National
Science
Foundation

ERC ENGINEERING RESEARCH CENTERS

FY 2020
ENGINEERING RESEARCH CENTERS PROGRAM REPORT

CREATING
LEADING
TECHNOLOGIES,
EDUCATING
TECHNOLOGY
LEADERS

CONTENTS

ERCs: THE POWER OF BOLD VISION

ERCS BRING DIVERSE SCIENTIFIC AND ENGINEERING DISCIPLINES AND PEOPLE TOGETHER TO PURSUE CONVERGENT TEAM RESEARCH ON GRAND CHALLENGE-LIKE PROGRAMS IN AREAS THAT WILL LEAD TO STRONG SOCIETAL AND TECHNOLOGICAL IMPACT BY STIMULATING INNOVATION, TRANSFORMING INDUSTRIAL PRACTICES, AND/OR ESTABLISHING NEW INDUSTRIES.

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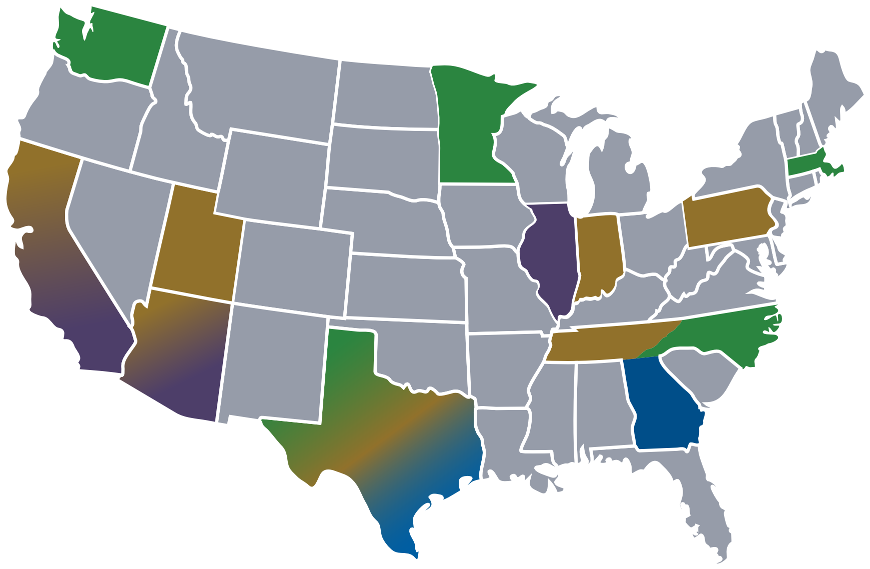
18 ERCs IN FY 2020

A landmark program in NSF Engineering, one that continues to evolve and thrive



🟩 Biotechnology & Health Care

🟫 Energy, Sustainability & Infrastructure

🟦 Advanced Manufacturing

🟪 Microelectronics, Sensing & IT

The National Science Foundation's Engineering Research Centers (ERC) Program was launched in 1985 as a new way for convergent research and education to foster technology and societal benefits. Since that time the world has seen sweeping change not only in technology but also in global economics and trade, energy and climate, and a wide range of societal trends. Throughout this time of change the ERC Program has adapted and flourished, playing a major role in revolutions in computing and microelectronics, communications, energy and infrastructure, manufacturing, biotechnology, healthcare, and many other fields of technology that enhance people's daily lives, connect communities, and strengthen the nation's economy, and global competitiveness. It has continued to be one of the National Science Foundation's brightest success stories and a landmark program in the Engineering Directorate.

Established at a time when the Nation's technological competitiveness was first coming under pressure from other countries, the ERC Program was designed to strengthen U.S. academic engineering research, education, and innovation. It did this by focusing on engineered systems, on strategic research planning, on cross-disciplinary team research (including undergraduate students as active participants), and on collaborative partnerships with industry. The new research model embodied by ERCs took hold and spread, giving rise to a "cultural change" in which interdisciplinary work and a focus on innovation became the standard model in our colleges of engineering. At the same time, the Program has been a leader in expanding access, diversity, and opportunity in engineering research and education and in developing a true culture of inclusion among all participants in the centers.

In 2021 the ERC Program consisted of 18 active centers, including four new ERCs added in FY 2020—for a total of 75 ERCs established since 1985. For an NSF investment of less than $2 billion in these centers over 35+ years, the return to the Nation has been estimated at well over $75 billion in new products and processes. On top of that, ERCs have given thousands of graduates the experience they need to hit the ground running as leaders in technology, engineering, and innovation. Today, NSF's ERC Program is stronger than ever, a testament to the power of NSF's commitment to strategic investments in the nation's science and engineering enterprise and workforce. In a world of ever-accelerating change, the ERC Program continues to be a key component of how we meet today's challenges and build a brighter tomorrow.

Sethuraman "Panch" Panchanathan
Director, National Science Foundation

Susan Margulies
Susan Margulies
Assistant Director for Engineering, NSF

1. THE ERC STORY

THE GOAL

TO CREATE INTERDISCIPLINARY ACADEMIC RESEARCH ENVIRONMENTS WITH A CULTURE THAT ACTIVELY STIMULATES TECHNOLOGICAL INNOVATION THROUGH PARTNERSHIPS WITH ALL RELEVANT STAKEHOLDERS BY MEANS OF COLLABORATIVE, TEAM-BASED CONVERGENT RESEARCH ON IMPORTANT AND COMPLEX SOCIETAL PROBLEMS, WHILE PRODUCING GRADUATES WHO REFLECT THE NATION'S RICH DIVERSITY OF TALENT TO BECOME CREATIVE, COMPETITIVE INNOVATORS IN THE GLOBAL ECONOMY.

THE 4 FOUNDATIONAL COMPONENTS of a Gen-4 ERC

- 🟦 Convergent Research
- 🟫 Workforce Development
- 🟩 Culture of Inclusion
- 🟦 Innovation Ecosystem

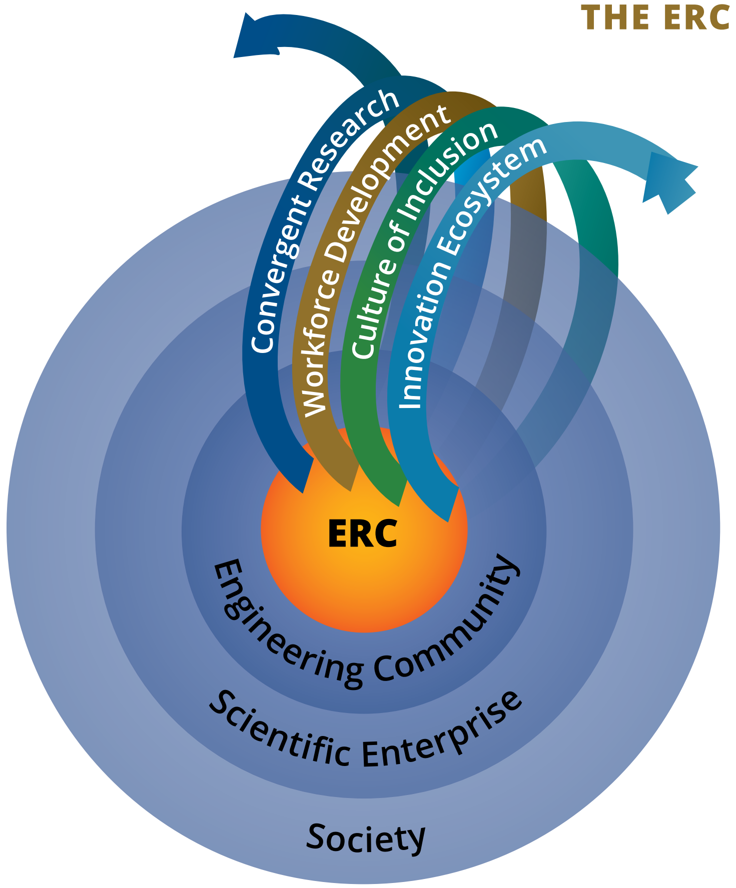


***Figure 1-1:** The four foundational components of a Gen-4 ERC*

The National Science Foundation-sponsored Engineering Research Centers (ERCs), first awarded in 1985, are interdisciplinary, multi-institutional centers that bring academia, industry, and government together in partnership to produce transformational engineered systems and engineering graduates who are adept at innovation and primed for leadership in the global economy. Over the past 36 years this partnership has produced a wide range of engineered systems and other technologies aimed at spawning entire new industries or radically transforming the product lines, processes, and practices of existing industries. At the same time it has produced new generations of engineering graduates who are highly innovative, diverse, globally engaged, and effective as technology leaders in industry.

