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Study of Operations and Maintenance Costs for NSF Facilities

May 24, 2018

NATIONAL SCIENCE BOARD

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MEMORANDUM FROM THE CHAIR OF THE NATIONAL SCIENCE BOARD

SUBJECT: *Study of Operations and Maintenance Costs for NSF Facilities*

The National Science Board is pleased to present its report, *Study of Operations and Maintenance Costs for NSF Facilities*. This report contains the findings and recommendations of the Board's Working Group on Operations and Maintenance (O&M) Costs that was created to examine the extent to which O&M costs potentially may upset the balance between funding for research facilities, research grants, and cross-cutting initiatives.

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

National Science Foundation

2415 Eisenhower Avenue • Alexandria, Virginia 22314 • (703) 292-7000 • www.nsf.gov/nsb • email: nationalsciencebrd@nsf.gov

Acknowledgments

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The National Science Board Office (NSBO) provided essential support to the work of the Working Group. Especially deserving of recognition are: Dr. Elise Lipkowitz, Science Policy Analyst and NSBO staff lead for the Operations and Maintenance Costs project, for her thoughtful and diligent work throughout the duration of this initiative; Dr. Brad Gutierrez, Executive Secretary to NSB, for his important contributions throughout this project; Dr. Reba Bandyopadhyay, Science Policy Analyst, for her reviews and edits; Dr. Mateo Munoz, AAAS Fellow, for his research and early drafting support, and Dr. John Veysey, NSBO Director, for his constant support and advice.

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Executive Summary

This National Science Board (NSB) report responds to a Congressional request to investigate whether major research facility operations and maintenance (O&M) costs at the National Science Foundation (NSF) are requiring an increasingly large percentage of funds from the agency's Research & Related Activities (R&RA) account; and to consider whether a change is needed in planning and funding principles, including whether a separate account for O&M is merited. At issue is how NSF will continue to plan for, construct, and support state-of-the-art research facilities in a constrained budget environment while also supporting other research infrastructure, maintaining a vibrant program of individual investigator grants, and continuing to undertake innovative cross-cutting initiatives as envisioned by the NSF's 10 Big Ideas.

NSF's facility portfolio and support for research grants are vital to maintaining the Foundation's status as a global leader in basic science and engineering research. Over the decades, the NSF has provided cutting-edge science facilities and equipment for a broad community of U.S. researchers. One only need look as far as the scientific achievements of the Laser Interferometer Gravitational-wave Observatory (LIGO) that resulted in the 2017 Nobel Prize for Physics to appreciate the return on NSF's investment of Major Research Equipment and Facilities Construction (MREFC) funds and to imagine the possibilities for future groundbreaking facilities.

In many scientific fields, principal investigators cannot advance their research without access to adequately funded facilities. Conversely, without sufficient funding for investigator grants, NSF risks underutilizing its facilities. Strategically balancing investments in these grants and the construction, operation, and maintenance of facilities is crucial, and it has become even more challenging given recent and forecast budget constraints. Moreover, in this current era of billion-dollar facilities in some fields, this strategic balance will rely increasingly on interagency and international partnerships. At the 25th anniversary of the Major Research Equipment account (the predecessor to MREFC account), the NSB welcomes the opportunity to explore how planning and funding principles can evolve to reflect the needs of the Foundation's now mature facility portfolio and position NSF for its next quarter century of leadership in large facilities.

Between Fiscal Year (FY) 2002 and FY 2017, NSF's budget grew, in real terms, an average of 1.1% per year, compared with an average of 1.9% per year for the U.S. economy. This relatively slow rate of growth emphasizes that budgetary strategy is a zero-sum game with competing and disparate NSF priorities ranging from investigator grants to facilities to cross-cutting initiatives.

During the same period, the number of proposals submitted to NSF increased by over 40%, contributing to a decline in success rates across NSF from 29% in FY 2002 to 23% in FY 2017. At the agency level, O&M outlays grew 3% while NSF budgets grew 18%[1] over this period. Proposal pressure is the single largest contributing factor to the agency-wide decline in success rate. But it is not the only factor. Programs such as the Small Business Innovation Research/Small Business Technology Transfer (SBIR/STTR), Graduate Research Fellowship Program (GRFP), and Established Program to Stimulate Competitive Research (EPSCoR) program accounted for over $650 million of NSF's budget in FY 2017. This is an increase from $300 million in FY 2002. It should be noted that the increases in these programs were a mix of Congressional directive (SBIR/STTR and EPSCoR) and NSF request (GRFP). O&M growth is

[1] Unless otherwise specified, all budgetary figures in this report are in constant FY 2015 dollars.

not the main driver of declining success rates agency-wide, though it does weigh heavily in select facility-heavy divisions, such as the Division of Astronomical Sciences.

Because O&M has not been a budgetary problem for the agency as a whole, the high-level view masks important details. To maintain balance, divisions and facility operators have made difficult choices, including deferring maintenance, descoping science, and underutilizing facility assets. These choices are not necessarily visible from an agency-level perspective, and may not align with NSF's strategic priorities.

Most decision-making, funding, and strategic choice authority at NSF, including for facilities, lies at the division level.[2] While this approach ensures that NSF is responsive to emerging scientific opportunities and engages research communities closely in setting priorities, NSF should be more than a loose federation of divisions. To increase coordination and ensure that NSF is more than the sum of its parts, the Director, in response to the 2017 *American Innovation and Competitiveness Act* and National Academy of Public Administration Report findings, recently created the position of Chief Officer for Research Facilities (CORF) in the Office of Director and formed the Facilities Governance Board.

NSB applauds these steps. This Board remains convinced that, in order to fulfill its central mission of promoting the progress of science and engineering, the agency must continue to manage and build ambitious facilities that expand the frontiers of knowledge. Going forward in a more competitive global landscape, and with a constrained budget, NSB has three recommendations:

1. **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.**

   Given the rising scale and concomitant cost of facilities and the increasing importance of convergent, international, and interdisciplinary research, a scientifically robust Foundation-wide strategy that is both transparent and fiscally responsible is critical.

   Planning horizons that are longer than the current 5-year projections required by statute could inform this strategy. The Department of Energy's Office of Science has found notable success using a 10-year planning model.

   While NSB does not believe that it is necessary to establish a central O&M account at this time, greater flexibility in use of the MREFC account would enhance visibility and agency-level ownership. A more flexible MREFC account could supplement — not replace — a division's primary responsibility for facility costs. In addition to incentivizing the development of new world-class facilities by allowing for partial, time-limited funding of initial O&M costs, a more flexible MREFC could be used to facilitate interagency and international partnerships, fund core elements of multi-disciplinary facilities, support facility divestment costs that may exceed the budgets of a single division or directorate, and fund the O&M for facilities that have strategic importance at the national or agency-level, but may not remain a top scientific priority for the

[2] In NSF's organizational structure, divisions are subsets of directorates, which are the principal organizational units.

division or directorate. Making this account accessible during all lifecycle stages for limited time periods while preserving community "skin-in-the-game" should be a priority.

2. **NSF and NSB should reexamine what share of the Foundation's budget should be devoted to research infrastructure.**[3]

   Over the past 15 years, research infrastructure investments have held steady at approximately 23.5% of the Foundation budget. This is at the low end of the 22-27% range recommended by NSB in its 2003 report.[4] The NSF and NSB should reexamine whether this range remains optimal, while recognizing the wide range of infrastructure requirements, depending on the scientific discipline in question.

3. **NSB and NSF should develop model funding and governance schemes for the next generation of partnerships at the agency, interagency, and international levels.**

   To ensure future U.S. scientific leadership, it is essential that U.S. scientists and engineers have access to cutting-edge facilities and have a strong voice in their planning and construction. As the capabilities of these facilities increase, they become more complex and costly, necessitating partnerships. NSF should develop models, accompanied by appropriate requests to Congress for the necessary implementation authorities, to provide projects involving interagency and international partnerships with the budget assurance to minimize impediments to such partnerships.

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[3] Research Infrastructure includes large facilities, midscale facilities, cyberinfrastructure, Federally Funded Research and Development Centers(FFRDC), National Center for Science and Engineering Statistics (NCSES), and Major Research Instrumentation.

[4] Science and Engineering Infrastructure for the 21st Century (2003)

Introduction

The vision for NSF's support of research infrastructure can be traced to *the National Science Foundation Act of 1950* and the 1957 NSF report, *Basic Research, A National Resource.*[5] In that report, the NSF's first Director, Dr. Alan T. Waterman, made several arguments and observations relevant to the basic research enterprise today, including the need for specially designed facilities:

> *The increasing intricacy of problems needing study, and the depth of knowledge of modern experimental methods of attacking them, call for apparatus and instruments and facilities that may be exceedingly complex and costly. Much apparatus must be specially designed and constructed — such equipment as nuclear or electron accelerators, or electronic telescopes for radio astronomy….*
>
> *The large sums of money required in some phases of modern research are beyond a university's resources, and private sources do not fill the gap. At the moment, there appears no alternative to the Federal Government's assistance as a vital step in its efforts to promote basic research and education for research.*[6]

With considerable foresight, he also noted that large research facilities, while beneficial to science, would pose budgetary challenges. As he stated, "It is widely recognized that continuing costs for operations and maintenance of large research equipment raise more problems than original construction costs. Continuing Federal support threatens an indefinite financial burden, a first claim against future appropriations."[7]

Dr. Waterman's observations are as relevant today as they were in 1957. O&M remains the longest and most costly stage of the facility lifecycle with many NSF facilities operating for 20-40 years and with annual O&M budgets approximating 7% of the original construction cost.[8]

In the intervening years, Presidential administrations and Congress have supported NSF's investments in constructing and operating telescopes, a magnet lab, gravitational-wave detection instruments, research vessels, accelerators, networked observing systems, cyberinfrastructure, and polar infrastructure. Since the late 1990s, NSF's quadrennial Strategic Plans have emphasized that NSF's provision of large facilities, along with other research infrastructure for the benefit of the U.S. science community, is central to NSF's basic research and educational mission. NSB's 2003 guidance to NSF to devote 22-27% of the agency's annual budget to research infrastructure – which includes but is not limited to large facilities – also reinforces the agency's commitment to enabling facilities, equipment, instrumentation, and computational hardware and software.[9]

In FY 1993, Congress created the Major Research Equipment account, the predecessor of today's Major Research Equipment and Facility Construction (MREFC) account. The MREFC account is funded at approximately $200 million annually and has enabled NSF to build several generations of world class

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[5] Mandates to include plans for facility construction, repairs, and upgrades in NSF's annual budget requests did not appear until the *National Science Foundation Appropriation Act of 1998*.

