of what is funded in the $10 million to $70 million range[3] classifying awards by type[4] and subdividing this cost range into three smaller ranges: $10 million to $20 million, $20 million to $40 million, and $40 million to $70 million. In the cyberinfrastructure and data segments, the Office of Advanced Cyberinfrastructure (OAC) accounts for 27%, 61%, and 100%, respectively, of the awards across the three bands. Single investigator grants do not fall in this range.

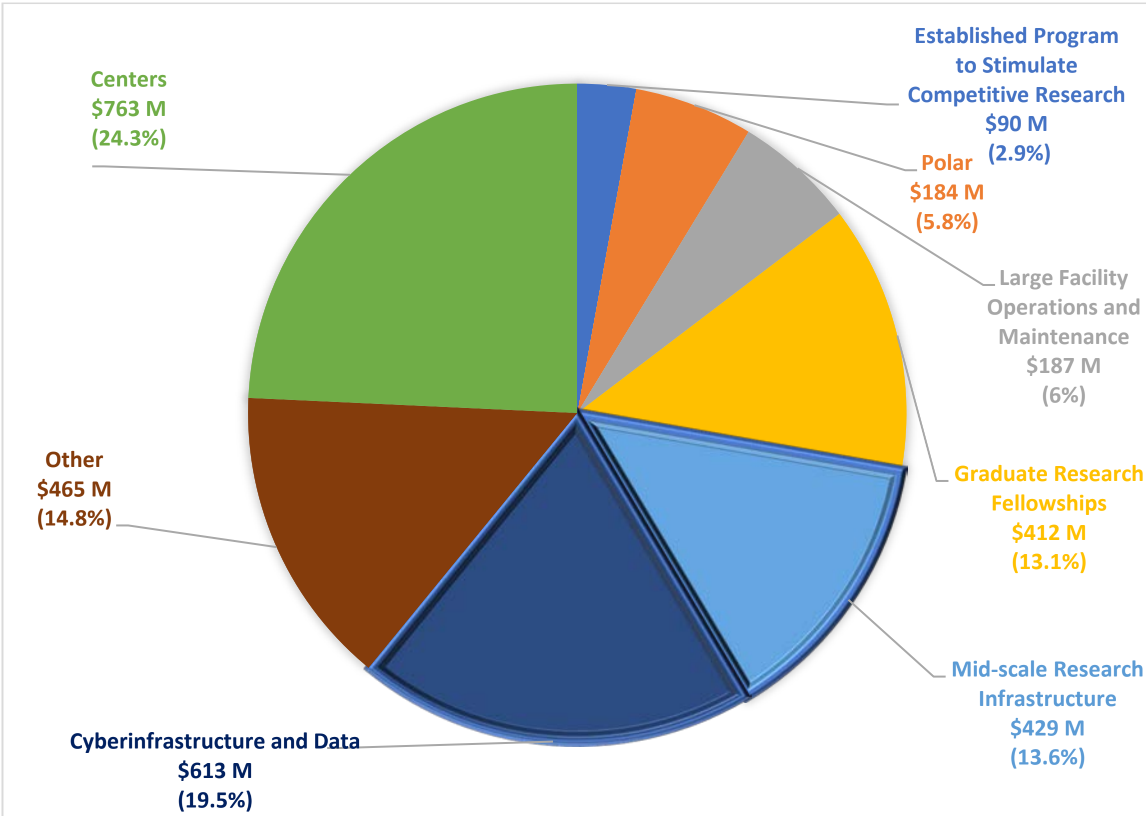

Figure 1: Share of Total Awarded Dollars in the $10 million - $20 million Range (includes 225 awards totaling $3.14 billion) by Type, 2008-July 2018. The award distribution in this budgetary band is diverse across a combination of designated programs such as the Established Program to Stimulate Competitive Research (EPSCoR) and Graduate Research Fellowship Program (GRFP) and NSF division commitments

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[3] The threshold for this analysis is $10 million based on the theoretical total cost cap of MRI at approximately $9 million.

[4] Awards have been sorted into the following categories: Centers (including institutes), Graduate Research Fellowship Program (GRFP), Established Program to Stimulate Competitive Research (EPSCoR), Large Facility Operations & Maintenance, Cyberinfrastructure and Data, Polar, Other (service contracts, non-GRFP fellowships, and investigator grants), and mid-scale research infrastructure (including distinct mid-scale research infrastructure, instrument upgrades for Large Facilities, and design and development for Large Facilities). While many of these awards are funded exclusively from a division's budget, there are exceptions. EPSCoR, for example, is managed through the Office of Integrated Activities (OIA) with co-funding from divisions as needed. The GRFP program has in the past eight years been funded jointly through the Division for Graduate Education in the Directorate for Education and Human Resources and OIA, though prior to FY 2009, Directorates for Engineering (ENG) and Computer and Information Sciences and Engineering (CISE) put some funds toward them.

such as centers and large facility operations and maintenance. Mid-scale research infrastructure and cyberinfrastructure awards account for nearly one-third of the investment in this space. It should be noted that the GRFP segment of this and the following charts reflects cumulative block awards to universities during the FY 2008-July 2018 time period. Awards to individual students were uniform in size and relatively small (roughly $150,000 over three years). See footnote #4 for a more detailed description of the funding profiles for EPSCoR and GRFP.