Because of the critical role that ERCs play in academe by integrating research, education, and industrial collaboration, NSF has long viewed these centers as "disruptive" change agents for academic engineering programs. It is no exaggeration to say that since their inception the ERCs have indeed changed the culture of academic engineering to include active collaboration across engineering and science disciplines, a greater focus on innovation and engineered systems, and closer interaction with industry.

Over the years, NSF has continually refined the goals and purposes of the ERC program to meet the evolving needs of industry and the Nation. Relying in part on guidance provided by the National Academies of Sciences, Engineering, and Medicine (NASEM) in its 2017 report, *A New Vision for Center-based Research*, in FY 2020 NSF initiated the fourth generation (Gen-4) of ERCs, intended to meet the needs of industry in an increasingly global economy where the U.S. competitive advantage lies in its capacity to innovate. The Gen-4 ERC program builds on the proven core features of previous generations of ERCs by continuing to advance transformational engineered systems and by producing graduates who will be creative innovators in the global economy.

ALL GEN-4 ERCs HAVE THE FOLLOWING FOUR "FOUNDATIONAL COMPONENTS"

Figure 1-1 depicts how these components combine to support the engineering community, the scientific/engineering research enterprise, and society as a whole.

1. **Convergent Research** that has the strong potential to lead to transformative solutions or new fields of study.

2. **Engineering Workforce Development** that strengthens a robust spectrum of engineering education and pathways occurring at all levels of the Center and that provides opportunities for engagement by all ERC members including students, faculty, and external partners.

3. **Diversity and Culture of Inclusion** within an ERC and its various teams that reflects an environment in which all members, including those from groups traditionally underrepresented in engineering, feel valued and welcomed.

4. **An Innovation Ecosystem** that involves trusted partners who work together to create and enhance the capacity for innovation by finding new ways to deliver value with positive societal impact. This includes implementing effective translational efforts from ideation to implementation, workforce development in support of the enterprise, and deliberate efforts to attract funding and resources.

An important indicator of the success of the NSF's ERC Program is its longevity and continued health. Since 1985, a total of 72 ERCs and 3 Earthquake ERCs have been formed. Of these, 47 have successfully "graduated" from their ten-year term of ERC Program support. Out of those 47, it is notable that 38 still exist as a center, with some degree of "ERC-ness" in that a group of faculty pursue cross-disciplinary research on engineered systems with the collaboration and support of industry. This represents 81% of all graduated centers. Figure 1-2 illustrates some of the achievements of the Program since its inception.

A map of the current and graduated ERCs is shown in Figure 1-3. The current ERCs are listed here by technology cluster. The map can be seen at **https://erc-assoc.org/content/all-current-and-graduated-ercs-august-2021** and abstracts of the centers with their partner institutions can be seen at **http://www.erc-assoc.org/centers#**.

This FY 2020 ERC Program Report describes significant events for the Program and for the individual ERCs in every area of their activity.

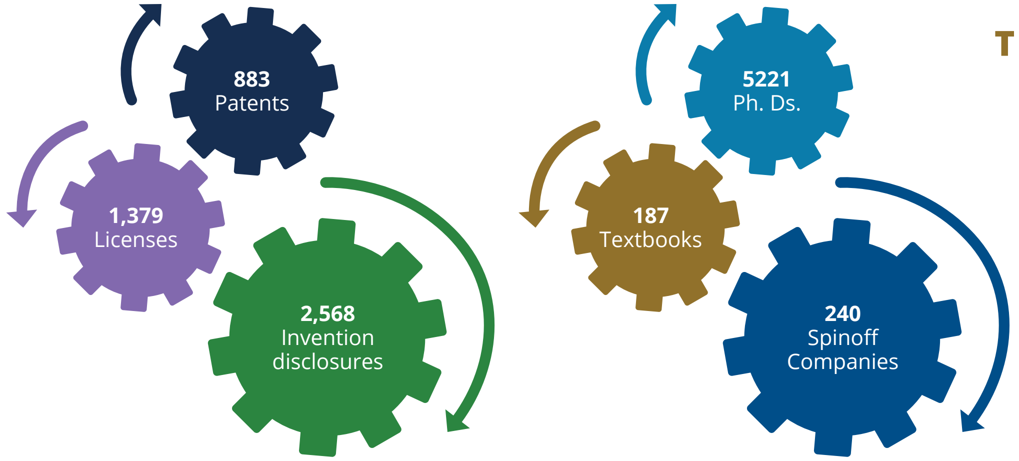


Figure 1-2: *A snapshot of ERC Program achievements since 1985.*

ERCs BY TECHNOLOGY CLUSTER

ADVANCED MANUFACTURING

ERC for Cell Manufacturing Technologies (CMaT), Class of 2017
Georgia Institute of Technology (lead institution) in partnership with the University of Georgia, the University of Wisconsin-Madison and the University of Puerto Rico-Mayaguez *(Mission: To transform the manufacture of cell-based therapeutics into a large-scale, low-cost, reproducible, and high-quality engineered process for broad industry and clinical use)*

Nanosystems ERC for Nanomanufacturing Systems for Mobile Computing and Mobile Energy Technologies (NASCENT), Class of 2012
The University of Texas at Austin (lead institution) in partnership with the University of New Mexico and the University of California, Berkeley *(Mission: To take nanoscience discoveries from the lab to the marketplace through the creation of high-speed, low-cost, reliable nanomanufacturing systems)*

BIOTECHNOLOGY & HEALTH CARE

Nanosystems ERC for Cellular Metamaterials (CELL-MET), Class of 2017
Boston University (lead institution) in partnership with the University of Michigan and Florida International University *(Mission: Create scalable, low-cost technologies for growing clinically significant cardiac tissues from cell-level building blocks)*

ERC for Advanced Technologies for Preservation of Biological Systems (ATP-Bio), Class of 2020
University of Minnesota (lead institution) in partnership with Massachusetts General Hospital, the University of California, Berkeley, and the University of California, Riverside *(Mission: Dramatically advance the field of biopreservation to achieve major societal benefits)*

Nanosystems ERC for Advanced Self-Powered Systems of Integrated Sensors and Technologies (ASSIST), Class of 2012
North Carolina State University (lead institution) in partnership with Pennsylvania State University, Florida International University, and University of Virginia *(Mission: Harness nanotechnology to improve global health by enabling correlation between personal health and personal environment and by empowering patients and doctors to manage wellness and improve quality of life)*

ERC for Precise Advanced Technologies and Health Systems for Underserved Populations (PATHS-UP), Class of 2017
Texas A&M University (lead institution) in partnership with the University of California at Los Angeles, Rice University and Florida International University *(Mission: To change the paradigm for the health of underserved populations by engineering transformative, affordable health care technologies and systems at the point of care)*

BIOTECHNOLOGY & HEALTH CARE (cont'd.)