[6] *Basic Research: A National Resource*, National Science Foundation, October 1957, 59.

[7] Ibid, 59.

[8] Annual O&M for currently operating NSF facilities range between 6-10% of original construction cost.

[9] Science and Engineering Infrastructure for the 21st Century (2003)

facilities and pursue significant upgrades to existing ones. The MREFC account – with its associated processes for project planning, review, prioritization, and oversight that elevate decision making to the highest levels of the Foundation – implicitly recognizes the importance of agency-wide ownership of decisions about major facility construction while also addressing the fact that the cost of facility construction exceeds the resources of a single NSF division or directorate.

The many facility-related recommendations in National Academy of Sciences Decadal Surveys and NSF Advisory Committee reports reflect sustained science community interest in pursuing state-of-the-art large research facilities and in developing an enduring NSF program to support midscale research infrastructure. These recommendations highlight the synergy between facilities and the researchers who use them. In light of these findings, it is important for NSF to maintain the proper balance of investments within the category of research infrastructure, as well as between research infrastructure and investigator grants, and across the range of NSF's portfolio activities.

Echoing research community concern about the budgetary balance required to manage the various components of NSF's portfolio, the U.S. Senate Committee on Appropriations issued the following guidance to the NSB in the Committee's report language accompanying the FY 2017 appropriations bill for the Departments of Commerce, Justice, Science and Related Agencies (S.2837):

> *Operations and Maintenance Costs.—The Committee is concerned that operations and maintenance costs for NSF-funded research facilities require an increasingly large percentage of the funding for Research and Related Activities, especially in a budget environment where overall domestic spending is restrained and annual operations and maintenance costs increase faster than overall NSF spending. The Board is directed to consider whether this issue merits a change in NSF's funding principles or budgetary formulation processes, including considering the research infrastructure funding approaches within other Federal agencies, and whether a separate operations account is merited. Not later than 180 days after enactment of this act, the Board shall submit a report to the Committee on its findings, including any recommendations to the Foundation and to the Committees on Appropriations.*

This report responds to the Congressional directive. It contends that NSF's current approach to planning, budgeting, and funding for large research facilities merits an update. As the MREFC account celebrates its quarter century and as NSF approaches its 70^{th} anniversary, NSF has a score of large facilities spanning all lifecycle stages, from development to divestment. It seems appropriate, at this juncture, to consider how the Agency's strategic planning and budget mechanisms could evolve to reflect the maturation of NSF's large facility portfolio and to manage challenges such as facility divestment, the larger investments needed for some new state-of-the-art facilities, as well as the development and stewardship of multidisciplinary facilities and those that rely on interagency and international partnerships.

The significant cost, lifecycle planning, partnership requirements, and high visibility associated with large facilities call for more robust, agency-level ownership of facilities across the entire facility lifecycle. Greater agency-level strategic planning and budgeting, built on the foundation of the existing MREFC model, will be essential if NSF is to continue to judiciously invest in and steward, either alone or in concert with partners, the world-class facilities that are crucial to the Foundation's mission. It will also be critical to ensure that such agency-level visioning, planning, and ownership complements the ongoing and essential engagement of divisions and directorates with their associated research communities.

The remainder of this report addresses the current planning and budgeting structure for the NSF's large facilities, examines budgetary dynamics and research proposal success rates, and offers examples of the effects of making divisions responsible budgetarily for all portions of the facility lifecycle other than construction. The report then provides recommendations to foster greater agency-wide visibility into and ownership of the facility portfolio.

In responding to this directive from Congress, NSB's thinking has been influenced by comparisons with the approaches to facility funding, strategic planning, and lifecycle management used by the National Aeronautics and Space Administration (NASA) and the Department of Energy's (DOE) Office of Science (SC). Appendix A provides a discussion of NASA and DOE approaches to facility planning and budgeting.

Current Structure for Planning and Budgeting for the Facility Lifecycle

NSF's planning and decision-making processes for large facilities vary by lifecycle stage, heretofore affording NSF's Senior Leadership and the NSB uneven visibility and influence into strategic budget planning. In the very early stages and in the operations stage, they rely on research community input, reflecting NSF's longstanding and crucial emphasis on empowering divisions and directorates to decide, in consultation with their research communities, how to balance and align their facility and research portfolios. These practices, combined with the statute that prescribes the Board's and the NSF Director's role in managing the MREFC account that funds only facility construction, have led to Foundation-wide strategy and priority setting processes focusing predominantly on the construction stage.[10]

Like NASA and DOE-SC, NSF conceives of the facility lifecycle as a series of stages. In the NSF model, there are five stages: Development, Design, Construction, Operations, and Divestment (from the NSF portfolio of facilities). These stages vary in length, with development sometimes taking ten years or more, design taking three to five years, construction taking five to ten years, and operations lasting anywhere from 20 to 40 years or more.

Development stage work typically begins within NSF's divisions, several layers deep in NSF's organizational chart. During this stage, research communities use community workshops, decadal studies, interagency processes, and focused working groups to identify research questions as well as the facilities and the research infrastructure needed to answer them. NSF divisions fund development work from their individual budgets. Awareness of projects in the development stage has likewise historically resided within NSF divisions and to a lesser extent within directorates. The Director first obtains visibility into such projects at the end of this stage when they are subject to their first agency-level internal review.

The design stage advances the definition of project scope and requirements, including a determination of Total Project Cost.[11] As was true of the development stage, design stage work is funded by the cognizant division. Because projects in design must pass through a series of stage gates to use MREFC

[10] Two appropriations lines are used to fund NSF's large facilities across the lifecycle. Construction and some major upgrades are funded from the MREFC account. All other stages of the facility lifecycle are supported with funds from NSF's Research and Related Activities (R&RA) account.

[11] Total Project Cost is defined as the cost of the construction stage, not the full lifecycle cost.

funds for construction, they are subject to central oversight via the Facilities Readiness Panel. This panel, which has recently replaced the MREFC panel, reviews projects as they pass from Conceptual Design to Preliminary Design and then from Preliminary Design to Final Design. This process also brings the project to the attention of the NSF Director, who, with NSB, is responsible for prioritizing projects that will eventually enter the MREFC account. While the Director assesses projects that have finished Conceptual Design, the NSB currently does not formally assess a project until it has completed Preliminary Design. Following the completion of Final Design, the Director and NSB again evaluate the project before the NSB decides to authorize the use of MREFC for facility construction.

The MREFC decision is an important milestone as it signifies agency-wide backing for construction and incurs for a directorate/division a long-term O&M commitment for the life of the facility. Under current NSF requirements, construction costs for large facility projects that cost $70 million or more may come from the MREFC account. The relevant division, the Grants and Agreements Officer in the Office of Budget, Finance, and Awards Management, and NSF's Large Facilities Office jointly monitor projects in construction.[12] The Director and NSB stay informed of progress on construction through bimonthly reports from the Large Facility Office.

During the Operations stage, NSF divisions have historically owned planning decisions and funding obligations. Planning for a given facility includes a 5-year, statutorily required budgetary projection. NSF relies on a variety of community inputs to determine the continuing science utility and relative priority of its facilities to a given community. In response to a NSB request, the NSF has recently adopted uniform guidelines for its decisions about continuing, recapitalizing, or sunsetting facilities. If the O&M costs for a facility exceed the current NSB Delegation of Authority threshold, NSB must authorize the Director to make a new O&M award. This gives the NSB and the Director visibility into the costliest facilities currently in operation. However, it is not uncommon that as facilities age and become lower priority their total budgets decrease. As a result, some facilities built with MREFC funds can fall below the authorization award threshold and off NSB's radar later in their lifecycle.

Following NSB approval of an initial O&M award for a facility, it becomes the funding responsibility of the sponsoring directorate. In practice, however, this responsibility most often lands on individual divisions within a directorate, due to a reluctance to require facility-light divisions to support another division's large facility investment(s). This responsibility, often termed "the O&M mortgage," then continues to impact directorate or divisional budget planning for the life of the facility — possibly 20 to 40-years. O&M covers personnel salaries and benefits, security for the facility and personnel, utilities, infrastructure upkeep, routine and some major equipment maintenance, early concept and development for major upgrades, data collection and distribution, student programs, education and public outreach. Significant upgrades and recapitalization are typically pursued through separate awards, some of which may be funded via MREFC funds. For example, the recently completed upgrade to the Laser Interferometer Gravitational-wave Observatory (LIGO) used MREFC funds.

Sometimes the facilities required to answer the next set of frontier scientific questions are not yet in the current portfolio. In these instances, divestment or transition of an existing facility may be necessary to accommodate a new one while maintaining portfolio balance However, in the current era of billion-

[12] NSF's No-Cost-Overrun Policy for its facilities, unique among Federal science agencies, is another key central management tool to ensure a construction project does not exceed its Total Project Cost.

dollar large facilities in fields like physics and astronomy, the savings from such divestments may not cover the new operational costs.

To date, the NSF has limited experience with divestment, although it has decommissioned ships and transitioned university-based cyclotrons to host universities.[13] Currently the Foundation is transferring the National Superconducting Cyclotron Laboratory assets to the Department of Energy and is examining the feasibility of divesting some smaller astronomy facilities. In addition, the NSF Director and NSB have recently strengthened their engagement on divestment. In August 2017, the NSB issued a statement that decisions about the partial or full divestment of major facilities “should be brought to the attention of the Board and that the NSF should seek appropriate involvement of the Board in all such divestment decisions.”[14] The costs associated with transition/divestment have, to date, been borne by divisions or directorates.

In sum, in NSF’s current model, divisions and directorates plan and fund the development and the design of large new facilities. As the process advances, the Director and NSB gradually gain visibility, culminating in the decision to build the facility with funds from the MREFC account. Once construction is complete, the divisions and directorates resume their responsibility for stewarding facilities and funding their operations, in many cases carrying these obligations for decades. Subsequently, divisions and directorates also lead divestment activities.