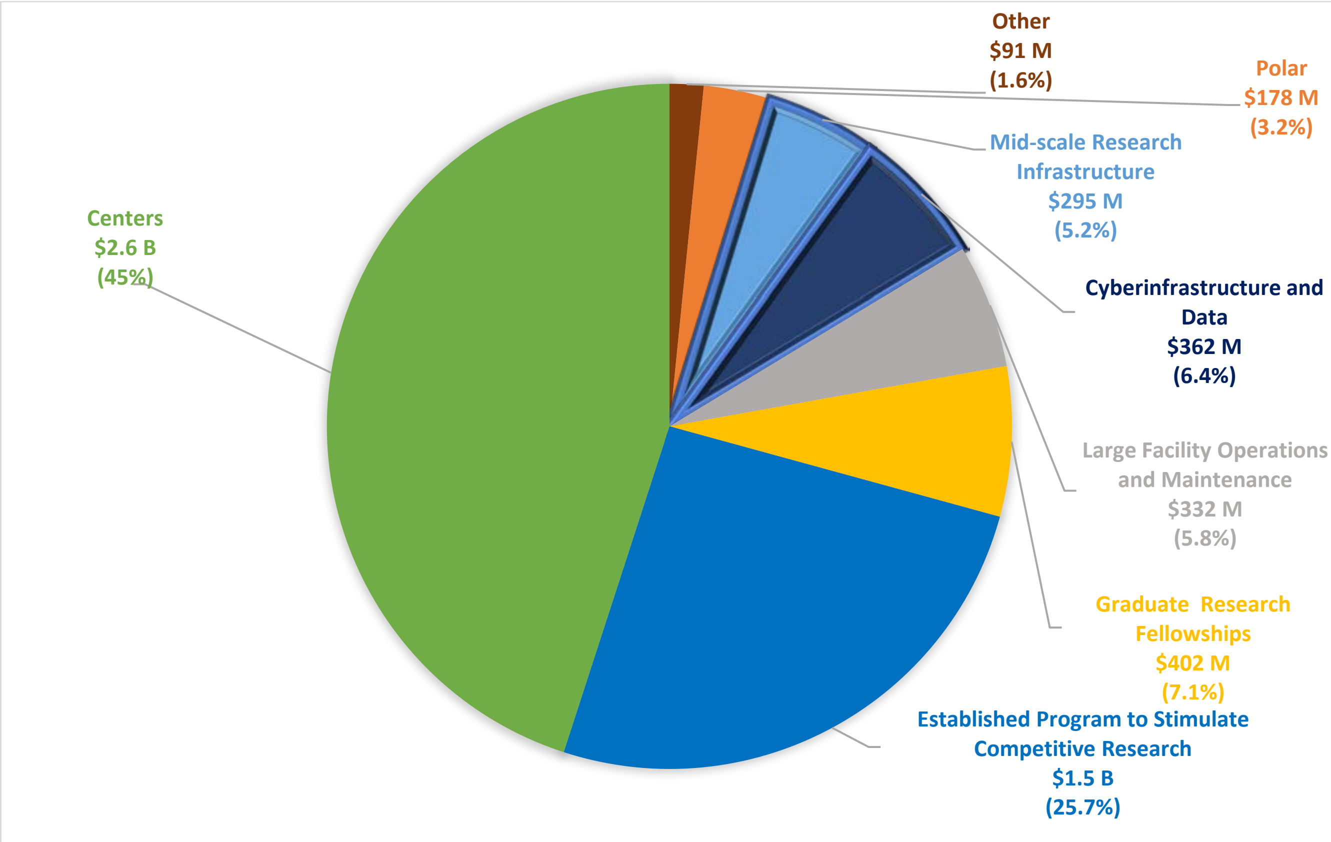

Figure 2: Share of Total Awarded Dollars in the $20 million -$40 million Range (includes 200 awards totaling approximately $5.68 billion) by Type, 2008-July 2018. In the $20 million to $40 million range mid-scale research infrastructure and cyberinfrastructure see noticeable decreases, while the majority of the award investment goes to centers and EPSCoR. Large facility operations and maintenance also begin to increase.