NSF Engineering Research Center for Neurotechnology (CNT), Class of 2011
University of Washington in partnership with the Massachusetts Institute of Technology and San Diego State University *(Mission: Engineer the interface between human brains and technology by using mathematical, computational, and engineering approaches to deliver neural-inspired and neural assistive sensorimotor devices)*

ENERGY, SUSTAINABILITY, AND INFRASTRUCTURE

ERC for Quantum Energy and Sustainable Solar Technologies (QESST), Class of 2011
Arizona State University (lead institution) in partnership with the California Institute of Technology, the University of Delaware, the Georgia Institute of Technology, the University of Houston, the Massachusetts Institute of Technology, and the University of New Mexico (co-funded with DOE) *(Mission: Transform the existing electricity generation system, making it sustainable, ubiquitous, and multifunctional by developing photovoltaic and quantum energy converters that fundamentally alter how energy is generated)*

ERC for Bio-mediated and Bio-inspired Geotechnics (CBBG), Class of 2015
Arizona State University (lead institution) in partnership with the Georgia Institute of Technology, New Mexico State University, and the University of California, Davis *(Mission: To understand and harness the scientific processes and principles of natural phenomena to develop more sustainable, safer, less intrusive, more resilient civil infrastructure systems)*

ERC for the Internet of Things for Precision Agriculture (IoT4Ag), Class of 2020
University of Pennsylvania (lead institution) in partnership with Purdue University, the University of California, Merced, and the University of Florida *(Mission: Transform the future of agriculture by creating and translating to practice Internet of Things (IoT) technologies for precision agriculture)*

ERC for Innovative and Strategic Transformation of Alkane Resources (CISTAR), Class of 2017
Purdue University (lead institution) in partnership with the University of New Mexico, Northwestern University, the University of Notre Dame and the University of Texas at Austin *(Mission: Provide the technological innovation and diverse workforce needed to responsibly realize the potential of shale hydrocarbons)*

Nanosystems ERC for Nanotechnology Enabled Water Treatment Systems (NEWT), Class of 2015
Rice University (lead institution) in partnership with Arizona State University, the University of Texas at El Paso and Yale University *(Mission: Apply nanotechnology to develop transformative and off-grid water treatment systems that both protect human lives and support sustainable economic development)*

ERC for Re-Inventing America's Urban Water Infrastructure (ReNUWIt), Class of 2011
Stanford University (lead institution) in partnership with the University of California, Berkeley, Colorado School of Mines, and New Mexico State University *(Mission: Facilitating the transition of water systems to a new state in which they consume less energy and resources while continuing to meet the needs of urban users and aquatic ecosystems)*

ERC for Ultra-wide Area Resilient Electric Energy Transmission Networks (CURENT), Class of 2011
University of Tennessee–Knoxville (lead institution) in partnership with Northeastern University, Rensselaer Polytechnic Institute, and Tuskegee University (co-funded with DOE) *(Mission: Design the nation's future electric power transmission system for greater efficiency, higher reliability, lower cost, and better accommodation of renewable sources)*

ERC for Advancing Sustainability through Powered Infrastructure for Roadway Electrification (ASPIRE), Class of 2020
Utah State University (lead institution) in partnership with Purdue University, the University of Colorado, and the University of Texas at El Paso *(Mission: To improve health and quality of life by catalyzing sustainable and equitable electrification in transportation)*

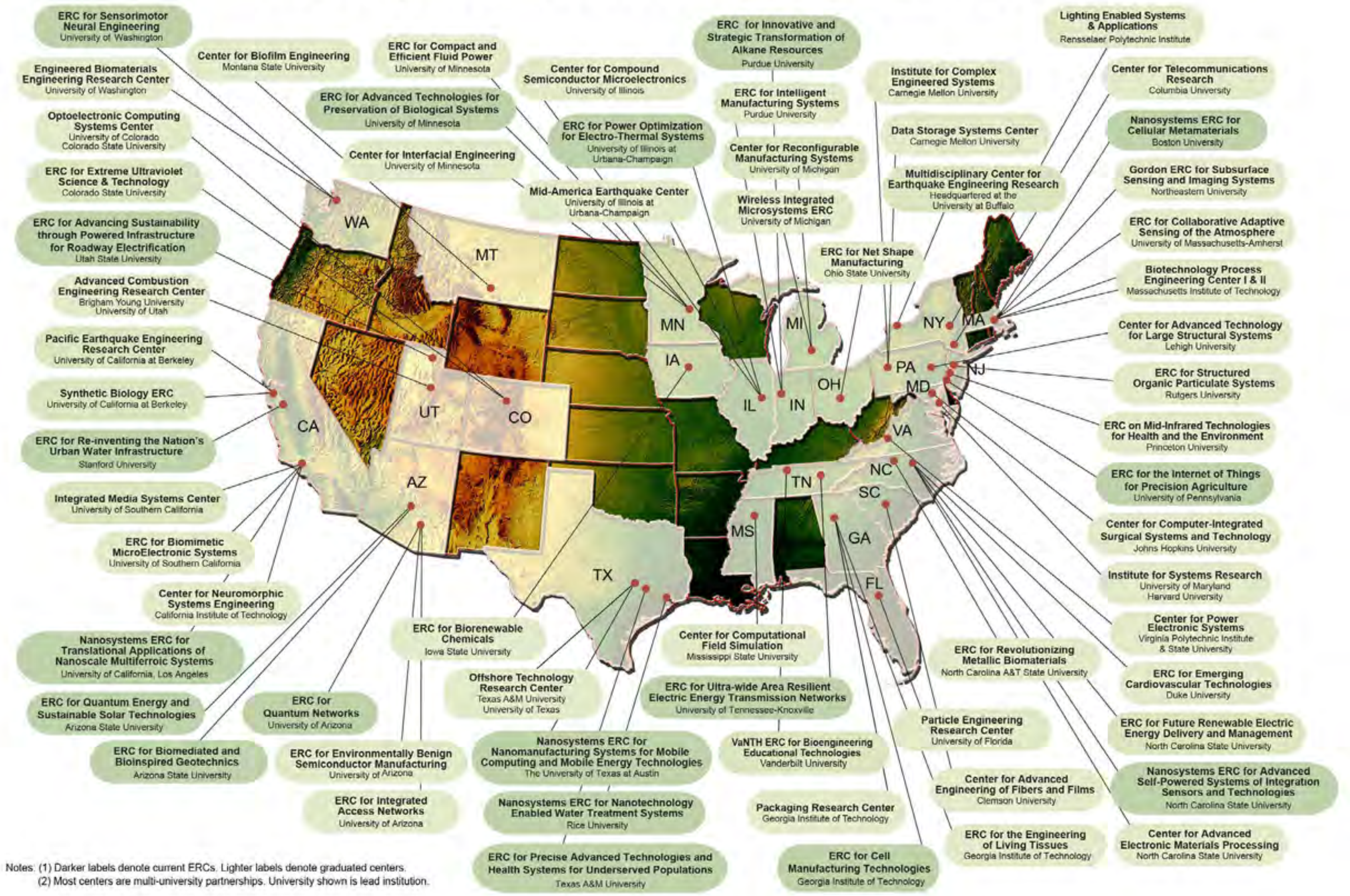
MICROELECTRONICS, SENSING, AND INFORMATION TECHNOLOGY

ERC for Quantum Networks (CQN), Class of 2020
University of Arizona (lead institution) in partnership with Harvard University, Massachusetts Institute of Technology, and Yale University *(Mission: To lay the technical and social foundations of the quantum Internet)*

Nanosystems ERC for Translational Applications of Nanoscale Multiferroic Systems (TANMS), Class of 2012
University of California, Los Angeles (lead institution) in partnership with Cornell University, the University of California, Berkeley, California State University, Northridge; Northeastern University, and the University of Texas at Dallas *(Mission: Engineer an efficiency, size, and power revolution in miniature electronic devices by using recent discoveries regarding nanoscale multiferroic materials)*

ERC for Power Optimization for Electro-Thermal Systems (POETS), Class of 2015
University of Illinois at Urbana-Champaign in partnership with Howard University, Stanford University, and the University of Arkansas *(Mission: Enable electrified mobility in air, highway, and off-road vehicles through dramatically increased power density)*

NSF ENGINEERING RESEARCH CENTERS 1985-2021



Notes: (1) Darker labels denote current ERCs. Lighter labels denote graduated centers.
(2) Most centers are multi-university partnerships. University shown is lead institution.

Figure 1-3: *All ERCs, past and present, totaling 75 (including three Earthquake ERCs)*

2. HIGHLIGHTS OF FY 2020

ON THE FIFTEENTH ANNIVERSARY OF THE NSF's ERC PROGRAM, IN 2000, THE THEN-DIRECTOR OF NSF, DR. RITA COLWELL, PROCLAIMED, "ONE OF THE MOST DARING EXPERIMENTS EVER UNDERTAKEN BY THE FOUNDATION HAS BEEN THE ERC PROGRAM. THIS LANDMARK PROGRAM CHALLENGES THE VERY NATURE OF ACADEMIC ENGINEERING RESEARCH, ENGINEERING EDUCATION, AND UNIVERSITY–INDUSTRY COLLABORATION. I AM PLEASED TO REPORT THAT THE EXPERIMENT HAS BEEN AN UNQUALIFIED SUCCESS." TWENTY YEARS LATER, THIS "DARING EXPERIMENT" CONTINUES TO BREAK NEW GROUND AND ACHIEVE AT A HIGH LEVEL.