The benefit of this model is that it permits each division or directorate, in concert with its research community, to make decisions about the optimal balance of its portfolio. Ideally, from a lifecycle management perspective, this approach incentivizes divisions and directorates to be judicious in what they build and operate and encourages them to divest facilities that provide lower scientific returns to their community.

The potential risk of this approach is that during facility development, and following construction, division or directorate-level choices are not necessarily visible from an agency perspective. They may, as a result, be uncoordinated, and even unaligned, with agency-level strategic priorities. Likewise, in facing zero-sum budgetary tradeoffs and the challenges associated with divestment and partnerships, NSF-wide priorities may differ from those of individual research communities. In both cases, visibility and engagement of the NSB and the NSF Director in the decision-making process is necessary.

NSF’s recent appointment of a Chief Officer for Research Facilities (CORF) in the Office of Director and the formation of a Facilities Governance Board in response to the *American Innovation and Competitiveness Act* and National Academy of Public Administration Report findings are resulting, as we write, in the continued evolution of NSF’s strategic planning and oversight structures. NSB applauds these developments, and anticipates that the CORF will play a central role in increasing NSF’s strategic planning around the facility portfolio and improving the Director’s and NSB’s visibility into the portfolio.

Budget

Analysis of the NSF budget trends between FY 2002 and FY 2017 suggests that the budgetary challenge is not due to O&M outlays overwhelming the agency’s budget. In fact, NSF’s overall budget growth

[13] The Indiana University cyclotron, for instance, was built with NSF funds in the early 1970s, transitioned to commercial and medical uses over a 10-year period beginning in 1993, and then ran for another decade.
[14] NSB-2017-33.

during those years outpaced the agency's increase in O&M outlays. Rather, the challenge lies in how such responsibilities are concentrated and planned for within the agency. A below agency-average growth in the Research and Related Activities (R&RA) account in facility-heavy directorates coupled with the concentration of O&M obligations in a select few divisions have strained individual budgets in those affected divisions, particularly in the Divisions of Astronomical Sciences and Ocean Sciences.

Between FY 2002 and FY 2017, NSF's budget increased by 18%, or 1.1% per year, after adjusting for inflation, a pace that fell short of projected rates of increase in the 2002, 2007, and 2010 authorization bills (**Figure 1**). The shortfall between projected and realized budget increases, coupled with the timescales required for facilities planning, may have contributed to a mismatch between planned scenarios and those that are being realized.

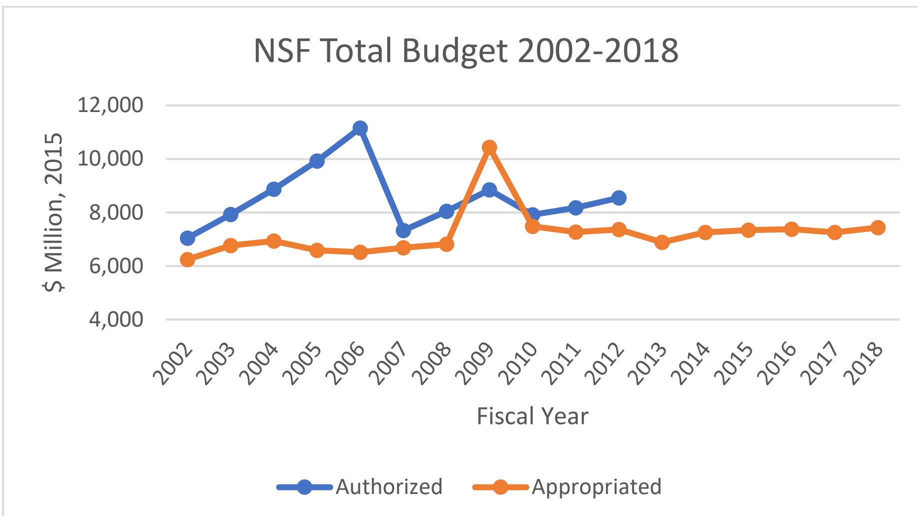

Figure 1, Showing limited real dollar growth in NSF appropriations and authorized levels

Some areas within NSF have had more budget growth than others. As **Table 1** shows, the facility-intensive directorates of Mathematical and Physical Sciences, Geosciences, and Biological Sciences received budget increases that were below NSF's average. In addition to substantial increases to the ENG and CISE Directorates[15], programs such as the Small Business Innovation Research/Small Business Technology Transfer (SBIR/STTR), Graduate Research Fellowship Program (GRFP), and Established Program to Stimulate Competitive Research (EPSCoR) collectively grew substantially more than the NSF average. SBIR/STTR, for example, by statute, must do no worse than the NSF average. However, it grew 89% in real terms between FY 2002 and FY 2017. New money has also gone to cross-cutting initiatives that reflect Administration, Congressional, or agency priorities.

[15] Despite the notable budgetary increases for the Directorate for Computer and Information Science and Engineering and the Directorate for Engineering, the success rates of grant proposals have fallen in those directorates alongside those for NSF as a whole.

	FY 2002	FY 2017	Change ($)	Change (%)
NSF Total	6185.4	7292.9	1107.6	18%
R&RA	4684.9	5837.5	1152.6	25%
NSF O&M	979.0	1005.9	26.9	3%
MPS	1192.5	1324.1	131.6	11%
GEO	789.8	841.3	51.5	2%
BIO	660.3	721.3	61.0	9%
CISE	667.3	909.6	242.3	36%
ENG[16]	507.5	711.3	203.8	40%
SBE[17]	185.4	213.5	28.6	15%

Table 1, Showing directorate-level budget growth between FY 2002-FY 2017, with NSF-wide growth at the top. MPS= Mathematical and Physical Sciences, GEO= Geosciences, BIO= Biological Sciences, CISE= Computer and Information Science and Engineering, ENG= Engineering, SBE= Social Behavioral, and Economic Sciences

Relative to the total increase in the NSF budget between FY 2002 and FY 2017, NSF-wide O&M outlays grew quite modestly at only 3% over the period. (**Table 1**) Yet NSF's O&M outlays are, in fact, concentrated in the agency's facility-heavy directorates and divisions. In these directorates and divisions, the rates of increase in O&M outlays have outpaced the increase in budget (**Table 2**). This is true for all facilities-intensive divisions except Physics. The facilities-intensive divisions in the Geosciences Directorate even saw their O&M outlays rise more, in absolute terms, than their budgets, meaning that their non-O&M resources shrank over the period.

In many facility-heavy divisions, simultaneous growth in proposal pressure and O&M costs have led to a variety of strategies aimed at containing the growth of O&M outlays. These strategies include descoping facilities, deferring maintenance when feasible, establishing partnerships, and limiting personnel cost increases.[18]

[16] These figures do not include SBIR/STTR grants managed by ENG.
[17] These figures do not include OISE (2002) nor NCSES (2017) budgets.
[18] Examples of these activities include reducing the number of detectors and aircraft deployed for NEON, operating research ships for fewer days each year, and reducing the number of OOI arrays from four to two, and deferring upgrades and replacements for aging astronomical instrumentation. The Antarctic Infrastructure Modernization for Science (AIMS) is an example of the effects of deferred maintenance. Replacement of dormitories, aircraft hangars, piers, and the near complete overhaul of the facilities at McMurdo Station are long overdue.

		Budget Growth ($2015 M)				O&M Growth ($2015 M)			
Dir	Div	FY 2002	FY 2017	Change ($)	Budget Change (%)	O&M Change (%)	Change ($)	FY 2002	FY 2017
MPS	Tot	1192.5	1324.1	131.6	**11%**	**14%**	34.1	246.9	281.0
	AST	215.1	245.0	29.9	**14%**	**18%**	23.6	130.7	154.3
	DMR	284.2	305.5	21.3	**7%**	**34%**	11.1	32.4	43.5
	PHY	253.8	273.5	19.7	**8%**	**1%**	0.5	82.5	83.0
GEO	Tot	789.8	841.3	51.5	**7%**	**27%**	65.5	238.3	303.8
	AGS	261.9	246.2	-15.7	**-6%**	**0%**	0.3	100.5	100.9
	EAR	163.6	174.1	10.5	**6%**	**108%**	18.2	16.8	34.9
	OCE	364.2	346.7	-17.5	**-5%**	**39%**	46.7	121.0	167.7
BIO	Tot	660.3	721.3	61.0	**9%**	**3706%**	53.0	1.4	54.4
NSF	Tot	6185.4	7292.9	1107.6	**18%**	**3%**	26.9	979.0	1005.9

Table 2, comparing FY 2002 and FY 2017 budgets in facilities-intensive divisions (constant dollars)[19] AST= Astronomical Sciences, DMR= Materials Research, PH = Physics, AGS= Atmospheric and Geospace Sciences, EAR= Earth Sciences, OCE= Ocean Sciences Note the significant increase in BIO's O&M is due to the beginning of operations for NEON. Before NEON, BIO had very low O&M commitments.

Figure 2 and **Figure 3** below show that in all divisions, excepting the Division of Astronomical Sciences (AST), the share of the division's budget devoted to facility O&M is leveling off. [20] As new facilities have entered operations, the strategies outlined above have tempered potential increases in the share of the division budget devoted to O&M. However, as the AST line demonstrates, this approach will become unsustainable after the entry of two more new facilities in 2019 and 2023, respectively. Moreover, continued squeezing of O&M outlays has both a natural limit and downsides in terms of science output, suboptimal staffing, and deferred maintenance.

[19] Divisions do not add to directorate totals as non-facility divisions are omitted.

[20] Future projects are based on the FY17 budget's 5-year estimates and assume flat budgets at the division level.

