CYBER-ENABLED MATERIALS, MANUFACTURING, AND SMART SYSTEMS (CEMMSS) $257,120,000 +$820,000 / 0.3%

Overview

The Cyber-enabled Materials, Manufacturing, and Smart Systems (CEMMSS) investment aims to integrate a number of science and engineering activities across NSF, including breakthrough materials, advanced manufacturing, and smart systems, which includes robotic, cyber-physical and autonomous systems. These investments are in response to the Materials Genome Initiative (MGI) and Advanced Manufacturing Partnership (AMP). Through CEMMSS-funded research, materials with unique properties and functionality are being discovered and developed more reliably and efficiently via the integration of theory, modeling and simulation, data analytics, and experiments. These new materials can in turn be fashioned into objects, structures, and systems embedded with computational intelligence, thereby transforming today's static systems, processes, and edifices into adaptive, pervasive, and smart systems through the use of advanced manufacturing strategies.

The smart systems of tomorrow and the materials from which they will be composed will vastly exceed those of today in terms of adaptability, autonomy, functionality, efficiency, reliability, safety, usability, recoverability, and recyclability. These smart systems will achieve high levels of autonomy, and will be able to act independently and intelligently in dynamic, uncertain, and unanticipated environments. These advances have the potential to accelerate scientific and engineering discoveries to address key national and societal challenges critical to U.S. security and competitiveness.

Total Funding for CEMMSS

(Dollars in Millions)

FY 2015 Actual	FY 2016 Estimate	FY 2017 Request
$269.83	**$256.30**	**$257.12**

Goals

Goal 1: Science and Engineering

CEMMSS is establishing a scientific base, a codified knowledge base, and shared principles for designing, manufacturing, and deploying cyber-enabled smart engineered systems and advanced materials.

Goal 2: Education, Workforce Development, and Community Building

CEMMSS investments are leading to the education of a cadre of high-caliber disciplinary and interdisciplinary researchers and developing a vibrant workforce so as to ensure a pipeline of talent and a growing community in these critical areas.

Goal 3: Research Infrastructure Development

CEMMSS is developing the critical research infrastructure that can be used to discover, test, refine, and validate the advanced materials, designs, and manufacturing and development methods so as to enable the deployment of smart systems.

Approach

The CEMMSS framework of bringing together researchers focused on breakthrough materials, advanced manufacturing, and smart systems is increasing collaboration and communication among these research communities. This is leading to enhanced disciplinary and interdisciplinary research. CEMMSS funds research that couples modeling and theory with experimentation, thereby shortening the time and resources required for the discovery of new materials, new approaches to advanced manufacturing, and novel

advances in smart and autonomous systems. Such efforts will aid in the transformation of static systems, processes, and edifices into adaptive, widespread smart systems with embedded computational intelligence that can sense, adapt, and react. Success in CEMMSS will drive transformations that address the pressing technological challenges facing the Nation and promote U.S. economic competitiveness.

Programmatic

CEMMSS comprises a research portfolio that synchronizes activities across three main research areas – breakthrough materials, advanced manufacturing, and smart systems – and encourages interdependencies and common research elements to surface and be exploited at each subsequent stage of the evolution of the program. The CEMMSS portfolio includes the following specific investment areas:

- ***Breakthrough materials***: This investment focuses on accelerating the discovery and development of the materials required for meeting societal needs and finding paths for sustainable and scalable manufacturing technologies. CEMMSS investments in this area will pursue a research approach in which computation, data analytics, and theory are combined with research in materials synthesis and characterization in a collaborative and iterative manner.
- ***Advanced Manufacturing***: CEMMSS investments in this area leverage both disciplinary and topical mechanisms to advance knowledge for the production of novel products through processes that depend on the coordination of information, automation, computation, networking, or other emerging scientific capabilities.
- ***Smart Systems***: This investment leverages synergistic advances made in the earlier years of CEMMSS to place an emphasis on smart systems. It supports basic research on both next-generation robotics and cyber-physical systems, as well as an emerging emphasis on the fundamental science of intelligent, autonomous systems. The supported fundamental research will enable new functionalities and provide the next generation of products, services, and manufacturing that vastly exceed those of today in terms of adaptability, functionality, reliability, safety, usability, and recyclability in dynamic, uncertain, and unanticipated environments.