THE ERC PROGRAM SUCCEEDED in managing the dislocations and uncertainty of the COVID-19 pandemic at the Center and Program levels.

NSF's ERC Program will soon be approaching its 40th year. While many federal government programs of that age have long been "sunsetted," with 18 high-quality centers in operation as of the end of FY 2020 this program is as vigorous and dynamic as ever. Four new centers were funded in August 2020. These four new Gen-4 ERCs were selected out of a large number of proposals received. Clearly, being an Engineering Research Center is still a coveted honor among U.S. universities.

Some highlights of FY 2020 are briefly described here.

RESEARCH ADVANCES

Using 3-D bioprinting to create badly needed artificial organs, such as hearts, for transplant would save thousands of lives annually. But 3-D printing of human tissue is in its infancy and currently lacks several vital functions. One is blood supply. A new process developed by researchers at the **Nanosystems ERC for Cellular Metamaterials** (CELL-MET) prints vascular channels directly into living tissue and thus represents an important step toward the creation of viable, fully functioning human organs.

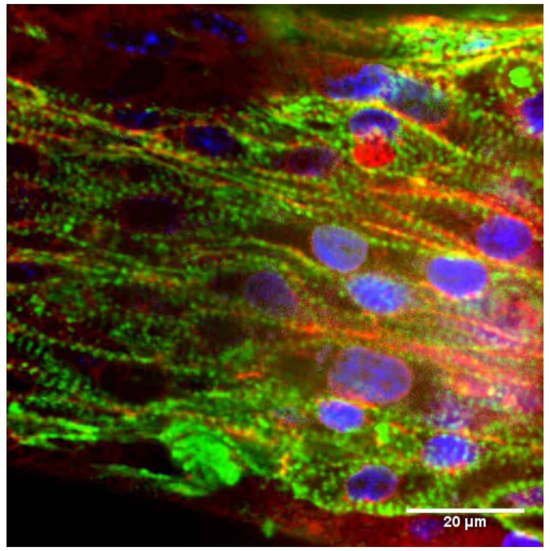


Figure 2-1: *An image of stained engineered cardiac tissues (Credit: CELL-MET)*

Over the lifetime of the NSF's ERC Program, some ERCs have focused on the understanding and control of biofilms—bacterial coatings that grow on wet surfaces of all kinds, from pipelines to teeth, and impede their effective or healthy functioning. The latest advance in this area was made by researchers with the **Nanotechnology Enabled Water Treatment** (NEWT) ERC. They designed transparent polymer coatings that emit germicidal ultraviolet light that inhibits the growth of *E. coli* bacteria in water. Side-emitting-optical fibers (SEOFs) coated with the polymer create a flexible, germ-killing "glowstick" that can be inserted into narrow-diameter channels such as piping or tubing, disrupting bacterial growth and eliminating the biofilm.

ENGINEERING WORKFORCE DEVELOPMENT

Over 2,500 students (from precollege to post-doctoral) participated directly in ERC education programs during FY 2020, with 15 ERCs reporting. Over 55,000 K-12 and community college students attended ERC-sponsored educational outreach events during the period. Collectively, 306 ERC-affiliated students received degrees in FY 2020, of whom 54% entered industry. By comparison, 41% entered academe.

Teachers and students participated in a multi-tiered mentoring model, mentored by researchers at the **Center for Power Optimization of Electro-Thermal Systems** (POETS), that included research presentations to their local school board and to a national conference. POETS was awarded a second Research Experience and Mentoring (REM) supplement, which supported the exploration of the multi-tiered mentoring model.

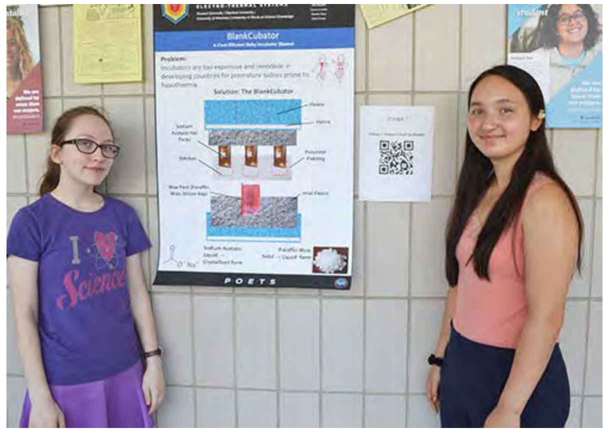


Figure 2-2: *High school students display their team's research poster. (Credit: POETS ERC)*

Participating students learned how to conduct research within a team, use scientific articles as a foundational guide, and solve problems as a group. Students reported feeling empowered as experts when explaining their research to board members and to a large audience at the 2020 Emerging Research Conference in Washington, D.C.

During their visit to the nation's capital they visited Howard University, a POETS partner, to speak with Center graduate students about their career paths. They also met with Sen. Tammy Duckworth's policy expert and discussed education issues relevant to students of color, and met with Rep. Rodney Davis as well.

Educators from the **Precise Advanced Technologies and Health Systems for Underserved Populations** (PATHS-UP) ERC developed new courses and fast-track Bachelors-to-Masters curricula. The coursework, which includes three new courses, a one-year capstone design project, and modules for six existing courses, prepares students for careers in the development of enabling technologies and advanced engineered systems leading to better healthcare.

Texas A&M University, a PATHS-UP partner institution, began offering two new five-year combination degree options that allow students to earn a Bachelor of Science in Industrial Engineering while also earning a Master of Public Health in Occupational Safety and Health. Students who complete this program graduate with both degrees in just five years.

DIVERSITY AND CULTURE OF INCLUSION

Although from their outset the ERCs have pursued efforts to increase the participation of women, underrepresented racial minorities, and Hispanics and Latinos in the centers, over the years and across each successive generation of ERCs these efforts have steadily increased. In FY 2020, the participation of all these groups exceeded national averages for engineering education programs—in some cases by a considerable margin. For example, 53% of ERC undergraduate students were women, compared to about 24% of all undergraduate engineering students nationwide. Twenty-two percent of ERC master's candidates were Hispanic or Latino, compared to 11% nationwide.

Figure 2-3: *Student attendees at the 2020 ERC Program biennial meeting. (Credit: ASEE)*

In June 2020 the **Cell Manufacturing Technologies** (CMaT) ERC participated in the nationwide #ShutDownSTEM movement, organized by the American Association for the Advancement of Science (AAAS). #ShutDownSTEM invited researchers and scientists to create specific action plans for ending racism in scientific communities. By interrupting "business as usual" for a day, the participants hoped to foster awareness that would help increase the representation, retention, and recruitment of Black scientists to academia and industry. CMaT participants developed and hosted a Center-wide Diversity and Inclusion (D&I) Training entitled, "Conversation that Motivates Allies to Take ACTION" (CMaT Training). Due to the pandemic, this mentor training program was made available virtually to all Research Experience and Mentoring (REM), Research Experience for Undergraduates (REU), and Research Experience for Teachers (RET) mentors at each of the four CMaT partner universities. By acting as mentors to other scientists in the community, CMaT's highly inclusive, D&I-trained groups will disseminate best practices that can be adapted to the recruitment, admission, and retention of underrepresented students.

During FY 2020 a new Best Practices chapter (chapter 7) on "Diversity and Culture of Inclusion" was begun. It was later completed and published on the ERC Association website.

INNOVATION ECOSYSTEM

Industrial participation in strategic planning and funding of both research and education at ERCs is an essential part of what defines these centers—and is at the core of the "innovation ecosystem" that the ERCs strive to build and maintain. In FY 2020, collectively the 15 ERCs had 278 total industrial memberships. This ERC/industry collaboration results in a variety of forms of technology translation. For example, in FY 2020 (during a pandemic) 12 new companies spun off from the ERCs, 57 inventions were disclosed, and 11 licenses to ERC-developed technologies were issued. Innovative products and processes derived from ERC discoveries continued to be put into practice.