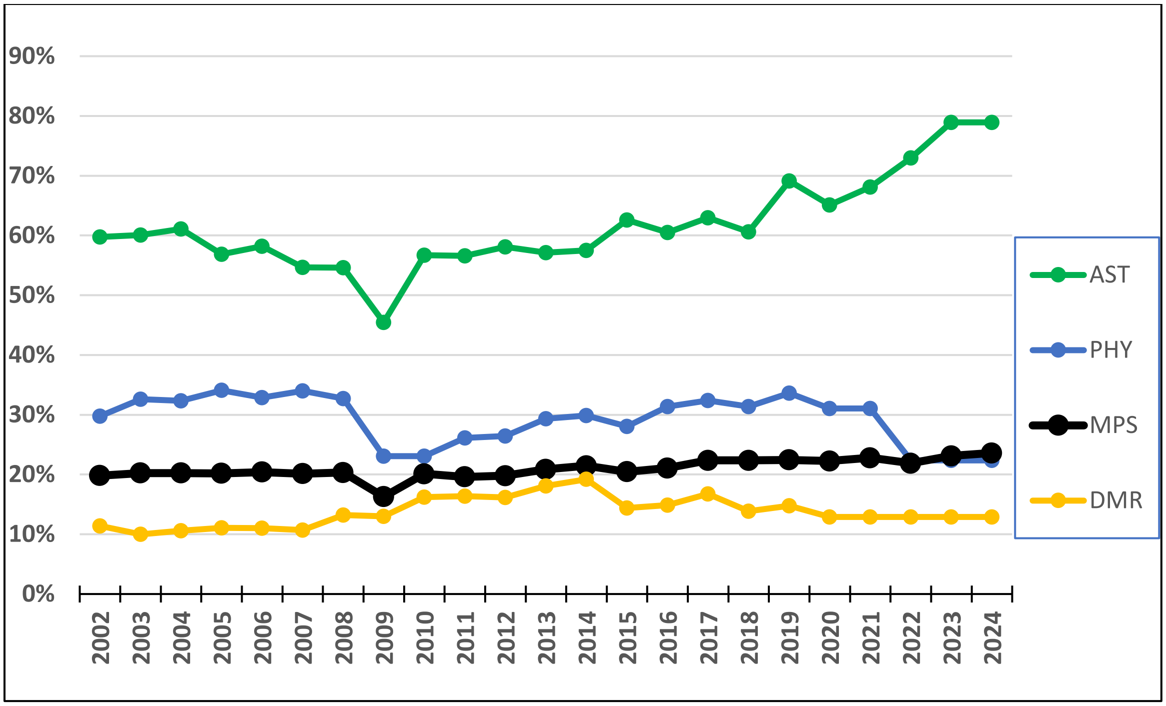

Figure 2, Percentage of Selected MPS Division Budgets to Facilities (O&M) and Overall MPS Share. AST: Division of Astronomical Sciences, PHY: Division of Physics, MPS: Directorate of Mathematical and Physical Sciences, DMR: Division of Materials Research

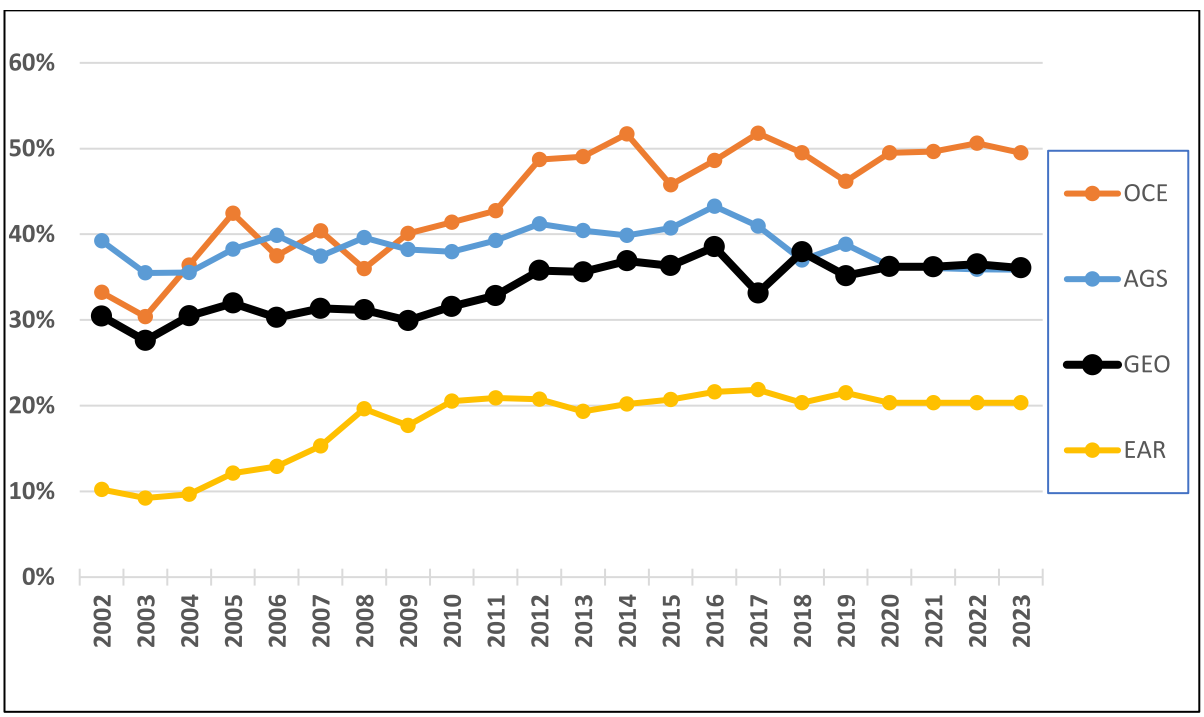

Figure 3, Percentage of Selected GEO Division Budgets to Facilities (O&M) along with Overall GEO Share. OCE: Division of Ocean Sciences, AGS: Divisions of Atmospheric and Geospace Sciences, GEO: Directorate of Geosciences, EAR: Division of Earth Sciences

The budget pressures faced by facility-intensive divisions suggests the need for strong agency-level planning and for increased coordination of decisions at the NSF and division levels. Some of the pressure now being experienced by the Divisions of Astronomical Sciences and Ocean Science was foreseeable. Between FY 2002 and FY 2017, 59% of MREFC funds ($4 billion) were allocated to six facilities across those two divisions. Together, these facilities will require an annual total O&M outlay of $254 million, in nominal dollars, to support full operations.

At the division level, absorbing the O&M cost associated with new large facility investments while maintaining existing facilities is not the only challenge. Addressing the significant and increasing community demand for mid-scale infrastructure (presently defined as those projects above the $4 million Major Research Instrumentation threshold and below the $70 million MREFC threshold) is also likely to further strain tight budgets.

The importance of midscale research infrastructure has been highlighted in the *2010 New Worlds, New Horizons* astronomy decadal survey, NSB's 2002 report, *Science and Engineering Infrastructure for the 21st Century*, NSB's 2011 *Report to Congress on Mid-scale Instrumentation*, through one of NSF's ten Big Ideas, *Mid-scale Research Infrastructure,* and through the community response to a request for information (RFI) on mid-scale projects conducted last fall in response to *American Innovation and Competitiveness Act* requirements.[21] NSF received almost 200 responses with projects in the $20-100 million range, totaling a demand in excess of $10 billion.[22] While the majority of the ideas came from the MPS and GEO communities, communities associated with every Directorate provided responses.

Steps such as the lowering of the MREFC threshold from $100 million to $70 million in November 2016 have created a pathway for some projects[23], but many divisions are still hard-pressed to fund fully a $30-50 million midscale project, plus any related development and O&M costs, without sacrificing other important science investments. While there are examples of NSF divisions and directorates supporting mid-scale projects, most have been in the $4-20 million range.

The budget picture presented here is not intended to second-guess past strategic decisions. It does, however, emphasize limitations to a division-centric strategy and planning model and to the current approach that places responsibility for O&M funding squarely on the divisions. Raising the facility portfolio discussion to the agency level would provide a more comprehensive assessment when making strategic tradeoffs. In addition, it would also ensure that NSF strategic priorities were not given lower consideration than the community priorities traditionally leveraged at the division level.

Success Rates

Proposals for competitive awards increased agency wide between FY 2002 and FY 2017, rising 41% to 49,423. Largely because of this, the Foundation-wide success rate dropped from 29% (FY 2002) to 23% (FY 2017), although the actual number of awards made has remained steady and even climbed slightly.

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[21] American Innovation and Competitiveness Act. 42 USC 1861, Sec. 109.

[22] Dr. France Córdova, NSF Director, Testimony to House Committee on Science, Space, and Technology, March 15, 2018, accessed at: https://science.house.gov/sites/republicans.science.house.gov/files/documents/HHRG-115-SY15-WState-FCordova-20180315.pdf

[23] NSF Important Notice no. 138. November 30, 2018. https://www.nsf.gov/pubs/issuances/in138.pdf

There are many other influences on success rate, ranging from budget availability to award size[24] and duration,[25] to differing implementation of the merit review criteria,[26] to community norms and structure. Proposal pressure and O&M investments are not independent. The opportunities and data created by infrastructure investments can and should increase proposals.

The other factor in success rates is the level of available funding. As highlighted in the budget section, increases in programs such as SBIR/STTR and GRFP that are not directly connected to facilities or divisional research grant programs have had a greater impact than the growth in O&M expenditures on the overall budget available for research grants.

	NSF			MPS			GEO			BIO		
	FY 2002	FY 2017	Δ (%)	FY 2002	FY 2017	Δ (%)	FY 2002	FY 2017	Δ (%)	FY 2002	FY 2017	Δ (%)
Proposals	35,433	49,423	39%	6,014	8,849	47%	4,143	4,088	-1%	5,185	5,010	-3%
Awards	10,630	11,400	7%	2,105	2,335	11%	1,450	1,296	-11%	1,400	1,147	-18%
Success Rate	29%	23%	-23%	35%	26%	-25%	35%	32%	-9%	27%	23%	-15%

Table 3, Proposals, Number of Awards, and Success Rates. Note that there are numerous factors that impact success rates, including budget availability, award size and duration, implementation of merit review, and community norms and structure.

While O&M is not a significant influence on success rates at the NSF-level (where it has grown much more slowly than the overall budget — **Table 1**), there is more nuance at the directorate and divisional level. **Table 3** shows proposals, awards, and success rates for NSF and three facilities-intensive directorates. The Directorate for Mathematical and Physical Sciences saw a significant decline in success rate, a significant increase in proposal pressure, and steady investment in facilities O&M (**Figure 2**). In the GEO and BIO, proposals fell, and O&M costs rose (but not significantly relative to either the overall directorate budgets or the increases in those budgets), and success rates fell – but significantly less than NSF as whole. Overall, there is not evidence that O&M costs are significantly impacting directorate-level success rates.