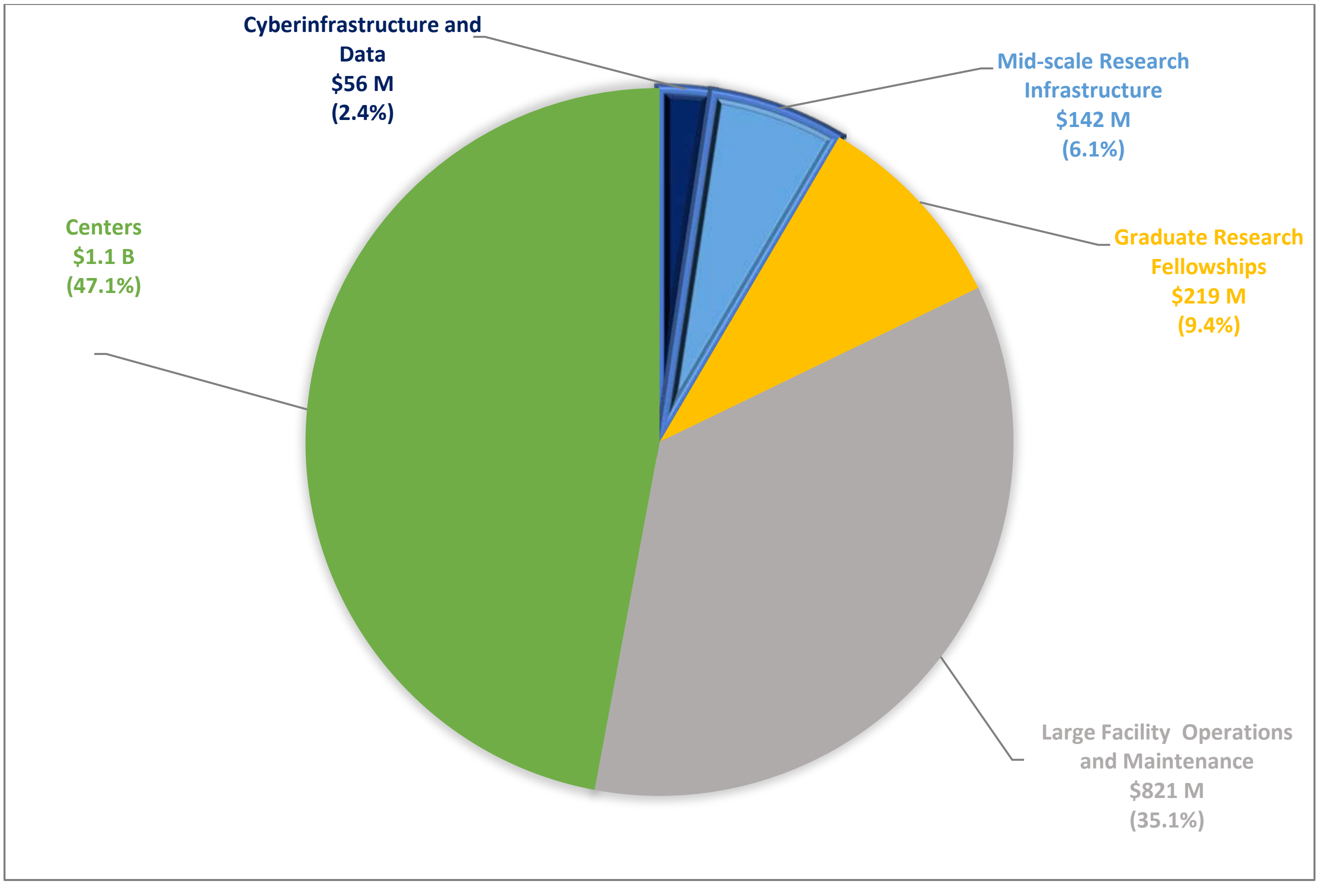

Figure 3: Share of Total Awarded Dollars in the $40 million -$70 million Range (includes 45 awards totaling approximately $2.34 billion) by Type, 2008- July 2018. At the top of the mid-scale funding range, large facility operations and maintenance becomes a major budget factor. Combined with their funding for centers, and the agency funding for GRFP, there are limited resources remaining for mid-scale research infrastructure and cyberinfrastructure.

Together, these pie charts demonstrate that mid-scale research infrastructure and cyberinfrastructure, while comprising a third of awarded dollars in the $10 million to $20 million range, comprise a significantly smaller share of awarded dollars in the $20 million to $40 million and the $40 million to $70 million range. As Figures 2 and 3 show, mid-scale research infrastructure and cyberinfrastructure and data accounted for only 11% of awarded dollars in the $20-40 million range and 9% of awarded dollars in the $40 million to $70 million range.

Collectively, the data in Figures 1-3 suggest that mid-scale research infrastructure and cyberinfrastructure and data appear to have been underrepresented in NSF's portfolio relative to other mid-scale investments, particularly in the $20 million to $70 million range. NSF, however made substantial investments in research infrastructure generally; it invested $10 billion in large facility O&M and $2.55 billion in MREFC investments during this period.[5] The relatively small percentage of the mid-scale budget range dedicated to research infrastructure and cyberinfrastructure reflected that much of

[5] Only 14% of NSF's award dollars for large facility O&M fall in the $10 million to $70 million range. The remainder exceeds this range but remains the responsibility of the divisions to fulfill.

the agency's infrastructure investment supported instrumentation that was less than $10 million or large facility O&M that exceeded $70 million in total award size, investments that are not captured in the pie charts. One can offer possible several explanations for the mid-scale research infrastructure gap:

- The **absence of an agency-level solicitation or program aimed at mid-scale research infrastructure/cyberinfrastructure.** Most of the other categories into which awards in the $20 million to $70 million range fell were associated with established programs (Centers, GRF, EPSCoR, Large Facility, Polar) supported by division and/or agency-level funding that is available via clearly designated solicitations. The research community responds to such opportunities, suggesting that the mid-scale research infrastructure and cyberinfrastructure gap could be addressed partially through clear, consistent signaling to the research community that NSF welcomes such proposals. Predictable signaling from NSF is particularly important for research infrastructure since such proposals often require a sustained developmental effort.
- The **funding profile for mid-scale research infrastructure** can have substantial upfront construction or acquisition costs. The result can be an uneven funding profile that meshes poorly with NSF's investment patterns. Mid-scale research infrastructure can cost more than $10 million / year in an acquisition or construction. Centers – which occupy the same price range – can, in contrast, be managed with a flat budgetary profile of $2.5 million to $5 million annually for a decade or more. Centers can also be more easily ramped up or down as budgets fluctuate.
- The **budgetary tradeoffs made at the division level**. As decadal surveys, Advisory Committee, and other community input tend to show, disciplinary communities are inclined to prioritize investments in research over those in research infrastructure.[6] As result, even in the best of budget circumstances, infrastructure investments are usually a lower priority. Slow budget growth and increased proposal pressure have likely compounded community pressure to commit available funds to research rather than research infrastructure. Furthermore, those divisions carrying substantial O&M mortgages related to major multi-user facilities have been understandably wary of mid-scale research infrastructure investments that may carry future Concept & Design and O&M obligations in addition to construction costs. While each decision to fund something other than mid-scale research infrastructure is in some fashion responsive to particular community interests or understandable in a specific budgetary or divisional context, the net result is a potential risk of overall NSF underinvestment in mid-scale research infrastructure.

Current NSF Approaches to Mid-scale Research Infrastructure and Cyberinfrastructure

Prior to introducing the Mid-scale Research Infrastructure Big Idea, NSF's approach to mid-scale research infrastructure was rooted in investments made at the division level. For the most part, potential infrastructure projects in the mid-scale range surfaced in conversations with program officers and were funded in an *ad hoc* manner. Some divisions with established infrastructure needs have dedicated, competed mid-scale research infrastructure programs that issue Requests for Proposals on a

[6] Although the Division of Astromomical Sciences also prioritizes research, its community is comfortable with a higher baseline share of its budget going to infrastructure than is the case with most NSF divisions.

periodic cadence. However, these programs are subject to inconsistent funding support from one fiscal year to the next.

Table 1 below provides information on mid-scale research infrastructure opportunities that are listed in a division's budget and/or are clearly identified in the division's budget narrative (i.e. ICER, CNS), and/or which have accompanying solicitations.[7] It is clear that even in those divisions that have had dedicated programs/solicitations for mid-scale research infrastructure, the awards reach only the lower end of the mid-scale funding range. Table 1 also shows that divisional budgets for mid-scale research infrastructure have not exceeded $25 million annually, providing a likely explanation for why most of these awards are for less than $10 million.

Conversations with division and directorate leadership confirmed that research infrastructure projects with a total cost exceeding $20 million are currently beyond a division's budgetary reach and that projects in the $10 million to $20 million range are often quite difficult for divisions to support. Division Directors spoke of often needing to plan for several years to make a single mid-scale research infrastructure investment and of extending the investment over a multi-year period to make financing feasible.

NSF division and directorate leadership also confirmed that these patterns are an artifact of budget constraints and the natural limits of what division budgets can sustain. They are certainly not due to a paucity of potential mid-scale infrastructure projects in astronomy, physics, chemistry, materials research, cyber, atmospheric sciences, and other disciplines. One division director stated candidly that, it is increasingly difficult to fully assess community demand because, after years of hearing that NSF does not have the resources to support mid-scale research infrastructure, researchers have stopped enquiring.

[7] The dollar figures in the table should not be equated to the mid-scale award percentages presented in the pie charts above. The pie charts include mid-scale awards that came from unsolicited proposals. The table presents only NSF's mid-scale research infrastructure and cyberinfrastructure support that is visible via public documentation including budget submissions and targeted mid-scale research infrastructure or cyberinfrastructure solicitations.

Mid-scale program	Directorate Division*	Year(s)	Budget (2016)	Budget (2017)	Budget Request (2019)	Cost-range in Solicitation	Sol. No.	Max Award Made
Midscale Innovation Program (MSIP)	MPS/AST	2013-2018	$21.25M	$20.67 M	$1.0 M	$4M - $30M	NSF-17-592 NSF-15-580 NSF-13-567	$9.5M
Materials Innovation Platforms (MIP)	MPS/DMR	2015-2018	$15.28M	$12.86M	$6.31M	$10M-$25M (over 5 years)	NSF-15-522	$25M
Mid-scale Research Infrastructure	MPS/PHY	2014-2018	$10.48M	$5.85M	$8.00M	>$4 M	NSF-18-564 Section II	
Mid-scale Research Infrastructure	GEO/ICER	2015-2016	$10M	Not Specified	Not Specified	no distinct program solicitation found		
NeuroNex	BIO/IOS/DBI	2016-	Not Specified	Not Specified	Not Specified	$1.5M-$10M	NSF 16-569	$4.4M
Data/Software Infrastructure	CISE/OAC	2015-	Not Specified	Not Specified	Not Specified	$500k-$25M	Multiple solicitations	$25M
International Research Networking (IRNC)	CISE/OAC	2014-	Not Specified	Not Specified	Not Specified	$250K-6.2M	NSF 14-554 NSF 16-523	$6M
Advanced/High Performance Computing	CISE/OAC	2014-	Not Specified	Not Specified	Not Specified	$6-30M	NSF-14-536	$30M
Mid-scale Research Infrastructure	CISE/ITR	2014-2017	$13.5M	$9.26M	N/A	$5M-$20M	NSF-16-585 NSF-17-540 NSF-13-602	$10M
	CISE/CNS		$12 M	$12 M	N/A			