Figure 2-4: *Students present their concept for an iPhone app to a panel of industry judges. (Credit: Marcus Donner, CNT)*

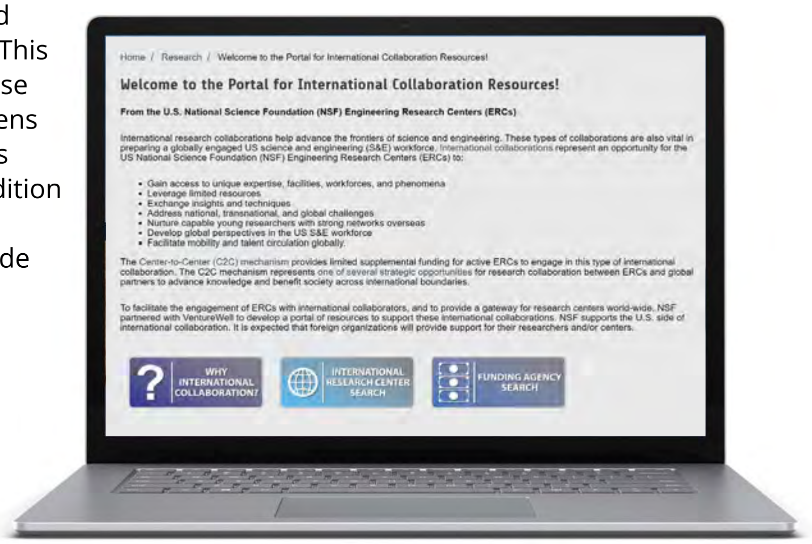
As just one example, SandBox Semiconductor, a Texas-based company founded by an alumna of the **Nanomanufacturing Systems Center** (NASCENT) ERC, won two Small Business Innovation Research (SBIR) awards that will further the startup's work on innovative software solutions for the manufacturing industry, in particular the development of next-generation manufacturing technologies for semiconductor devices through the application of physics-based and artificial intelligence/machine learning-based models.

The newest generation of ERCs, Gen-4, assemble their innovation ecosystem not only with industry partners but with any type of stakeholders that have missions related to the scope of interest of the ERC.

Sometimes ERCs catalyze even broader collaborations, facilitating networking among researchers internationally. For example, the **Quantum Energy and Sustainable Solar Technologies** (QESST) ERC, headquartered at Arizona State University (ASU), has evolved a global research practitioner network for sustainable energy solutions that attracts community participation in innovations that directly address social gains. Prior QESST research had demonstrated the importance of using user-centered design methods to create solar energy systems that enhance the social value of energy and disrupt the energy-poverty nexus. Through the help of the QESST network, small businesses and non-governmental organizations are building capacity by leveraging user-centered design practices for solar energy projects. Researchers in ASU's Grassroots Energy Innovation Laboratory and universities in Europe, Canada, India, the Philippines, Nepal, and Pakistan have participated with organizations around the globe demonstrating the need and demand for more feasible and humane energy innovations. As a result of QESST's global research practice network, community partnerships focused on sustainable energy have taken place in Brazil, India, Uganda, Sierra Leone, Puerto Rico, Bolivia, Nepal, Pakistan, the Philippines, and Canada's First Nations.

ACADEMIC PARTNERSHIPS: GLOBAL COLLABORATION

All ERCs are multi-institutional (having a lead institution and one or more core partners). This diversity draws in a greater scope of expertise for collaboration in the research and broadens the educational impact of the centers across more institutions and more students. In addition to the core partners, all ERCs are connected with several outreach institutions that provide a third circle of impact. In FY 2020 a total of 739 institutions, including 54 lead and core partners, were participating in the 18 ERCs. Among the outreach institutions were 54 foreign institutions in 16 countries—an indication of the global vision of the ERCs.


Home / Research / Welcome to the Portal for International Collaboration Resources!

Welcome to the Portal for International Collaboration Resources!

From the U.S. National Science Foundation (NSF) Engineering Research Centers (ERCs)

International research collaborations help advance the frontiers of science and engineering. These types of collaborations are also vital in preparing a globally engaged US science and engineering (S&E) workforce. International collaborations represent an opportunity for the US National Science Foundation (NSF) Engineering Research Centers (ERCs) to:

- Gain access to unique expertise, facilities, workforces, and phenomena
- Leverage limited resources
- Exchange insights and techniques
- Address national, transnational, and global challenges
- Nurture capable young researchers with strong networks overseas
- Develop global perspectives in the US S&E workforce
- Facilitate mobility and talent circulation globally.

The Center-to-Center (C2C) mechanism provides limited supplemental funding for active ERCs to engage in this type of international collaboration. The C2C mechanism represents one of several strategic opportunities for research collaboration between ERCs and global partners to advance knowledge and benefit society across international boundaries.

To facilitate the engagement of ERCs with international collaborators, and to provide a gateway for research centers world-wide, NSF partnered with VentureWell to develop a portal of resources to support these international collaborations. NSF supports the U.S. side of international collaboration. It is expected that foreign organizations will provide support for their researchers and/or centers.

***Figure 2-5:** The new Center-to-Center (C2C) collaboration program was disseminated in 2020 through a Portal for International Collaboration*

The newly formed **Center-to-Center** (C2C) mechanism for collaboration between ERC and foreign research institutions was broadened during FY 2020 to a worldwide scope, with the setting up of a dedicated area of the ERC Association website as a Portal for International Collaboration Resources through which hundreds of foreign research centers were invited to invited to join in collaborative research partnerships with ERCs.

CROSS-CENTER KEY EVENTS

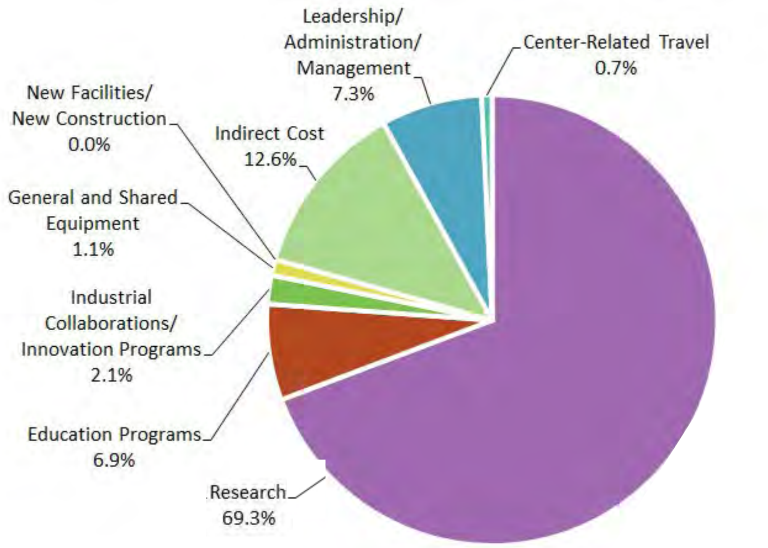
In FY 2020, four new ERCs were established to become the Class of 2020, the first cohort of Gen-4 ERCs. They are:

- **ERC for Advanced Technologies for Preservation of Biological Systems** (ATP-Bio) – University of Minnesota, lead institution, in partnership with Massachusetts General Hospital, the University of California, Berkeley, and the University of California, Riverside
- **ERC for Advancing Sustainability through Powered Infrastructure for Roadway Electrification** (ASPIRE) – Utah State University, lead institution, in partnership with Purdue University, the University of Colorado, and the University of Texas at El Paso
- **ERC for the Internet of Things for Precision Agriculture** (IoT4Ag) – University of Pennsylvania, lead institution, in partnership with Purdue University, the University of California, Merced, and the University of Florida
- **ERC for Quantum Networks** (CQN) – University of Arizona, lead institution, in partnership with Harvard University, Massachusetts Institute of Technology, and Yale University

ERC PROGRAM MANAGEMENT

Total direct support for the 15 ERCs from all sources in FY 2020 was $123M, an average of $8.2M per center (up from $6.6M in FY 2019). See Figure 2-6. Of this, the great majority (69.3%) was allocated to research. The ERC Program budget at NSF in FY 2020 was $54.61M.