Table 4 (Appendix B) shows changes in success rate for selected divisions. At this level, the impact of O&M growth is in general even less clear. Interestingly, the success rate in the Division of Ocean Sciences increased, despite increases in O&M. In the Division of Astronomical Sciences, the marked decrease in success rate is due, in roughly equal measure, to both the 63% increase in the number of proposals and the 14% increase in facilities O&M.[27]

[24] Over this period the NSF average real research grant award size increased 14% (to $171,588 in FY 2017 dollars)
[25] Largely unchanged NSF-wide over this period
[26] In FY 2017, for instance, some divisions in the Directorate for Geosciences increased success rates by eliminating deadlines. Some divisions in the Directorate for Biological Sciences used a pre-proposal process in the same year.
[27] An increase in average award size also contributed, but significantly less than either O&M or proposal pressure.

While the decline in award success rates is prevalent across the agency, the data — except for the Division of Astronomical Sciences — do not support the perception that this is because O&M costs are squeezing research grant dollars.

Case Studies

This section examines recent and distinctive efforts from the Division of Ocean Sciences (OCE), the Division of Astronomical Sciences (AST) and the Directorate of Biological Sciences (BIO) to address challenges associated with strategic balance. Their different approaches to accommodating the transition of one or more new large facilities from construction to O&M, and with it the transfer in funding responsibility back to the directorate or division, illustrate the limits of NSF's current planning and budgetary processes and the choices that they elicit. These examples can inform how NSF and NSB refine their planning and budgetary approaches to optimize agency wide planning in a fiscally constrained environment.

Ocean Science

The Division of Ocean Sciences (OCE)'s decision several years ago to use a National Academies-led decadal survey process to determine how to rebalance its portfolio is one example of how a NSF division and its associated research community have addressed the competing pressures on a division's budget. Concerns about achieving a budgetary balance amid flat budgets and O&M costs that rose rapidly were at the core of *Sea Change: 2015-2025 Decadal Survey of Ocean Sciences*. Its introduction states:

> *Within NSF, OCE encompasses a broad portfolio of interests and activities. Managing this enterprise has been made more challenging with the continued increase in operations and maintenance costs for the ocean research facilities, especially the academic research fleet, scientific ocean drilling through the International Ocean Discovery Program (IODP [2013-2018]), and the launch of the Ocean Observatories Initiative (OOI). Infrastructure expenses have risen over the past decade (about 18% in 2014 dollars), even as the total NSF OCE budget fell by more than 10%. With no significant budget increases anticipated by NSF in the near future, strategic decisions are required to ensure that key programmatic elements are supported to maintain the overall health of the ocean sciences community.*[28]

After examining NSF's role in the context of the broader Federal science ecosystem, the *Sea Change* report identified key science priorities for NSF-sponsored research and evaluated how well its existing portfolio of ocean research facilities matched. The report recommended eight "course corrections," most notably:

- Holistic fiscal planning to maintain a balance of investments between core research programs and infrastructure. To sustain core research amid flat or declining budgets, infrastructure expenses should not be allowed to escalate further.
- The Division of Ocean Sciences should reduce the O&M costs of its major research infrastructure and restore funding to core science. If budgets remain flat or have only inflationary increases, the division should allocate no more than 40-50% of the division's budget to major research infrastructure.

[28] National Research Council, *Sea Change: 2015-2025 Decadal Survey of Ocean Sciences, pp. 1-2.*

- The Division of Ocean Sciences should undertake two phases of infrastructure cost reductions and apply those savings immediately to strengthening core science. Reductions to existing infrastructure were suggested based on alignment with science priorities. In support of the recommendation to reduce O&M, the report also called for the Division to build no more than two Regional Class Research Vessels (RCRVs).
- The Division of Ocean Sciences should plan for its facilities in the context of the broader budget environment, maintain conservative infrastructure investment strategies, and seek partners to help absorb the cost of major ocean research infrastructure.

The Division of Ocean Sciences has evaluated these recommendations and, with the support of the NSF Director and the Board, has followed the report's guidance. NSF has descoped the Ocean Observatories Initiative (OOI) to reduce its funding profile by 20%, sought additional partnerships for International Ocean Discovery Program to reduce NSF's share of O&M, and put forward a request for the MREFC construction of two rather than three RCRVs. As **Figure 3** above shows, these efforts are projected to keep the share of the division's budget devoted to facility O&M below 50% through FY 2023.

The Division of Ocean Sciences' response is an example of how a division, in concert with its community can engage in planning, set targets for the balance between facilities and research grants, and re-adjust its investment portfolio to live within its means. On the other hand, a division's ability to descope a facility that has only recently completed construction, supported by centrally allocated MREFC funds, raises a worrisome structural question as to how NSB and the Director ensure that centrally funded assets deliver expected value. A similar question arises with the *Sea Change* report recommending that NSF "should plan to build no more than two RCRVs," while Congress has directed the Foundation to construct a third RCRV. As a result of this directive, the Division of Ocean Sciences will now need to plan for an additional $4.4 million per year in O&M costs for the third vessel (about 1% of the Division's budget).

Astronomy

As the primary source of federal funding for ground-based astronomy, NSF's Division of Astronomical Sciences (AST) plays a unique role in the federal ecosystem, ensuring that all U.S.-based researchers have open access to world-class telescopes, instrumentation, and grants. Reflecting the essential role of facilities, the division, with an approximately $250 million annual budget, has devoted over 55% of its budget to facilities O&M since FY 2002 (**Figure 2**). Yet, with limited budget growth, the almost $100 million in steady-state O&M needed when three state-of-the-art facilities that were, or will be, completed between 2012 and 2023[29] is challenging the division's ability to manage its portfolio of existing and future facilities without severely affecting its investigator research program. NSF forecasts nearly 80% of division's budget going to facilities O&M in 2023, assuming the Division of Astronomical Science's budget remains at its nominal FY 2017 levels.

The Division of Astronomical Sciences has long recognized the need for international partnerships to construct and support cutting-edge facilities and has pursued such partnerships. For example, NSF contributes $43.5 million of the roughly $115 million total annual O&M (in nominal 2017 dollars)

[29] The Atacama Large Millimeter Array (ALMA), the Daniel K. Inouye Telescope (DKIST), and Large Synoptic Survey Telescope (LSST).

associated with Atacama Large Millimeter/Submillimeter Array (ALMA), while international partners contribute the remainder. Construction costs of approximately $1.4 billion (the most expensive ground-based telescope in history at the time) were similarly shared[30], with NSF having provided $531 million (in nominal dollars) from the MREFC account. Even with the external partnerships that made such an ambitious construction project viable, ALMA O&M still imposes substantial budgetary pressures on the division.

Recognizing the challenge, in 2011 Division of Astronomical Sciences charged an external Portfolio Review Committee to examine the Astronomy decadal survey recommendations in a context of limited budget growth. This committee's report[31] recommended divesting "less critical" facilities and placing higher priority on the mid-scale program recommended by the 2010 decadal survey. Subsequently, the National Research Council issued a midterm assessment[32] in 2016 that reviewed the responses of NSF, NASA, and the Department of Energy to the 2010 decadal survey and of NSF to the Portfolio Review. This report affirmed the recommendations of the Portfolio Review regarding divestment, but emphasized that "divestment alone will not resolve the budget stresses imposed by rising facilities costs."[33]

The Division of Astronomical Sciences has taken steps toward adopting the Portfolio Review's recommendations. The transition from the National Solar Observatory toward DKIST and reduced support for other legacy facilities have yielded some savings. Collectively, these efforts generated approximately $15 million in annual cost savings. Full divestment of the legacy facilities, including Arecibo, the Green Bank Observatory, and the Very Long Baseline Array, which have been rated as lower priority in recent astronomy Senior Reviews and Portfolio Reviews, could realize an additional savings of approximately $15 million per year. While significant, this will not remedy the projected budgetary imbalance between facilities and investigator grants that was predicted by the 2016 midterm assessment.

In contrast with the Division of Ocean Sciences' "course corrections," the Division of Astronomical Sciences has found itself with limited options for rebalancing its portfolio in an era of effectively flat budgets. The National Research Council's midterm assessment of the astronomy decadal survey acknowledged that this dilemma could not be solved at the community level, and appealed to the NSF and the NSB for help:

> *The NSF and the National Science Board should consider actions that would preserve the ability of the astronomical community to fully exploit the Foundation's capital investments in ALMA, DKIST, LSST, and other facilities. Without such action, the community will be unable to do so because at current budget levels the anticipated facilities operations costs are not consistent with the program balance that ensures scientific productivity.*

The astronomy decadal survey made recommendations to the NSF that were built on an assumption of budgetary growth, specifically doubling over a decade. However, the 2010 decadal report also noted that: "If the realized budget is truly flat in FY 2010 dollars … there is no possibility of implementing any

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[30] http://www.eso.org/public/news/eso1312/

[31] Advancing Astronomy in the Coming Decade: Challenges and Opportunities, p. 240.

[32] National Research Council, *New Worlds, New Horizons: A Midterm Assessment*

[33] National Research Council, *New Worlds, New Horizons: A Midterm Assessment*

of the recommended program this decade." From a planning perspective, the Division of Astronomical Science's situation illustrates what happens when a community initiates several investments at the division level in cutting-edge facilities, based, in part, on budgetary assumptions that did not materialize.

Biology

Over the past several years, as construction for the National Ecological Observatory Network (NEON) has neared completion, NSF's Directorate for Biological Sciences (BIO) has been planning for its anticipated $65 million annual O&M. NEON accounts for almost all of the growth in O&M in BIO that is illustrated in Table 1. To put the scale of the NEON project in context, budgets for BIO's divisions vary between $130-$215 million annually.

Recognizing that the NEON O&M obligation would take 45% of the Division of Environmental Biology's (DEB) budget, and that there were expected benefits for other divisions, BIO elevated NEON to a directorate-level priority investment. It did so by moving responsibility for funding long-term O&M to its Division of Biological Infrastructure (DBI). DBI serves as a predominantly large and mid-scale facility-focused division within the directorate.

BIO's decision to fund NEON O&M via a dedicated facility division minimized NEON's effects on DEB's grant budget and, instead, spread NEON's impact on the directorate's grant portfolio across the entire directorate.