Organizational

CEMMSS leadership is shared across the relevant division directors in the Biological Sciences, Computer and Information Science and Engineering (CISE), Engineering (ENG), and Mathematical and Physical Sciences (MPS) directorates. The CEMMSS coordination team comprises program directors from these directorates, and this group is charged with developing and implementing the suite of CEMMSS activities. The team is also working with internal and external program evaluation experts to develop a set of metrics by which program progress can be assessed over time.

Scope

Numerous CEMMSS interdisciplinary connections exist at NSF. Many are pairwise and expanding, such as robotics and manufacturing; materials and manufacturing; cyber-physical systems and robotics; cyber-physical systems and manufacturing materials; cyber-physical systems and advanced manufacturing; manufacturing and the biological sciences; robotics and the biological sciences; and advanced manufacturing and technician education. NSF has sponsored, and will continue to hold, community-building workshops. The intention is to drive new research directions, and this is being achieved through a combination of new solicitations and Dear Colleague Letters (DCLs). CEMMSS currently includes many interagency activities, and new cross-agency partnerships are continuously being developed. Industry partnerships also are a key element in CEMMSS's success; industry and venture capital groups are invited to workshops and principal investigator (PI) meetings. CEMMSS presents a unique opportunity to accelerate integrative research and educational activities. The interaction of research ideas that is promoted by CEMMSS multiplies their impact across multiple research communities.

Investment Framework

CEMMSS Funding by Directorate

(Dollars in Millions)

Directorate	FY 2015 Actual	FY 2016 Estimate	FY 2017 Request
Biological Sciences	$4.99	$5.48	$5.48
Computer and Information Science and Engineering	89.00	90.98	92.50
Engineering	110.77	110.00	112.00
Mathematical and Physical Sciences	65.07	49.84	47.14
Total	**$269.83**	**$256.30**	**$257.12**

Totals may not add due to rounding.

FY 2015– FY 2016

The specific CEMMSS investments in Advanced Manufacturing, Designing Materials to Revolutionize and Engineer our Future (DMREF), and Smart Systems, including investments in Cyber-Physical Systems (CPS) and the National Robotics Initiative (NRI), continued to focus on increased integration of the highest-priority areas, such as those related to materials and manufacturing, and developing smart systems. NSF is continuing to support NRI, CPS, and DMREF, as well as core research programs, focused on the highest-priority areas related to advanced manufacturing.

NSF continued to fund the Scalable Nanomanufacturing (SNM) program in FY 2015. The SNM program funds interdisciplinary projects that present explicit strategies for transitioning advanced nanomanufacturing methods into practice. In FY 2016, NSF is continuing to support research in SNM for manufacture of demonstrably useful nano-enabled products in high volume and at low cost.

Cybermanufacturing has become an important area of focus in advanced manufacturing. In FY 2015, ENG and CISE jointly issued a DCL on Cybermanufacturing Systems to encourage collaborative Early-Concept Grants for Exploratory Research (EAGER) for novel, early-stage, multidisciplinary, and high-risk/high-reward research on cybermanufacturing systems. ENG and CISE are jointly funding a workshop to be held in FY 2016, *Enabling Composable and Modular Manufacturing through Abstractions: Where Computer Science Meets Manufacturing*, to advance this emerging research area further. In FY 2016, NSF is continuing to emphasize investments in cybermanufacturing systems. Such investments will enable research on the networked integration of manufacturing machines, equipment, and systems into an increasingly accessible manufacturing service infrastructure. This activity will leverage investments through the FY 2015 DCL and existing programs within ENG, as well as previous and ongoing investments in cross-directorate activities including NRI and CPS.

Advanced biomanufacturing also emerged as an important emphasis research area in the overall portfolio of advanced manufacturing research. ENG, MPS, BIO, and the Department of Energy (DOE) previously jointly funded a National Academy of Sciences (NAS) study on the Industrialization of Biology. The study focused on the research, education, and infrastructure needs to enable advances in biomanufacturing, including the commercialization processes for biologically-based manufacturing of high-value products. NAS published the final report from this study in FY 2015.[1] Additionally, NSF and the European Commission sponsored one in a series of community-driven workshops on synthetic biology standards in March 2015; this workshop was attended by representatives from the National Institute of Standards and Technology (NIST) and the Defense Advanced Research Projects Agency (DARPA). NIST also sponsored a Synthetic Biology Standards Workshop in March 2015. This workshop supported the development of

[1] www.nap.edu/catalog/19001/industrialization-of-biology-a-roadmap-to-accelerate-the-advanced-manufacturing

standards to enable data sharing and automation in advanced biomanufacturing and engineering biology.[2]