*Note: MPS: Directorate for Mathematical and Physical Sciences, AST: Division of Astronomical Sciences, DMR: Division of Materials Research, PHY: Division of Physics, GEO: Directorate for Geosciences, ICER: Division of Integrative and Collaborative Education and Research, CISE: Directorate for Computer and Information Science and Engineering, ITR: Division of Information Technology Research, CNS: Division of Computer and Network Systems

Table 1: NSF Mid-scale Programs and Solicitations. NSF Mid-scale Programs and Solicitations that have been identified by separate solicitations, program announcements, or in directorate budget requests.

NSF's October 2017 RFI on existing and future needs for mid-scale research infrastructure projects in the $20 million to $100 million range provided additional evidence that the existing mid-scale research infrastructure gap is a product of existing NSF structures and choices rather than a lack of community demand.[8] In two months, the RFI yielded approximately 192 unique responses. Examples included instruments to be added to particle beam lines, telescopes, and neutrino observatories; instrumentation to study the biology, chemistry, and geophysics of oceans, land, and atmosphere; infrastructure to support large data collections, and instrumentation to enable molecular synthesis and analysis; and living labs. NSF evaluated each response for appropriateness based on the level of community support as indicated by National Academies reports, directorate strategic plans or advisory groups, and potential for high scientific impact.

The "home" directorates for the 192 submitted projects, and the 86 projects that NSF judged to have potentially High Impact[9], are given in Table 2 below. Replies relevant to all seven of NSF's research directorates were submitted, showing interest across all fields. MPS and GEO together accounted for more than 60 percent of the total responses and 80 percent of those that NSF judged to be potentially High Impact.

Responses	BIO	CISE	EHR	ENG	GEO	MPS	SBE	Total
Total	13	16	3	27	58	60	15	192
High Impact	2	7	1	5	33	36	2	86

Table 2: Summary Results of Mid-scale RFI Survey.

NSF estimates that the RFI's High Impact projects in the $20 million to $70 million range represented about $3 billion in demand for NSF investment. Because the $3 billion estimate does not represent the full range of possibilities in the $20 million to $70 million range or demand between the upper end of the MRI program and $20 million this measurement likely underestimates demand.

Community Perspective

To complement these analyses and to more fully understand community and NSF perspectives, NSB examined an extensive collection of National Research Council (NRC) and NSF Advisory Committee reports, conducted interviews with National Academies of Science, Engineering, and Medicine (NASEM) affiliated scientists, and met with internal and external stakeholders across NSF's funding portfolio.[10] NSB's conversations with scientists who make extensive use of research infrastructure as well as its readings of the aforementioned reports highlighted the pervasive perception that NSF does not have a

[8] NSF 18-013, Dear Colleague Letter: Request for Information on Mid-Scale Research Infrastructure, https://www.nsf.gov/pubs/2018/nsf18013/nsf18013.jsp . Although the new threshold for Major Research Equipment and Facilities Construction (MREFC) is $70 million, "major multi-user research facilities" are defined by the *American Innovation and Competitiveness Act* (AICA) as those in the MREFC budget line or those costing over $100 million from the Research and Related Activities (R&RA) line, so the "mid-scale" definition used in the RFI included projects that might cost NSF up to $100 million.
[9] NSF's assessment of "high impact" was based on staff analysis of short project descriptions. It does not necessarily indicate how more detailed proposals would fare under merit review.
[10] See Annex 1 for a full list of reports and interviewees.

well-defined “home” for mid-scale research infrastructure projects. An observation from the 2013 decadal survey for heliophysics, *Solar and Space Physics: A Science for a Technological Society,* captures the gist of the view expressed by researchers with whom the Board spoke:

> *While different NSF directorates have programs to support unsolicited mid-scale projects at different levels, these may be overly prescriptive and uneven in their availability, and practical gaps in proposal opportunities and funding levels may be limiting the effectiveness of mid-scale research across the foundation. It is unclear, for instance, how projects like the highly successful [Advanced Modular Incoherent Scatter Radar (AMISR)] would be initiated and accomplished in the future. Mechanisms for the continued funding of management and operations at existing mid-scale facilities are also not entirely clear.*[11]

The key message arising from teleconferences with individuals recommended by NASEM can be distilled to the following: Mid-scale research infrastructure and cyberinfrastructure are areas that require continual attention and resources and *must* be growth areas for NSF, if NSF is to continue to promote the progress of science and engineering.

Viewpoints expressed in reports and the Board’s calls with NASEM affiliated scientists coalesced around these themes:

- NSF would benefit from having clear, competed mechanisms through which to propose mid-scale research infrastructure projects;
- NSF’s ad hoc approach to mid-scale research infrastructure creates challenges to preserving a sustained commitment;
- There is a growing need for more regionalized, integrated suites of mid-scale research infrastructure that can serve multiple communities; and
- Computation and big data are transforming how science and engineering are practiced and cyberinfrastructure and data needs in the $10 million to $70 million range will continue to grow rapidly across all fields of science and engineering.