Other Considerations

Several other aspects of today's NSF Large Facility portfolio also point to the need to refine the current structure for facility planning, strategic decision making, and budgeting. They include:

The MREFC Pipeline

AS NSB looks toward the future, there is some concern regarding prospective construction projects on the scale of the National Ecological Observatory Network (NEON) or the Large Synoptic Survey Telescope (LSST).[34] There are as yet none in the design stage. MREFC outlays are currently projected to fall from $223 million in FY 2017 to $95 million in FY 2019 (requested) to $6 million in FY 2022.[35] Anecdotal evidence suggests that the prospect of future O&M obligations associated with new large projects may be discouraging to NSF directorates and divisions. Nevertheless, judicious NSF investment in future large facilities is vital to future cutting-edge science. NSB recognizes that a key step for the Foundation will be to address how NSF will assign life-cycle budgetary responsibility – and, in particular, the placement of the O&M burden primarily on divisions – if the agency is to build ambitious facilities in the future.

Interagency and International Partnerships

Some years ago, the particle physics community recognized that next generation accelerators were too large for a single country. As a result, the United States joined with other countries to construct and operate the Large Hadron Collider. Similarly, as the costs of certain ground-based telescopes or maintaining the Academic Fleet have exceeded what NSF can alone afford, NSF has had to partner with

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[34] The Antarctic Infrastructure Modernization for Science project is of this scale, but it is arguably an upgrade rather than a new project.

[35] The decrease in the NSF's FY 2019 MREFC funding request is somewhat artificial because NSF requested R&RA funding rather than MREFC funding for AIMS.

other countries or agencies. The cost of new large facilities in some fields of science underscore that the NSF, in the coming decades, will need to be even more reliant on partnerships to pursue and operate ambitious facilities.

The value of partnerships extends beyond the financial benefits of cost sharing. Partnerships have the potential to bring the world's brightest people with the most innovative ideas to bear on the most pressing scientific questions. NSF, as a recognized leader in basic scientific and engineering research and facility construction and stewardship, has much to offer as a leader in these partnerships. To retain that status, the agency must continue to bring its people, ideas, and financial resources to the table.

Given this reality, it is crucial that steps be taken to provide projects involving interagency and international partnerships with the necessary budget assurances and processes to minimize impediments to such partnerships. NSF's ability to make multi-year funding commitments and establish clear sets of governance roles and responsibilities for partnership participants will, in the future, be increasingly essential to NSF's success. NSB recognizes that some of the critical elements, such as authority to make multi-year funding commitments, depend on Congressional action.

Because the dimensions of such partnerships go well beyond science, it is imperative that NSF's senior management and NSB play a strategic decision-making role in the lifecycle planning and funding of large facilities that involve interagency and international partners.

Facilities that Serve Multiple NSF Disciplines

Some NSF facilities, such as the Arecibo Observatory, the Cornell High Energy Synchrotron Source, and the National High Magnetic Field Laboratory, are supported by multiple NSF divisions. To date, the NSF has managed this by having one division serve as the "lead" division, managing and overseeing the O&M award. This model however, poses both funding and planning challenges, particularly if divisions ascribe different priorities to a facility and/or one division advocates for divestment. To mitigate against this and ensure that all relevant communities are engaged in lifecycle decision making, greater NSF central ownership of both decision-making and budgeting for facilities that serve multiple disciplines would be beneficial.

Divestment

When a facility reaches its expected life span of service or is no longer a science priority for the sponsoring division or directorate, the decision to divest requires early NSF Senior Leadership and NSB engagement. Congress, state government, local communities, science partners, diverse disciplines, and environmental advocates may all have an interest in the future of a facility that transcends the specific science and budgetary considerations that might drive a division's choices in divesting that facility. The NSF leadership's ability to respond effectively to concerns about possible divestment activities requires early insight into such plans and the development of an approach that serves the interests of the division, the agency as a whole, and the nation.

Recommendations

To ensure that the NSF can, amid budgetary constraints, maintain the conditions for new large facilities, strategically invest in building ambitious facilities, and sustain existing large facilities, while also meeting other mission needs, the NSB recommends:

1. **NSB and the NSF Director should enhance agency-level ownership of the facility portfolio through processes that elevate strategic and budgetary decision-making.**

   The rising cost and scale of facilities, budget constraints, the growing importance of convergent and interdisciplinary research, and the need to align better division-level decisions with NSF-wide strategy require central visibility and planning. The goal should be a scientifically robust Foundation-wide strategy that is both transparent and fiscally responsible.

   NSF should continue to strengthen its agency-level facility oversight, initiated in 2017 with the creation of the Chief Officer for Research Facilities (CORF) position in the Office of the Director. NSB believes that:

   - NSB and the NSF Director must enhance their strategic responsibility for the agency-wide impacts of facility acquisition, operation, and divestment. This could mean expanding their engagement with the large facility portfolio beyond the design and construction stages. Current reliance on community inputs through decadal surveys and advisory committees, and day-to-day oversight of individual facilities at the division/directorate level must be harmonized with NSF-level strategic priorities and an overarching agency facility planning. Additional guidelines for determining which decisions can be made independently by a division/directorate and which require Office of Director and possibly NSB involvement may be warranted.
   - NSF should adopt longer planning and budgetary horizons. Current facility budgets contain 5-year projections, as required by statute. The Department of Energy's Office of Science has found success using a 10-year planning model. Relatedly, the Director and NSB would benefit from greater visibility into potential projects in development. This would better align NSF practices with those of NASA and DOE-SC.
   - NSB's facility-related work must complement its engagement on discrete facility award decisions with regular engagement of the Director and the CORF on strategy, budgeting, and lifecycle planning for the facility portfolio.
   - NSF could benefit from additional Advisory Committees at the divisional level to supplement the community guidance received through the decadal survey process.

   NSF's budgetary model for facilities may also need to evolve in concert with its strategic planning processes. One way to elevate strategic decision-making and achieve greater agency-level ownership is through additional flexibility in the use of the existing MREFC account.

   NSB envisions that the design and implementation of a flexible MREFC account could potentially provide several benefits. Limited term, partial funding of O&M (e.g. for a period of 5-10 years at less than 50%) could be used as a budgetary "on ramp" that would allow the O&M costs of a new facility to be absorbed gradually into a division's or directorate's budget. MREFC funding for the "core" O&M of multidisciplinary facilities could ensure stable support for base operations while allowing individual divisions to evolve their science priorities. Use of "no year" MREFC funds to support O&M for some facilities that involve international partnerships could also help NSF in cases where the ability to make multi-year funding commitments is crucial. In rare instances, the MREFC account might also be used to fund O&M when compelling national or agency strategic imperatives require the NSF to continue to operate a facility that may not rank as high priority within a single research community.

A more flexible approach to use of the MREFC could also be considered as a way of promoting incentives to develop new ideas for facilities and/or to mitigate challenges associated with divestment. For example, at the end of the facility lifecycle, facility deconstruction and site refurbishment can be prohibitively expensive for a division or directorate.

2. **NSB and NSF should reexamine what share of the Foundation's budget should be devoted to research infrastructure.** [36]

   NSB believes that providing support for research infrastructure including large facilities, midscale, and Major Research Instrumentation is a fundamental component of NSF's mission. In its 2003 report, NSB recommended that NSF strive to maintain research infrastructure investments in their historical range of 22-27%. The NSB and the NSF should study whether this planning guideline remains useful as a safeguard against under- or over-investment, while recognizing that there is a wide range of infrastructure requirements, depending on the scientific discipline in question. The average over the past 15 years has been at the low end of this range at approximately 23.5%.

3. **NSB and NSF should develop model funding and governance schemes for the next generation of partnerships at the agency, interagency, and international levels.**

   As the costs of building and operating the most ambitious facilities continue to increase, so will the need for partnerships. NSF is well positioned to build on its existing relationships and models. As the dimensions of such partnerships go well beyond science, it is crucial that NSF senior management and NSB play a strategic decision-making role in the lifecycle planning and funding of large facilities that will involve interagency and international partners. This may require appropriate requests to Congress for the necessary implementation authorities, including the recommended flexible MREFC account.

   Dependable commitments for multi-year funding for core operational costs of partnership facilities are critical to negotiating and sustaining partnerships. Leveraging the flexibility envisioned in a re-defined MREFC account could be an important step to assuring NSF remains a leader in these facilities.

[36] Research Infrastructure includes large facilities, midscale facilities, cyberinfrastructure, Federally Funded Research and Development Centers(FFRDC), National Center for Science and Engineering Statistics (NCSES), and Major Research Instrumentation.

Appendix A: Approaches Used by Other Agencies

This appendix considers other federal agencies' approaches to facility lifecycle planning and Operations and Maintenance (O&M).[37] Initially, NSB identified the National Aeronautics and Space Administration (NASA), the Department of Energy's (DOE) Office of Science, the National Oceanic and Atmospheric Administration (NOAA), and the National Nuclear Security Administration (NNSA) for comparative study. However, NSB quickly narrowed its focus to the NASA's Science Mission Directorate and the DOE's Office of Science since these two entities have the most in common with NSF. Like NSF, DOE's Office of Science (SC) and NASA's Science Mission Directorate (SMD):

- Invest in sophisticated facilities/instruments that go beyond the capabilities of individual research institutions and require significant allocation of agency resources over an extended period
- Maintain portfolios of facilities/instruments/missions to support fundamental research in one or more scientific fields
- Use formal processes for planning, developing, operating, and divesting of facilities/instruments
- Rely on science community input and priority-setting as part of lifecycle planning
- Weigh investments in individual research facilities/instruments/missions against other existing facility/instrument/mission commitments as well as research-related considerations including support for research grants
- Engage in external partnerships and co-stewarding to share costs and leverage capabilities

Despite these similarities, NASA missions and DOE Office of Science facilities are not entirely analogous to NSF facilities. Noteworthy differences include:

- While the science-dedicated portions of the NASA, DOE, and NSF budgets are comparable in size despite the overall larger size of DOE and NASA, major research infrastructure represent a smaller share of NSF's "science" budget.[38] Large Facilities currently represent roughly 17% of NSF's "science" budget and research infrastructure as a whole represents about 23-25% of NSF's budget.
- NSF's mission complements that of other agencies. Its mandate to promote the progress of science in all non-medical fields necessitates that it serve a wider set of scientific disciplines than either NASA or DOE-Office of Science. Therefore, NSF requires programs that meet the diverse research infrastructure needs (large facilities, midscale facilities, major research instrumentation) of the disciplines it serves and attend to equities between fields like astronomy that rely heavily on NSF to fund large facilities and those like chemistry that tend not to require large facilities.