Throughout FY 2020, Kon-Well Wang, a Professor of Mechanical Engineering at the University of Michigan, served as Division Director of the Division of Engineering Education and Centers, in which the ERC Program is housed.



Direct Support Total: $123,196,745

***Figure 2-6:** Functional Budgets of ERCs in FY 2020*

Beginning in March 2020, as the COVID-19 epidemic surged into a worldwide pandemic, NSF began to operate virtually. All in-person office operations ceased in April 2020 and remote management of the ERC Program via Zoom and other virtual meeting platforms became the norm, not only for NSF and the ERC Program but for all the ERCs as well.

In August 2020 a book-length history of the ERC Program entitled *Agents of Change: NSF's Engineering Research Centers—A History* was completed, published on the ERC Association website, and disseminated by email notice to a worldwide audience.

BIENNIAL MEETING

The NSF ERC Program Biennial Meeting was held on October 23-25, 2019. A highlight of the meeting was a keynote plenary talk given by Kelvin Droegemeier, then-Director of the White House Office of Science and Technology Policy. Dr. Droegemeier had once been Deputy Director of the ERC for Collaborative Adaptive Sensing of the Atmosphere. A major theme of the meeting was on ways to improve the diversity of students, faculty, and staff and to strengthen the culture of inclusion within the centers.

3. RESEARCH ADVANCES

ERCS BRING DIVERSE ENGINEERING AND SCIENTIFIC DISCIPLINES TOGETHER TO PURSUE CONVERGENT TEAM RESEARCH ON LARGE, GRAND CHALLENGE-LIKE PROBLEMS IN AREAS THAT WILL LEAD TO STRONG SOCIETAL AND TECHNOLOGICAL IMPACT BY STIMULATING INNOVATION, TRANSFORMING INDUSTRIAL PRACTICES, AND/OR ESTABLISHING NEW INDUSTRIES.

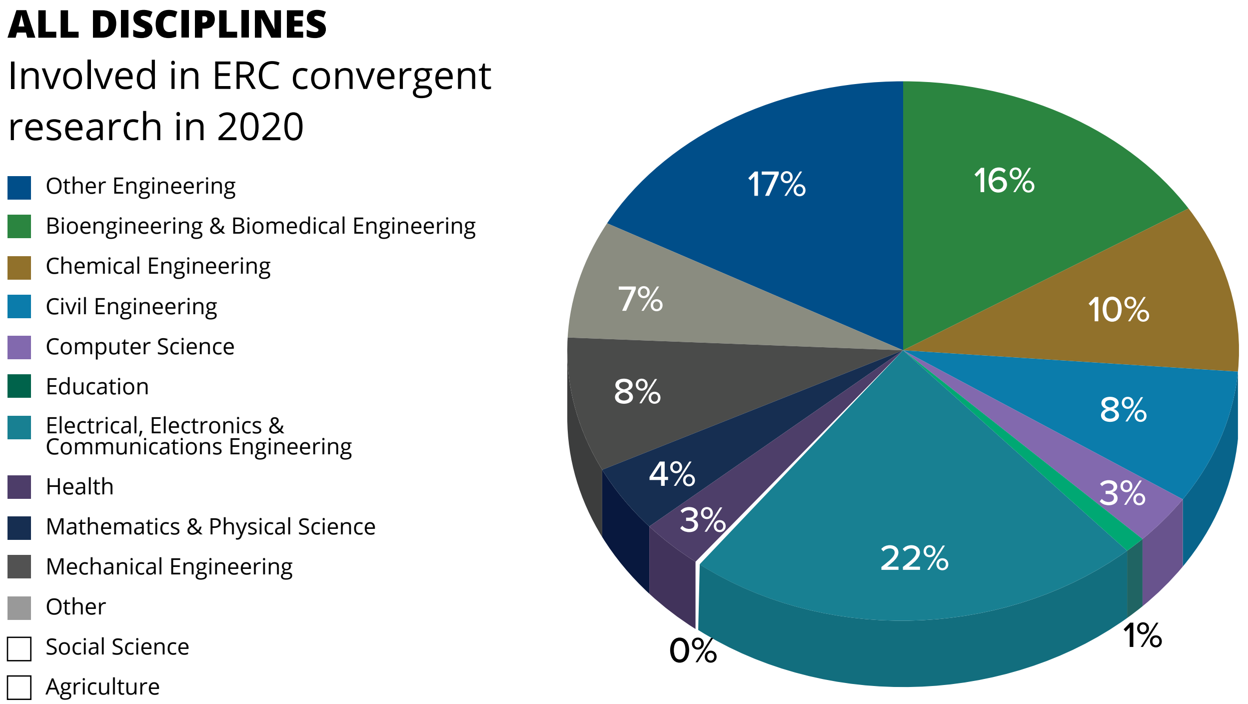
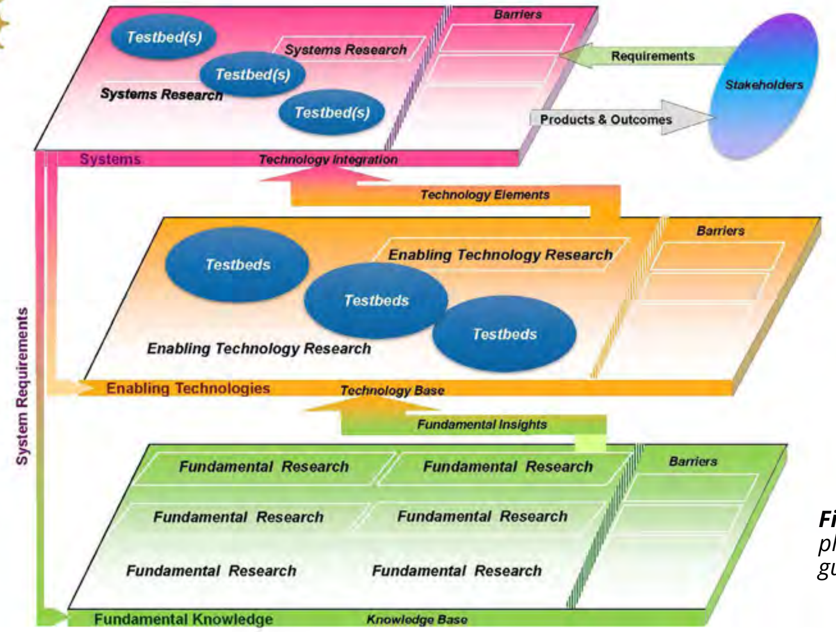


Figure 3-1: *All disciplines involved in ERC research in FY 2020*

Research is one of the four foundations of an ERC, along with engineering workforce development, a culture of diversity and inclusion, and value creation within an innovation ecosystem. Indeed, it is the central activity without which no other component of an ERC can function. Research at an Engineering Research Center has a special configuration that is unique to these centers. It is convergent, in that it brings together teams of experts from multiple disciplines who collaborate deeply. It is driven by a focus on a high-impact societal or technological need. It blends fundamental work with more technology-focused efforts aimed at proving concepts underlying a new technological system and overcoming barriers to achieving it; it follows a strategic plan developed in concert with industry; and it is integrated with education programs offered through the center and its partner universities.

The disciplines contributing to ERC research are not restricted to engineering alone; they draw from all areas of the physical, biological/biomedical, and social sciences, business, and even the arts and humanities that have a useful contribution to make in progressing toward the systems goal. Figure 3-1 shows the wide range of disciplines that were actively involved in ERC research in FY 2020 across all the centers.

A primary organizing principle for the research at ERCs is a "strategic framework" that was developed by NSF program management in the early years of the program and has been refined over time into a specific and yet flexible concept describing the relationships between fundamental research, research on enabling technologies, and the system-level integration of these components into useful deliverables. This "three-plane chart" is a template on which every ERC bases its strategic plan for research. Each ERC devises its own custom-tailored variant of the chart as a roadmap for its work. Figure 3-2 shows the generic three-plane chart in use in FY 2020.



3-Plane Chart

Figure 3-2: *The 3-plane strategic planning chart employed to guide ERC research*

Like all academic research units and academic researchers, ERC faculty and to some extent the ERCs themselves are "graded" in part according to their research output and the publication of research results. In addition, a major objective of the ERCs is to stimulate the emergence of new industries and/or transform current industrial practices.