The Board, the Foundation, and NASEM-referred interview participants agree that the needs in mid-scale research infrastructure come in various shapes and, if unmet, can inhibit the pursuit of frontiers of science and engineering. Some major instruments that were already funded by the NSF’s MRI program now have “next-generation” aspirations that exceed the MRI cost cap and have no clear route to funding. Examples include cryogenic transmission-electron-microscopes, attosecond lasers, and instrumented classrooms. For similar reasons, upgrades to existing field stations and facilities are being delayed or abandoned. It should be noted that some of these proposed upgrades involve much needed cyberinfrastructure modifications to facilitate data collection, processing, and dissemination.

The Board’s conversations with NASEM affiliates and NSF staff also underscored the genuine concern that U.S. investments in mid-scale research infrastructure are far outpaced by those of our European, Japanese, and Chinese counterparts. In one example, NSF provided $1.5 million in design and development funds for a project for which the NSF division could not afford the $60 million needed to build without exhausting its mid-scale resources for five years. This project is now being pursued by

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[11] *Solar and Space Physics: A Science for a Technological Society,* National Research Council, National Academies Press, 2013, pg. 117.

China. Respondents reported that Europe is on course to surpass the United States in petawatt lasers, computing, high-tesla magnet technology, instrumentation for telescopes, and next generation adaptive optics.

Community members stressed some of the implications for U.S. competitiveness in allowing this disparity to continue unaddressed. They recounted stories of countries using research infrastructure unavailable in the United States as a means to attract U.S. scientists to work abroad. They also noted that because mid-scale research infrastructure can seed the next generation of major research facilities, underinvestment in mid-scale relative to other countries could render the U.S. less well prepared to build the next generation of large facilities. They also observed the lost training opportunities; scientists and engineers in countries that invest in mid-scale infrastructure obtain valuable experience in advanced instrumentation design and construction.

When asked for ideas for how to design an agency-level mid-scale research infrastructure program, NASEM colleagues returned frequently to the themes of sustainability, flexibility, and oversight. They stressed that mid-scale infrastructure investments cannot be sustained if they are made on an "as able" basis. At the same time, they emphasized the need for divisions to have a role in the decision-making process, and for well-defined avenues to fund associated C&D, O&M, and research costs. In terms of flexibility, they noted that a NSF mid-scale infrastructure program should accommodate the speed of scientific change and encourage novel ideas to be proposed and funded. Oversight procedures should be commensurate with the size and complexity of the project. Several noted that MREFC processes designed for $500 million projects would make $30 million to $50 million mid-scale infrastructure projects cumbersome and conservative. Community discussions also surfaced the idea of creating a dedicated program for *mid-scale* computing and data.

Both the data in this report and the observations gathered from the NASEM conversations and NSF staff have reinforced the wisdom of NSF's decision to include mid-scale research infrastructure as one of its 10 Big Ideas. As part of its plan for investing in the Big Ideas, NSF has already proposed devoting $60 million to mid-scale research infrastructure in its FY 2019 Budget Request. The request reflects what the Board believes is a realistic path for NSF to begin mid-scale research infrastructure investments in a restricted funding environment.

Recommendations

The Board believes strongly that NSF must provide an opportunity for all great ideas to compete. To that end, the Board recommends that **NSF affirm and sustain the mid-scale Big Idea with a long-term *agency-level* commitment to mid-scale research infrastructure**. Ideas for mid-scale research infrastructure investments should be based on a transparent, competitive process across all disciplines. The Board's call for an agency-level mid-scale research infrastructure program is consistent with the recommendation in our recent *Study on Operations and Maintenance Costs for NSF Facilities* that "NSB and the NSF Director should continue to enhance agency-level ownership of the facility portfolio through processes that elevate strategic and budgetary decision-making."

NSB advocates the following principles for agency-level investments in mid-scale research infrastructure and cyberinfrastructure:

- NSF should welcome all great ideas that promote the progress of science.

- NSF should balance mid-scale research infrastructure investments against competing investment opportunities at all cost scales and with awareness of discipline-specific requirements for global science and engineering leadership.
- A mid-scale research infrastructure program should be flexible enough to accommodate projects of varying types, sizes, and risk profiles. This includes use of oversight structures that are appropriate for the risks associated with and the agility needed for this scale of infrastructure.
- NSF Divisions and their associated communities should retain some strategic and financial stake in the infrastructure investments they champion.

Implementing future agency-level programs in mid-scale research infrastructure will require developing new structures and procedures to compare mid-scale research infrastructure opportunities across fields and identify agency-level strategic priorities. NSB believes that these processes should also accommodate cyberinfrastructure, upgrades to major research facilities, and “pathfinder” ideas that progress from smaller to larger projects.

The near universal need for robust computing capacity also calls for a close look at NSF’s strategies for supporting cyberinfrastructure and data to ensure that this crucial infrastructure for all fields of science and engineering is being pursued in a strategic and coordinated manner. NSF and NSB should include, as part of their long-term, strategic planning for research infrastructure, an evaluation of cyberinfrastructure requirements across the disciplines.