[37] Federal science agencies vary in how they define a "facility." At a number of science agencies, facilities refer to building infrastructure such as walls, roofs, HVAC systems, and other capital infrastructure. For example, NASA excludes satellites and NOAA excludes ships from their respective agency definition of facilities. As a result, this report focuses on comparable units of analysis to NSF's large facilities including NASA satellites and probes and DOE user facilities such as light and neutron sources, regardless of whether the agency terms such items as "facilities." As a result of these differing definitions of facilities, facility budget lines across agencies are not comparable.

[38] In FY 2017 NSF R&RA was $6B, DOE Office of Science was $5.6B, and NASA SMD was $5.7B.

- The scope of NSF's mandate in terms of constructing and operating facilities differs from NASA's and DOE's.
    - NSF does not design and develop instruments "in-house" as NASA frequently does.[39]
    - Unlike most of the facilities of DOE-Office of Science, NSF facilities are not built on government land or co-located with existing laboratories.[40]
- NSF's Organic Act prohibits it from operating facilities.[41] By contrast, NASA and DOE-Office of Science operate facilities under the government owned, government operated (GOGO) model and the government owned, contractor operated (GOCO) models.
- Neither NASA nor DOE-Office Science has the equivalent of NSF's MREFC account which can be used to fund construction of both the instrument and associated infrastructure (buildings, roofs, roads, HVAC systems) that support the instrument. Construction costs for the instrument itself (e.g., rovers or beam lines) come out of program funds at both NASA and DOE.
- NSF's "large" projects have historically been smaller than NASA's and DOE's "large projects."

In spite of these differences, all three agencies have somewhat similar stages and processes associated with mission/facility lifecycle planning.[42] During the development, design, and construction stages, all three have somewhat comparable "stage gate" processes through which projects either advance or are off-ramped. Once the facility or mission is operating, each entity conducts periodic reviews of the facility's or mission's utility and has processes associated with decisions to continue, terminate, or, if applicable, upgrade the facility.[43] In all three cases, independent review of project design, cost, and science utility inform decision-making. Likewise, all three entities have project assurance functions and use dollar thresholds to help determine the necessary reviews and approvals with the most expensive projects requiring engagement from senior officials at the respective agencies.

NASA's Science Mission Directorate

NASA's SMD manages about 125 flight projects or missions in various stages of development and operations.[44] SMD projects address fundamental science questions related to the universe's origins and destiny; the Sun and its effects on the solar system; the Earth's climate; the solar system's evolution, and the potential for life elsewhere in the universe. Examples of current SMD missions include the Europa Clipper, the Ionospheric Connection Explore (ICON), and the James Webb Space Telescope (JWST). SMD also funds research related to these missions.

Each SMD mission is associated with one or more of SMD's science programs – Heliophysics, Earth Science, Planetary Science, and Astrophysics – and is also tied to one or more of the 10 NASA Research

[39] One or more of NASA's 10 Centers play a significant role in either directly developing and building instruments for NASA missions or overseeing outsourced efforts.
[40] Almost all of the DOE Office of Science's facilities including light, photon, and neutron sources, nanocenters, the Genome Institute, accelerator test facilities, and the heavy ion collider are co-located at one of DOE's 10 National Laboratories.
[41] An exception to this is NSF's Congressionally-mandated direct engagement in Antarctic operations.
[42] William L. Miller, "Preconstruction Planning for Large Science Research Infrastructure Projects: A Comparative Analysis of Practices and Challenges at DOE, NASA, and NSF," (2010), 50.
[43] Because NASA's instruments are often sent deep into space, upgrades are much less common. The Hubble Space Telescope, which orbited the Earth and had five upgrades, was the exception for NASA, not the rule.
[44] NASA Inspector General Top Management Challenges 2017 Report (December 6, 2017), p. 10

Centers. Plans for SMD missions are informed by scientific community priorities as articulated in National Research Council decadal surveys that are carried out in each of the fields served by the SMD.[45]

NASA takes a life cycle cost (LCC) approach to its missions, programs, and projects. LCC on NASA projects include "the total of the direct, indirect, recurring, nonrecurring, and other related expenses both incurred and estimated to be incurred in the design, development, verification, production, deployment, prime mission operation, maintenance, support, and disposal of a project, including closeout, but not extended operations."[46]

The formulation phase for a NASA mission consists of concept studies, concept and technology development, as well as preliminary design and technology completion (known as Pre-Phase A, Phase A, and Phase B, respectively). Phase A culminates in a systems definition review/mission definition review. Prior to entering Phase B, projects also develop a range for a project's expected cost and schedule that is used for budget planning.[47] During the preliminary design phase, programmatic measures and technical leading indicators are developed and the project team completes technology development and its preliminary design. Phase B culminates with a preliminary design review. Following the end of Phase B and before Phase C gets underway, projects undergo "project confirmation." Project confirmation establishes cost and schedule baselines, determines how much funding is needed in each fiscal year to manage the project to the agency's baseline commitment, and creates an agreement between the agency and the project manager.[48] Thereafter, project managers are tasked to carry out the project within the outlined parameters. After a project is confirmed, it begins development. Phases C and D focus, respectively, on final design and fabrication and system assembly, integration, test and launch. Each of these stages has review points and, together, Phases C and D account for the greatest proportion of a mission's LCC. For example, systems acquisition (i.e., final design, fabrication, testing, and launch) for the Magnetospheric Multiscale (MMS) mission accounted for almost 80 percent of the mission's LCC. Much of the design and assembly work is executed by scientists and engineers at NASA centers.

Operations and sustainment - Phase E of a NASA mission - begins after launch and ends with deorbiting. This period can range from 3 to over 10 years. Operations costs, which represent 6-10% of a NASA mission's total lifecycle costs, cover on-the-ground command and control, operation systems, flight software, and their associated workforces. Maintenance is not commonly discussed in the context of NASA missions. Once launched, NASA's space-based missions typically incur no maintenance costs. The

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[45] Each division's history with decadal surveys varies. For example, Astrophysics has had six Decadal Surveys, Earth Science has had only two Decadal Surveys. https://science.nasa.gov/about-us/science-strategy/decadal-surveys; https://science.nasa.gov/earth-science/decadal-surveys

[46] NPR 71205E, NASA Space Flight Program and Project Management Requirements

[47] "NASA: Assessment of Major Projects," GAO May 2017 (GAO-17-303SP), pp. 4.

[48] Projects with LCC estimated to be greater than $250 million must also develop a joint cost and schedule confidence level (JCL). To arrive at the JCL, NASA looks at all cost and schedule elements in phases A through D, identifies and incorporates known risks, assesses the state of cost and schedule to date, and considers available annual resources. NASA policy requires that projects are baselined and budgeted at the 70 percent confidence level and funded at a level equivalent to at least the 50 percent confidence for the project. See NASA Procedural Requirements (NPR) 7120.5E.

Hubble Space Telescope was a notable exception; since its deployment in 1990, there have been five planned servicing missions to Hubble.[49]

Decommissioning costs are typically low, and cover disposal of the spacecraft and supporting systems, as well as provision of final deliverables, closeout of contracts, and archiving of project data for continuing scientific analysis.[50] Missions are typically decommissioned and deorbited when they fail or run out of fuel.

Within NASA, decisions about which missions to pursue are made at the division level with the concurrence of SMD and agency leadership. Within SMD, each division evaluates its own priorities, selects its missions, and makes tradeoffs.[51] Mission planning, development, deployment, and operations as well as research are all supported from the cognizant SMD division's budget line.[52] As missions mature, some appear as line items in the NASA budget.

Several NASA SMD practices that may be useful to NSF in its facility planning include:

Prime & Extended Mission Concepts: NASA missions in the operations phase are designated as either "prime" missions or "extended" missions. The "prime mission" consists of the necessary operations to meet the scientific goals that inspired NASA to undertake the project. SMD projects are developed and costed from the outset to reflect the goals of the prime mission and only prime mission costs are figured into NASA's calculations of LCC. The length of the prime mission period varies. At the end of the prime mission, missions are either closed out or transformed into an extended mission. Extended missions can continue activities in process or start new ones. Extended missions are evaluated every two years for their continued utility.

"Strategic" vs. "Competed" missions concept: NASA uses two basic models for planning missions: "strategic missions" and "competed missions." Individual SMD divisions follow about a 50-50 percent split between the models, but there is no prescriptive rule.

Strategic missions stem from a more "top-down" approach based on specific science goals identified in Decadal Surveys and are typically larger, with costs upward of $500M and usually over $1B. Also known as "facility-class assigned missions," they are assigned directly to Centers that have the critical capabilities necessary to carry out the mission, though individual instruments may be competed. Strategic missions include Cassini, James Webb Space Telescope, Ocean Surface Topography Mission, and Lunar Atmosphere and Dust Environment Explorer (LADEE).[53] Such missions also require the approval of NASA Headquarters' leadership.

Competed missions, also known as "principal investigator (PI)-led missions," use a more "bottom-up" approach, which encourages creativity and allows for missions that can be more responsive to emerging

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[49] https://www.nasa.gov/mission_pages/hubble/servicing/index.html [mentioned 5 servicing missions]

[50] NPR 71205E, NASA Space Flight Program and Project Management Requirements

[51] While Division leadership generally determines project selection, life cycle planning, and budgets for missions, program, and large projects, NASA Associate Administrator (AA) signs off on missions and large projects and the Mission Directorate Associate Administrator (MDAA) signs off on smaller projects.

[52] As the project develops, the NASA centers associated with the mission are given control over the mission's budget and can make decisions about how to allocate resources.