For both these reasons, disseminating the results of their research is a high priority for ERCs. As Table 3-1 shows, in 2020 alone the 15 ERCs averaged nearly 70 articles per center published in peer-reviewed journals and conference proceedings—of which about 40% included ERC students among the co-authors. Over the life of the program the total output of ERC publications has numbered well over 40,000. In addition, many thousands of symposia, workshops, and short courses have been organized by the centers, further expanding the "culture change" originally envisioned for this ground-breaking NSF program.

EXAMPLE ACHIEVEMENTS IN RESEARCH

The myriad of research advances achieved by the ERCs and reported in FY 2020 can perhaps be best illustrated by examples, chosen from the four technology areas or "clusters" into which the ERCs are divided.

Table 3-1: *ERC Information Dissemination (FY 1985-2020)*

	FY 2020 (15 ERCs)		FY 2015-2019 Annualized		FY 1985-2020 (65 ERCs)
Peer-Reviewed Publications (Total)	**Total**	**Per Center**	**Total**	**Per Center**	**Total**
Journals**	668	45	918	51	24,685
Conference Proceedings**	316	21	519	29	18,435
Trade Journals	4	<1	10	1	644
Coauthorized With ERC Students	411	27	582	33	12,993
Peer-Reviewed Publications (Total)	**Total**	**Per Center**	**Total**	**Per Center**	**Total**
Education and Colloquia	644	43	922	52	17,612
Workshops, Short Courses, and Webinars	467	31	370	21	6,017

* Does not include centers from the Earthquake Technology Sector

** Includes publications that result from center support, associated projects, and sponsored projects

BIOTECHNOLOGY AND HEALTH CARE

Using 3D Bioprinting to Create Functioning Human Tissues and Organs

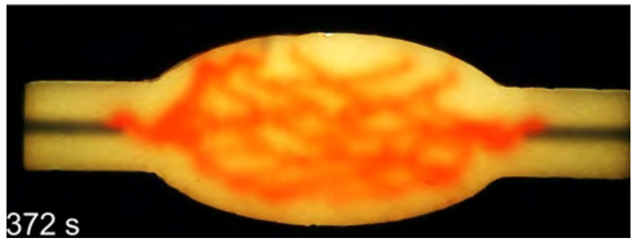


Figure 3-3: *3D-printed blood vessel networks can be integrated into living cardiac material. (Credit: CELL-MET)*

Artificially grown human organs would provide urgently needed help for thousands of people on organ transplant wait lists. One possible solution is tissue engineering using 3D bioprinting. But 3D-printed human tissue currently lacks the cellular density and functions needed for use in organ repair and replacement. In particular, tissue engineering is unable to provide sufficient blood supply after implantation. Researchers at the **Nanosystems ERC for Cellular Metamaterials** (CELL-MET), led by Boston University, developed a 3D bioprinting method that recreates the complex network of blood vessels in the human heart, allowing bioengineered cardiac tissue to remain viable after implantation.

The process developed by the CELL-MET team, called sacrificial writing into functional tissue (SWIFT), prints vascular channel networks directly into living tissue (Figure 3-3). This enables the creation of larger tissues approximating the size and function of organs, including heart tissue that beats on its own over a seven-day period. This technique may ultimately be used therapeutically to repair and replace human organs with lab-grown versions containing a patient's own cells. The 3D bioprinting method developed by the ERC team is a huge step toward creating functioning human organs like the heart, outside the body.

Using Smart Bandages to Monitor Chronic Wounds

Chronic wounds are difficult to heal, and treatment is often complicated and lengthy. Currently, chronic wounds can only be assessed visually by physically removing the bandages. Florida International University researchers at the **ERC for Advanced Self-Powered Systems of Integrated Sensors and Technologies** (ASSIST) developed bandages that incorporate flexible electronics to monitor chronic wounds and conducted human clinical trials using them. These "smart bandages" (Figure 3-4) measured the uric acid, pH, and lactate levels of diabetic patients.

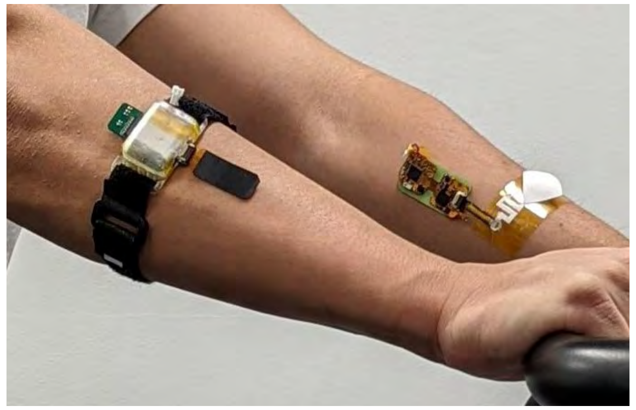


Figure 3-4: *Wearable systems for health monitoring via multimodal optical, electrical, and biochemical measurements. (Photo credit: ASSIST)*

The ability to monitor chronic wounds in real time allows better timed treatment to improve chances of healing, and also provides the ability to monitor for secondary infections. This is especially relevant for wounds from burns, diabetes, and other medical conditions.

Affordable Diagnostics and Analysis of Cells and Molecules at the Point of Care

Researchers at Texas A&M University (TAMU) engineered a novel portable and robust microscale system enabling advanced diagnostics and analysis of cells and molecules without the sophisticated instruments previously required, opening up new opportunities for helping people at the point-of-care in the developed and developing world. This work, carried out at the **Precise Advanced Technologies and Health Systems for Underserved Populations** (PATHS-UP) ERC, headquartered at TAMU, is aimed at improving the ability to create uniform chemical compounds in sufficient quantity to enable affordable new approaches for analyzing single cells and molecules and accelerating the adoption of cutting-edge applications.

Simple mixing of aqueous and oil solutions with amphiphilic particles leads to the spontaneous formation of uniform reaction volumes ("dropicles") that can enable many kinds of applications in the analysis of biological entities such as cells and molecules. Nonlinear fluid dynamic effects are usually not considered in microfluidic systems, but might provide simple methods to manipulate and sort rare populations of cells at high throughputs. In contrast to traditional emulsions, particle-templated drops of a controlled volume occupy a minimum in the interfacial energy of the system, such that a stable monodisperse state results, with simple and reproducible formation conditions.

The researchers investigated the tunable manufacturing of concentric amphiphilic particles, with outer hydrophobic and inner hydrophilic layers, fabricated by flowing reactive precursor streams through a 3D-printed device with coaxial microfluidic channels, and curing the structured flow by UV exposure through a photomask (Figure 3-5).

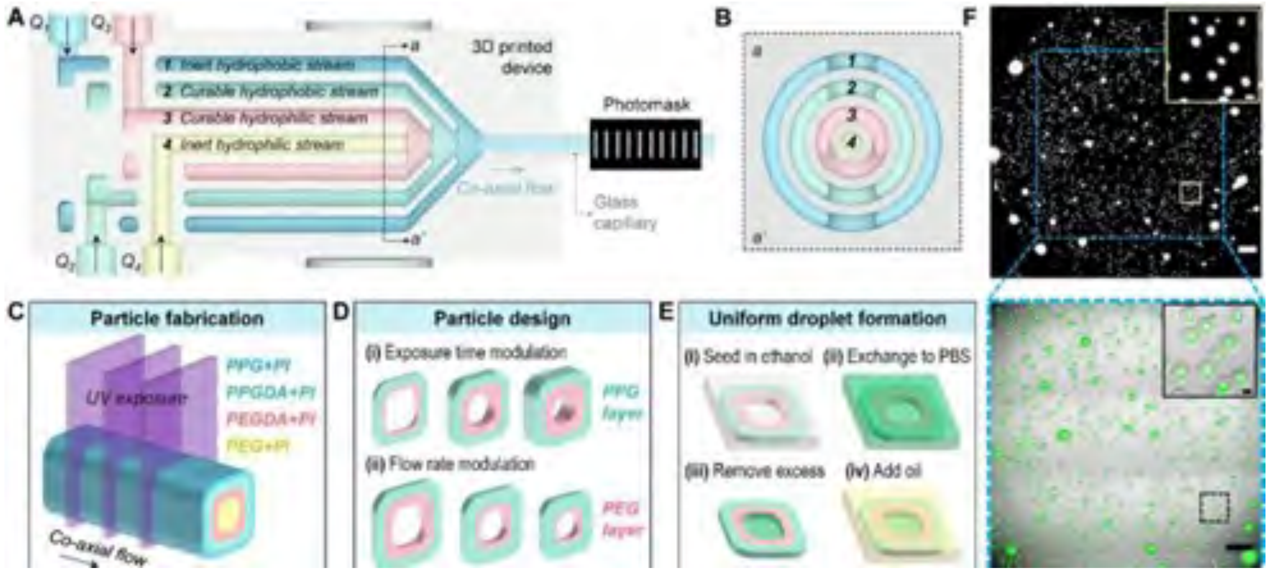


Figure 3-5: *The figure depicts amphiphilic particle design, fabrication, and dropicle formation. Diagram A is a schematic of the 3D-printed coaxial flow device with a glass capillary connected to the outlet. Inert and UV-curable hydrophobic and hydrophilic polymer precursors, pumped from separate inlets, flow through coaxially stacked channels separated by thin walls. A photomask atop the outlet capillary is used to shine UV light through rectangular slits.*