Processes with cells as products present major engineering challenges, and new therapies and cell-based products may depend critically on robust and reliable manufacturing approaches at the cellular level. In FY 2015, ENG released a DCL that called for EAGERs to support research that addresses these critical aspects of cellular biomanufacturing. In FY 2016, NSF is continuing to support research in advanced biomanufacturing; this research will focus on studying theories and technologies of design, engineering, and manufacturing of bio-related (natural or synthetic) products, such as cells and cell-based therapeutic products (e.g., individualized tissues and organoids), or devices with biomaterials and/or cells as components. NSF will leverage the Biomedical Engineering and Biotechnology and Biochemical Engineering programs within ENG, as well as the Systems and Synthetic Biology program within BIO, and build on groundbreaking discoveries, many of which have been supported by NSF in the past, such as three-dimensional additive manufacturing, genome editing, systems and synthetic biology, stem cell biology, computational modeling, micro- and nano-fabrication, and tissue engineering and regenerative medicine. These efforts offer, in part, the promise of enabling the manufacturing of products for low-cost therapeutic research, personalized therapeutic products, and high-value chemicals and materials.

Accelerating U.S. Advanced Manufacturing, the October 2014 report produced by the Steering Committee of the Advanced Manufacturing Partnership 2.0 (AMP 2.0) for the President's Council of Advisors on Science and Technology (PCAST),[3] calls for the creation of a technology-focused consortium to provide coordinated private-sector input on national advanced manufacturing technology research and development priorities. In response to the report, NSF and NIST jointly issued a solicitation to establish the Consortium for Advanced Manufacturing Foresights (the "Consortium") in FY 2015. NSF and NIST made the award to establish the Consortium in early FY 2016 to the Alliance for Manufacturing Foresight (MForesight), and commissioned two rapid reports with the goal of identifying emerging technologies with crosscutting appeal, opportunities for public-private partnerships, and barriers to commercialization in the areas of advanced biomanufacturing. Additionally, ENG and CISE collaborated on a DCL through the Industry/University Cooperative Research Centers (I/UCRC) program to support collaborative clusters among I/UCRC in response to AMP 2.0. ENG and BIO funded a planning grant for an I/UCRC in the area of advanced biomanufacturing in response to a FY 2014 DCL, and full proposals for an advanced biomanufacturing center are being evaluated in FY 2016. The goal is to create a cross-disciplinary, cross-sector portfolio of research projects that hold the potential to catalyze technology breakthroughs and advance national priorities, particularly in advanced manufacturing.

The DMREF program developed a multi-directorate solicitation in FY 2015 for proposals that integrate theory, simulation, and/or cyber-enabled data analytics with synthesis and characterization experiments in an iterative manner. This research will accelerate new materials discovery, design, and innovation. The solicitation was revised for FY 2016. Additionally, to spotlight opportunities for mathematical sciences research in connection with DMREF, NSF supported a Symposium on Mathematical and Computational Aspects of Materials Science in FY 2015 at the Conference on Computational Science and Engineering of the Society for Industrial and Applied Mathematics (SIAM).[4] In FY 2016, DMREF will continue through a joint solicitation spanning MPS, ENG, and CISE.

Through FY 2015, NSF investments in smart systems were primarily in the areas of NRI and CPS. In FY 2015, NSF and the Office of the Secretary of Defense (OSD) signed an MOU to allow participation of the Department of Defense (DOD) in NRI. DARPA joined NRI, with a particular interest in validation of simulation methods; this topic is important to many manufacturing problems. The DOD/DARPA

[2] https://jimb.squarespace.com/sbsc-0315-workshop-report
[3] www.whitehouse.gov/sites/default/files/microsites/ostp/PCAST/amp20_report_final.pdf
[4] http://connect.siam.org/nsf-siam-symposium-on-mathematical-and-computational-aspects-of-materials-science-at-cse15/

participation in NRI adds to the existing partnerships with the National Institutes of Health (NIH), National Aeronautics and Space Administration (NASA), and U.S. Department of Agriculture (USDA). In FY 2016, DOE joined the NRI solicitation, and plans to fund research that focuses on the handling of high-hazard, high-consequence materials. Meanwhile, in the case of CPS, NSF previously partnered with the Department of Homeland Security (DHS) and the U.S. Department of Transportation to broaden the scope of the CPS solicitation. In FY 2015, the solicitation further broadened to include the participation of NASA and NIH. USDA is joining the CPS solicitation in FY 2016.