To ensure that NSF is well positioned to consider mid-scale research infrastructure and cyberinfrastructure proposals in the context of disciplinary portfolios, the Board also encourages NSF, when charging and constituting advisory bodies, to stress the importance of receiving input on both research infrastructure needs at all scales and on the appropriate balance between research and research infrastructure investments. Several community reports perused for this report only generally alluded to the nature and scope of the mid-scale research infrastructure or cyberinfrastructure deficit in their communities. More specific descriptions in such reports of the needs as well as the community’s recommendations on how to balance its investment portfolio would better inform NSF program officers, leadership, and NSB of a community’s strategic priorities.

NSB oversight and NSF management processes will need to be adapted to achieve a sustained agency commitment to mid-scale research infrastructure. In this report, NSB reiterates its strong belief in a joint role for NSF leadership and NSB in strategic, agency-level portfolio management. This includes consideration of both the overall share of budget devoted to different types of NSF investments and long-range planning for research infrastructure to ensure strategic investment in research infrastructure that spans the gamut from MRI through MREFC. Mindful that the form and function of the MREFC account may be modified as a result of NSF’s response to this report and the NSB’s May 2018 report on Facilities O&M and that mid-scale research infrastructure – whether funded through MREFC or otherwise – brings its own set of considerations, current Board procedures including its Delegation of Authority should be revisited.

The development of a sustainable mid-scale research infrastructure program will require a careful evaluation and assessment regime to monitor progress. In order for NSF to fully assess the demand for mid-scale research infrastructure, the levels suggested by the RFI need to be validated through a full, competitive proposal solicitation process, preferably across at least two iterations. Through examining the response to the solicitations, conducting full proposal reviews, making awards to the best qualified proposals, and managing those programs over the first two-three years, NSF can better judge the scale of the demand and the suitability of NSF's processes, and programs to meet that demand. **Through developing a careful evaluation and assessment program, NSF can monitor the strategic balance of the awards and assess initial program efforts to build a sustainable mid-scale research infrastructure program.**

NSB recognizes that the full mid-scale range defined in this report will encompass a mix of potential investments from off-the-shelf instrument acquisition to mid-scale multi-user research facilities that have substantial design, construction, and O&M costs. To address some of this complexity, we offer more specific recommendations in two ranges: from the current MRI cap to $20 million and from $20 million to the current $70 million MREFC threshold.

$20 million to MREFC Threshold

NSB recommends creating a centrally-managed account to fund mid-scale research infrastructure, cyberinfrastructure, and major research facility upgrades in the $20 million to $70 million range. Such an account would elevate the strategic decision making and portfolio prioritization responsibilities to the agency level but ensure that divisions retain a stake in these investments.

While decadal surveys, interviews with experts, and NSF's 2017 RFI all suggest a wealth of ideas for mid-scale research infrastructure in the $20 million-$70 million range, the Board is mindful of opportunity costs and therefore suggests building an agency-level mid-scale research infrastructure program gradually, while monitoring progress carefully and adjusting based on experience. NSB believes that an initial investment of $60 million-$100 million per year for mid-scale research infrastructure and cyberinfrastructure programs in the $20 million-$70 million range will foster proposals at the required competitive level. Such an investment will also enable NSF to determine the resources needed for a sustained agency-level approach that balances mid-scale research infrastructure and cyberinfrastructure investments against competing opportunities at all cost-scales.

While noting that the exact size of the investment may be adjusted according to the level of enacted NSF budgets, NSB affirms its support for an agency-level mid-scale research infrastructure program to be sustained, at some level, whatever budget constraints may prevail.

One option: Using the MREFC Account

The Appropriations Committee requested that NSB consider a process for funding mid-scale research infrastructure through the MREFC account. **While the MREFC account is not the only funding option, using it for this purpose aligns with NSB's opinion that a centrally-managed account is key to ensuring agency-level strategic planning and management of the infrastructure portfolio.** Use of MREFC for this purpose could also make sense from a strategic planning/portfolio standpoint since some projects in this range encompass instruments for major research facilities or prototypes/pilots that could lead to future major multi-user research facilities. Additionally, to the extent that MREFC funds would be used to construct or acquire mid-scale research infrastructure, this usage aligns with the MREFC account's history as a capital account. While NSB perceives use of MREFC funds to support some mid-scale research infrastructure projects to be a viable option, it is mindful of the need to manage the share devoted to mid-scale projects with care so as to avoid undermining the MREFC account's crucial role in enabling major multi-user facilities.

There are some challenges involved in using the MREFC account for mid-scale research infrastructure and cyberinfrastructure, but they are not insurmountable. Under current law, the MREFC account is restricted to funding the acquisition, construction, and commissioning of major research facilities and equipment. Statute also prescribes specific management and oversight requirements for MREFC facilities; some of these requirements would be inappropriate for the budget and risk profiles associated with most mid-scale research infrastructure. Thus, to take full advantage of the centrally-managed MREFC account option, statutory changes would be necessary. Changes to the MREFC account statute should allow for possible funding of research infrastructure from both the MREFC and R&RA accounts, different NSF and NSB decision-making processes as they relate to the inclusion of mid-scale research infrastructure projects in the MREFC account, and a tiered, risk-appropriate oversight model.

Since it would be difficult to meaningfully weigh a $20 million mid-scale research infrastructure project against a $1 billion traditional MREFC project, NSB would support an approach that clustered an ensemble of mid-scale research infrastructure proposals into a single mid-scale research infrastructure "bundle". The bundle would be composed of projects competed on merit and aligned with agency strategic priorities.