[53] https://science.nasa.gov/about-us/science-strategy/mission-models-strategic-and-pi-led

technologies and innovation.[54] These missions are typically small- or medium-sized and cost less than approximately $250M and between approximately $250M and $1B, respectively. They are initiated through an Announcement of Opportunity (AO). Teams from universities, industry, government laboratories, and small businesses can compete to develop and conduct the mission. Competed missions include Phoenix, MESSENGER, and Nu-STAR.[55]

Bundling some research money with the mission: Each division within NASA's SMD offers competitive research grants to investigators from NASA Centers and other government agencies, as well as academia and the private sector.[56] While most NASA research grants are supported by funds from a separate research line in each division's budget, a substantial portion of those research funds are devoted to conducting research related to the data provided by the missions, to fuse data generated by the mission with other sources, and to develop new research questions. Occasionally, NASA has included funds for related research as part of the mission's operations budget. For example, the Hubble Space Telescope project within the Astrophysics Division allocates approximately 30 percent of its $98M per year operations budget to research.[57]

DOE's Office of Science

DOE's Office of Science focuses on delivering "scientific discoveries and major scientific tools that transform our understanding of nature and advance the energy, economic, and national security of the United States."[58] The Office of Science, the largest Federal sponsor of basic research in the physical sciences, provides research grants and contracts to investigators nationwide and supports 26 national user facilities – most of which are housed on the campuses of DOE's national laboratories - that provide state of the art tools for research in areas related to energy, environment, and fundamental physical science.[59] With a $5.39 B budget, the Office of Science supports approximately 22,000 researchers annually on grants and provides through its user facilities tools that are used annually by nearly 32,000 scientists from universities, national labs, industry, and international partners. Examples of Office of Science user facilities include light sources, neutron sources, nanocenters, and particle accelerators.

The Office of Science manages its research grant programs and user facilities through six program offices: 1) Advanced Scientific Computing Research, 2) Basic Energy Sciences (BES), 3) Biological and Environmental Research (BER), 4) Fusion Energy Sciences (FES), 5) High Energy Physics (HEP), and 6) Nuclear Physics (NP). Budgets within the Office of Science are appropriated by program office. Program

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[54] National Academies of Sciences, Engineering, and Medicine. 2017. Powering Science: NASA's Large Strategic Science Missions. Washington, DC: The National Academies Press. https://doi.org/10.17226/24857.
[55] NPR 71205E, NASA Space Flight Program and Project Management Requirements
[56] FY18 Budget Estimates
[57] Interview with current Hubble Program Manager.
[58] https://science.energy.gov/~/media/budget/pdf/sc-budget-request-to-congress/fy-2019/FY_2019_SC_Congressional_Overview.pdf
[59] A DOE-Science user facility is a federally sponsored research facility available for external use to advance scientific or technical knowledge and is open to all potential users, free of charge and whose allocation of facility resources are based on merit review of the proposed work. User facilities in DOE-Science are distinct from infrastructure, which typically refers to the demolition, revitalization, or construction of buildings that will house scientific equipment or user facilities. For a full definition see https://science.energy.gov/~/media/_/pdf/user-facilities/memoranda/Office_of_Science_User_Facility_Definition_Memo.pdf

funds support research grants and contracts as well as user facilities. Portfolios for each program are managed to advance science and maintain a balance of activities.

Like NASA SMD and the NSF, the Office of Science engages in rigorous lifecycle planning processes for its user facilities. As is done at NSF and NASA, total project cost thresholds help to determine where in the organization the authority lies to pursue new user facilities, with more costly projects requiring approval higher in the agency's hierarchy. Decisions to start new facilities are informed by guidance from the research community. The Office of Science relies heavily on Federal Advisory Committee Act committees, National Academies studies, and community workshops.

Facilities under development and construction move through five stages (known as CD 0-4) that are each associated with preparation of documents and analyses and culminate in stage gate reviews that determine either advancement or off-ramping. CD-0 focuses on pre-concept planning and mission alignment; it finishes with reviews that assess the project's alignment with mission need. CD-1 is the project definition and conceptual design phase; concept exploration, requirements analyses, acquisition strategies, and risk identification and analysis are all components of this stage. CD-2 is the preliminary design phase. It ends with a review that ensures that design can be implemented within the project budget. CD-3 includes final design and culminates with approval to start construction and execution. CD-4 marks the end of the construction phase and ends with an approval of project completion and the start of operations.

Office of Science user facilities operate on average for 25-30 years. Upgrades to user facilities may be funded along the way. For Office of Science user facilities, O&M consists of funding for operations staff for user facilities, utilities, maintenance and repair. Research funds dedicated to improving the equipment can also be supported from O&M.

The Office of Science phases out facilities that are no longer at the forefront of science and/or no longer retain a specific mission role. When possible, the Office of Science tries to plan to deactivate and decommission user facilities to coincide with the planning for or start of a new facility located on the same National Laboratory campus.

Unlike NSF, DOE Office of Science does not have a separate, central budget account for user facility construction. Program funds support the entire lifecycle of the user facility including facility development, construction, operations, and decommissioning costs. The Office of Science has two budget lines for research infrastructure that help it flag and track these investments. Major Items of Equipment (MIE) funds are often used for the purchase of capital equipment and Line Item of Construction (LIC) funds are often used for construction itself. Because research infrastructure is generally housed within National Laboratories, the Office of Science can also draw on Science Laboratory Infrastructure (SLI) funds to support buildings to house user facilities or fund utility services.[60]

Office of Science programs support research grants that are competed through Funding Opportunity Announcements, and undergo a peer-review process similar to that of NSF and other science agencies. Grant recipients are not limited to relying on the programs' user facilities, though they may do so.

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[60] SLI funds may not be used to pay for scientific instrument & equipment and salaries.

Below are some Office of Science practices that may be useful to NSF:

Adoption of a rule of thumb associated with the budgetary balance between user facilities and research: BES and the Office of Science have, for well over a decade, maintained a budgetary principle that allocates roughly 40 percent of the program's budget to facility operations, 40 percent of the budget for "research", and 20 percent of the budget to facility construction and other programmatic activities. By necessity, this rule is not applied rigidly across the Office of Science. For example, it does not apply in BER, a program that maintains few facilities and has a long history of devoting more than 40 percent of its budget to research. Similarly, it does not apply in NP where less than 40 percent of its budget has long gone into research and where a forced increase would harm the rest of the program's portfolio. Such a rule of thumb, however, helps to guide budgetary planning and communicate DOE's Sciences' investment strategy to stakeholders.

Annual 10-year Planning Exercise: Annually, DOE-Science undertakes a 10-year internal budget planning exercise to obtain indicators of program imbalance in the out years. During annual budget formulation, DOE-Science program offices must explicitly list research; every operating facility; every ongoing construction project; every MIE; every proposed new construction project; and deactivation and decommissioning plans. The facility versus research breakdown for each individual program office as well as for the Office of Science overall is calculated and then tracked by year. This helps the programs as well as the Office of Science see how a particular program budget is faring and how well facility construction, operation, and research needs are being balanced. The Office's Director uses the 10-year budget planning exercise to determine which new construction starts will occur.

Facility Prioritization efforts within the Office of Science: The programs within the Office of Science routinely engage in prioritization activities related to their facilities. In the past, the Office of Science has also experimented with an office-wide (that is to say cross field) prioritization exercise. In 2004, then-Director of Office of Science Raymond Orbach provided each program office a budget envelope and tasked each Program's Associate Director with generating a prioritized list of major facilities required for scientific leadership in their respective fields in 20 years. Director Orbach then used the lists generated by the programs to generate a prioritized list across the DOE-SC programs based on the criteria of scientific need and project readiness. Subsequently, DOE published a report, *Facilities for the Future of Science, A Twenty-Year Outlook,* identifying 28 of the most important facilities over the next 20 years to support the Nation's research needs.[61] DOE updated the report again in 2007, and then used the report to help identify what facilities to support—particularly in BES.[62]

Continuity of Leadership: Part of the Office of Science's success is its reliance for facility planning and execution on career civil servants who have decision-making power. NASA SMD also has this feature.

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[61] https://science.energy.gov/~/media/_/pdf/news/press%20releases/2007/20_Year_Science_Plan.pdf
[62] https://science.energy.gov/~/media/_/pdf/news/press%20releases/2007/USA_DOE_20-Year-Outlook_2007.pdf

Appendix B: Division-level Success Rates

MPS	PHY			AST			DMS			DMR			CHE		
	2003	2017	Δ %	2003	2017	Δ %	2003	2017	Δ %	2003	2017	Δ %	2003	2017	Δ %
Proposals	545	816	50%	456	745	63%	2133	2786	31%	1225	1887	54%	1167	1512	30%
Awards	252	256	2%	161	154	-4%	549	655	19%	390	367	-6%	354	417	18%
Success Rate	46%	31%	-32%	35%	21%	-41%	26%	24%	-9%	32%	19%	-39%	30%	28%	-9%
BIO	**MCB**			**DBI**			**IOS**			**DEB**			**EF**		
	2003	2017	Δ %	2003	2017	Δ %	2003	2017	Δ %	2003	2017	Δ %	2003	2017	Δ %
Proposals	1034	1132	9%	224	419	87%	1419	1169	-18%	1213	1031	-15%	346	251	-27%
Awards	271	189	-30%	53	132	149%	284	221	-22%	292	249	-15%	56	38	-32%
Success Rate	26%	17%	-36%	24%	32%	33%	20%	19%	-6%	24%	24%	0%	16%	15%	-6%
GEO	**AGS**			**EAR**			**OCE**								
	2003	2017	Δ %	2003	2017	Δ %	2003	2017	Δ %						
Proposals	677	761	12%	1492	1483	-1%	1429	1226	-14%						
Awards	322	297	-8%	436	383	-12%	365	354	-3%						
Success Rate	48%	39%	-18%	29%	26%	-12%	26%	29%	13%						

Table 4, Division-level Success Rates – Proposals, Number of Awards, and Success Rates.

Key:
MPS: Directorate of Mathematical and Physical Sciences
PHY: Division of Physics
AST: Division of Astronomical Sciences
DMS: Division of Mathematical Sciences
DMR: Division of Materials Research
CHE: Division of Chemistry
BIO: Directorate of Biological Sciences
MCB: Division of Molecular and Cellular Biosciences
DBI: Division of Biological Infrastructure
IOS: Division of Integrated Organismal Systems
DEB: Division of Environmental Biology
EF: Emerging Frontiers Office
GEO: Directorate of Geosciences
AGS: Division of Atmospheric and Geospace Sciences
EAR: Division of Earth Sciences
OCE: Division of Ocean Sciences