In FY 2015, NRI convened a workshop encouraging collaboration between the research communities of locomotion and manipulation, particularly in areas of planning, control, perception, and design. NRI ran a PI meeting that included industry participation, enabling PIs to discern gaps and promote exchange in research collaborations related to manufacturing. NSF also sponsored technical workshops in many of the key areas of CPS, including cybersecurity for CPS, critical research problems related to time with respect to CPS, and cloud computing for CPS. Additionally, NSF previously funded an NAS study on CPS education, seeking to understand current and future needs in education for CPS. NAS convened two workshops, including one in FY 2015, and issued an interim report in FY 2015.[5] A final report is anticipated in FY 2016. NSF also continued to support the CPS Virtual Organization (CPS VO), which is a broad community of interest for CPS researchers and developers. In FY 2015, NSF funded a proposal that will support the CPS VO as it evolves to a long-term, sustainable, community organization.

NSF held a workshop in FY 2015 to bring together researchers in the robotics and CPS communities to develop a set of foundational problems common to the two communities, as well as related challenges in autonomous systems. In FY 2016, NRI and CPS are continuing to support workshops to connect researchers across the robotics and CPS communities. During these meetings, attendees are developing a set of foundational research questions that will serve as a source of synergy between NRI and CPS, with an eye toward smart and autonomous systems. NSF is leveraging synergistic advances made in the earlier years of CEMMSS in NRI and CPS to place an emphasis on smart and autonomous systems in future years; these investments will include the traditional NRI and CPS areas, as well as an increased focus on the science of intelligent, autonomous systems.

In FY 2016, NSF is holding workshops that explore the research opportunities with NRI, CPS, and smart and autonomous systems in emerging research and application areas, including Smart and Connected Communities and the Internet of Things. NSF is holding workshops on new research advances needed in the technical and socio-technical understanding of the science of autonomy. These workshops are also helping to identify and pursue research gaps in the NSF portfolio for smart and autonomous systems. NSF is continuing to engage additional agency partners in joint solicitations for NRI, CPS, and the emerging area of smart and autonomous systems. For example, the CPS Strategic Steering Group will explore partnerships with mission agencies to facilitate translation of NSF-funded research into further development and deployment activities.

In FY 2016, NRI and CPS are increasing their focus on Transition to Practice (TTP), while continuing to maintain strong foundational research emphases. NRI is conducting a joint academic-industry-government workshop on evaluating alternative means of TTP. CPS is focusing on funding an I/UCRC, and on holding a session at the annual CPS PI meeting describing programs that enable TTP and showcasing successful CPS TTP efforts. NSF is further identifying opportunities for its researchers to engage with interagency-supported Institutes for Manufacturing Innovation.