In this model, proposals would be centrally solicited and managed, though divisions could choose to invest in concept and design activities and would be responsible for funding after construction. The Director and her team would determine the appropriate size of the bundle and its priority relative to other MREFC projects. The Board would be asked to approve that prioritization as required by law but could comply with 42 USC 1862n-4 by explicitly approving the "bundle" with a single vote. As part of its oversight, NSB would also be consulted on the criteria NSF uses for including projects in the "bundle" and be briefed annually on the bundle's content.

The Board notes that new advisory or review mechanisms may need to be created to compete projects from all disciplines and to ensure that those projects selected for inclusion in the bundle address the most promising scientific opportunities.

Major Research Instrumentation to $20 Million

To meet the demand between the MRI cap and $20 million, NSB supports NSF's current efforts to study the feasibility of creating a Mid-scale Research Instrumentation Program. The diversity of the projects in this range calls for continued community involvement in setting priorities and retention of some degree of division management of any such program. NSB strongly believes in the need for NSF to address the effects of inflation that have eroded the purchasing power of MRI awards since its cap was last updated via the 2007 America COMPETES Act.

Appendix

List of NASEM Call Participants and Reports Consulted

NASEM Call Participants

Dr. Geoffrey Blake, Astronomy, California Institute of Technology

Dr. Marianne Bronner, Biology, California Institute of Technology

Dr. Amanda Clarke, Earth Sciences, Arizona State University

Dr. Robert Harrison, Computational Chemistry and Computer Science, The State University of New York at Stony Brook

Dr. Petra Klein, Atmospheric Science, University of Oklahoma

Dr. Mary Lidstrom, Biology, University of Washington

Dr. Bruce Macintosh, Astronomy, Stanford University

Dr. Roberta Marinelli, Ocean Science, Oregon State University

Dr. William Phillips, Physics, National Institute of Standards and Technology

Dr. Kaliat Ramesh, Materials Science, Johns Hopkins University

Dr. Steven Ritz, Physics, University of California, Santa Cruz

Dr. Mauro Sardela, Materials Science, University of Illinois

Dr. Robert Sinclair, Materials Science, Stanford University

Dr. Dan Stanzione, Computer Science, University of Texas

Dr. Edwin Thomas, Materials Science, Rice University

Dr. Steve Wofsy, Atmospheric Science, Harvard University

Dr. James Yoder, Ocean Science, Woods Hole Oceanographic Institution

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List of NSF Staff Interviewed

Dr. Fleming Crim, Chief Operating Officer

Dr. James Ulvestad, Chief Officer for Research Facilities

Mr. Matthew Hawkins, Office Head, Large Facility Office, Office of Budget, Finance, and Award Management

Mr. Vernon Ross, Senior Advisor, Office of the Director

Dr. Stephen Meacham, Section Head, Office of Integrative Activities, Office of the Director

Dr. Randy Phelps, Staff Associate, Office of Integrative Activities, Office of the Director

Dr. Anne Kinney, Assistant Director, Directorate for Mathematical and Physical Sciences

Dr. C. Denise Caldwell, Division Director, Division of Physics, Directorate for Mathematical and Physical Sciences

Dr. Linda Sapochak, Division Director, Division of Materials Research, Directorate for Mathematical and Physical Sciences

Dr. Lin He, Deputy Division Director (Acting), Division of Chemistry, Directorate for Mathematical and Physical Sciences

Dr. Richard Green, Division Director, Division of Astronomical Sciences, Directorate for Mathematical and Physical Sciences

Dr. Joanne Tornow, Assistant Director (Acting), Directorate for Biological Sciences

Dr. Carol Bessel, Deputy Assistant Director (Acting), Directorate for Biological Sciences

Dr. Karen King, Program Director, Division of Research on Learning in Formal and Informal Settings, Directorate for Education and Human Resources

Dr. James Kurose, Assistant Director, Directorate for Computer and Information Science and Engineering

Dr. Erwin Gianchandani, Deputy Assistant Director, Directorate for Computer and Information Science and Engineering

Dr. Manish Parashar, Office Director, Office of Advanced Cyberinfrastructure, Directorate for Computer and Information Science and Engineering

Dr. William Easterling, Assistant Director, Directorate for Geosciences

Dr. Scott Borg, Deputy Assistant Director, Directorate for Geosciences

Dr. Lina Patino, Division Director (Acting), Division of Earth Sciences, Directorate for Geosciences

Dr. Stephen Harlan, Secction Head (Acting), Disciplinary Programs Section, Division of Earth Sciences, Directorate for Geosciences

Dr. Terrence Quinn, Division Director, Division of Ocean Sciences, Directorate for Geosciences

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Dr. Alexandra Isern, Section Head (Acting), Section for Antarctic Sciences, Office of Polar Programs, Directorate for Geosciences

Dr. Brian Midson, Program Director, Ship Acquisition and Upgrade Program, Division of Ocean Sciences, Directorate for Geosciences

Dr. Allena Opper, Program Director, Nuclear Physics Experiment List, Division of Physics, Directorate for Mathematical and Physical Sciences