[5] http://sites.nationalacademies.org/cstb/CurrentProjects/CSTB_084351

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- NSF will continue to support and emphasize research in cybermanufacturing systems to enable the networked integration of manufacturing machines, equipment, and systems into an increasingly accessible manufacturing service infrastructure. These investments will build upon initial activities within the advanced manufacturing, NRI, and CPS programs.
- NSF will continue to invest in the SNM program and advanced biomanufacturing.
- NSF will regularly perform gap and opportunity analysis of emerging research areas through support for workshops and studies, and through the Consortium for Advanced Manufacturing Foresights. This analysis will allow for prioritization of advanced manufacturing research topics that should receive increased investments. Based on the initial reports delivered in FY 2016, NSF will target investments in advanced biomanufacturing.
- NSF will continue to support DMREF through an annual solicitation. NSF will invest in infrastructure needs in support of DMREF.
- The most effective activities of FY 2016, as identified through evaluation of the NRI and CPS programs, will be continued and expanded in FY 2017, with an emphasis on areas of autonomous, intelligent systems.
- NSF will update the NRI and CPS solicitations, with new emphasis areas and/or solicitations based on gap analysis results and community input, especially relating to autonomous, intelligent systems. These solicitations will also be updated to suggest engagement of projects in cross-disciplinary workforce development (academic and industrial) as a key consideration in evaluating the broader impacts criterion. NSF will pursue involvement of additional agencies and international partners in NRI, CPS, and smart and autonomous systems appropriate to the program objectives.
- Building on the successes of the CPS and NRI programs, NSF will provide initial support for a new investment in Smart & Autonomous Systems. This investment area will focus on fundamental science and engineering addressing how intelligent physical systems sense, perceive, and operate in environments that are dynamic, uncertain, and unanticipated. This research activity will accelerate the transformation of static systems, processes, and edifices into intelligent, autonomous systems, such as those that can sense, learn, and adapt.
- NSF will sponsor workshops to examine the social, behavioral, and economic research issues associated with the design and deployment of smart and autonomous systems, such as smart buildings, smart communities, automated ground transportation, automated flight systems, disaster response and recovery, automation and extra-planetary science and exploration, automation and agriculture, construction automation, automated in-home services, and automation for law enforcement.
- PI meetings in NRI and CPS will continue, with areas of focus to include advancing cross-project interaction and collaboration; establishing safety standards and risk metrics; and planning for project transitions to partners, other projects, and industry.
- NSF will continue to hold, with its partner federal agencies, annual MGI/DMREF PI meetings.
- NSF will sponsor smart and autonomous systems challenges and competitions on topics requiring solutions and implementations that call upon multidisciplinary CEMMSS knowledge and systems integration. Such activities will involve existing NRI and CPS participants, as well as new participants in smart and autonomous systems.
- NSF will develop plans for data, software, and physical infrastructure for smart and autonomous systems, including NRI and CPS, with an emphasis on engaging the community through workshops in a discussion on requirements for such infrastructures and incentives for their use. NSF will fund at least two proposals in community testbed/infrastructure for NRI, CPS, and/or smart and autonomous systems.
- NSF will continue integration of functional components developed in the NRI, CPS, and smart and autonomous systems areas; promote designs for specific knowledge domains (e.g., manufacturing, healthcare); and promote high-risk, breakthrough applications and testbeds not previously possible.

FY 2018

While the NSF-wide CEMMSS investment will conclude at the end of FY 2018, the collaborative research activities of CEMMSS are expected to continue. Some specific investments will be assimilated back into core programs within and across participating directorates, while others will continue as crosscutting investments that span multiple NSF divisions and directorates. NSF will continue to develop several comprehensive, integrated programs across CEMMSS focus areas, such as cyber-manufacturing, advanced materials, and smart systems as well as further develop the new investment made in FY 2017 in Smart and Autonomous Systems. These investments will encourage new connections, discoveries and/or emerging fields of science and engineering.

It is expected that at the end of CEMMSS there will be evidence of an integrated and thriving ecosystem of cyber-enabled systems and advanced materials; improved interdisciplinary education based on longitudinal study of education outcomes; and advanced research infrastructure used by CEMMSS scientists and engineers. Such outcomes are in line with the overall goals of this investment.

Evaluation Framework

NSF engaged the Science and Technology Policy Institute (STPI) in FY 2012 to assist with the development of a plan for an impact assessment of the CEMMSS initiative. This formulation has entailed discussions with CEMMSS management, including division directors, as well as CEMMSS program directors. These discussions are also helping to formulate appropriate synergistic working groups spanning Smart Systems (including NRI, CPS, and smart and autonomous systems), Advanced Manufacturing, DMREF, and other related CEMMSS activities. The approach outlined below is being followed for CEMMSS program evaluation and assessment:

- A portfolio analysis was conducted to understand the scope and scheme of the overall CEMMSS initiative. The first step entailed gathering information and understanding the baseline portfolio, stakeholders, and related activities that NSF currently supports in the CEMMSS area. This included examining the current state of research in the research subfields and analyzing the various recommendations from federal advisory boards and the stakeholder communities on how future investments in CEMMSS areas should be focused.
- The results of the portfolio analysis are providing analytical input to support the CEMMSS coordination team's efforts to bring the community together to develop the interdisciplinary research questions for CEMMSS.
- STPI developed a logic model to help NSF track progress toward the major scientific, educational, and infrastructure objectives of CEMMSS.
- Given the diversity of research communities under the CEMMSS umbrella, NSF is sponsoring multiple workshops to understand research challenges and opportunities. The results of these workshops are being used to identify a clear set of research challenges that will be used by NSF to guide the CEMMSS investment area going forward.

By the end of FY 2016, a report summarizing the portfolio analysis and evaluation feasibility study will be submitted to the CEMMSS coordination team.

The progress of the implementation of CEMMSS also was monitored and reviewed quarterly as part of an agency performance goal in FY 2014 and FY 2015. For more information about monitoring key program investments, see the FY 2015 Annual Performance Report in the Performance chapter.