Improving Hand and Arm Function After Spinal Injury Using Electrical Stimulation

Combining innovative electrical stimulation with intensive training has improved the lives of six people with spinal injuries in research conducted at the **Center for Neurotechnology** (CNT), an ERC based at the University of Washington.

Growing evidence indicates that electrical spinal cord stimulation improves motor functions immediately by modulating the excitability of spinal circuitry in patients with spinal cord injury. The Center's research suggests that noninvasive stimulation of spinal cord networks can help the human nervous system to reorganize nerve connections. When paired with intensive training a novel, non-invasive, well-tolerated and painless electrical stimulation applied through the skin was demonstrated to be effective for improving motor function in healthy individuals and in patients with spinal cord injury.

In the six individuals in this project, improved hand function persisted for at least three to six months without further treatment. Some participants regained hand function more than a decade after their injury and were able to return to their hobbies such as oil painting and playing musical instruments (Figure 3-6).

Figure 3-6: *CNT research study participant Jon Schlueter (right) performs a grip-strength test while electrical stimulation is applied to his spine. CNT Co-Director Chet Moritz (left) and researcher Fatma Inanici (center) conduct the study. Schlueter, a musician prior to his spinal cord injury, experienced numerous functional improvements that resulted in increasing independence and enabled him to play the guitar again, for the first time in 15 years after the injury. (Credit: Marcus Donner, CNT)*

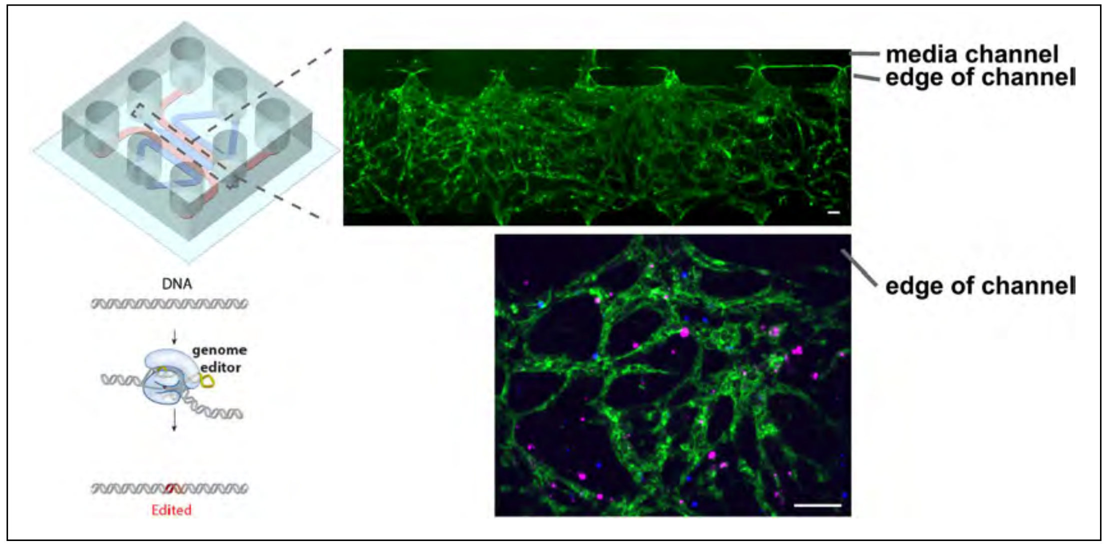
ADVANCED MANUFACTURING

Tissue Chips That Can Assess CAR T Cell Quality in Fighting Cancer

T cells are a type of white blood cells that are important in the human immune system and play a central role in the adaptive immune response. Chimeric antigen receptor T cells (also known as CAR T cells) are T cells that have been genetically engineered to produce an artificial T cell receptor for use in immunotherapy. CARs on the surface of T cells attack unhealthy cells such as cancer cells. Genetically engineered CAR T-cell therapies show promise for treating multiple myeloma and glioblastoma cancers by allowing for more specific recognition of antigens and T-cell signaling domains.

Researchers with the **ERC for Cell Manufacturing Technologies** (CMaT), led by the Georgia Institute of Technology, have developed tissue chips that can more quickly evaluate the potency of CAR T cells against these cancers. The engineered tissue chips integrate label-free impedance and optical metabolic imaging (OMI)—a non-invasive, high-resolution, quantitative tool for improved monitoring of T-cell activation and cytolysis (Figure 3-7). The tissue chips developed by CMaT researchers will therefore help to ensure more consistent, scalable, and low-cost production of high-quality living therapeutic cells for such cancers.

Figure 3-7: *OMI reveals a bone marrow chip created by CMaT researchers. The chip contains a permeable vascular network of endothelial cells (green; top) with an editable coculture network of primary multiple myeloma cells (magenta; bottom) and CAR T cells (blue; bottom) (Credit: CMaT).*



A Novel Database Improves Data Analysis of Silicon Nanostructures

Nanostructures are made from a variety of materials and have dimensions of just a few nanometers. Silicon nanostructures show great promise for the improvement and development of biomedical and other sensing devices. With a large capacity to reflect light, nanostructures are measured by shining a light on the structure and measuring the light reflected. The resulting reflectance measurements generate enormous list-based datasets that must be managed and mined to identify patterns.

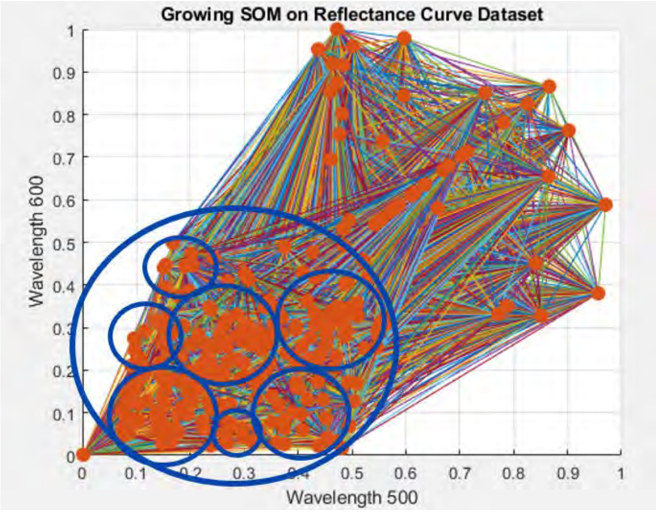


Figure 3-8: *A "growing self-organizing map" of a silicon nanostructure dataset. (Photo credit: The University of Texas at Austin)*

In order to organize and utilize this data, researchers at the **Nanomanufacturing Systems Center** (NASCENT), an ERC headquartered at the University of Texas at Austin, developed a data organization model called a growing self-organizing map, which is based on a hierarchical tree-based structure (Figure 3-8). This model significantly increases both search speed and accuracy using just 10 percent of the data obtained from the silicon nanostructure. Specifically, the search speed using the tree-based database organization was 672 times faster than the search speed using a traditional list-based database. Search precision of the data was 99.67 percent accurate, and recall measures – the ability of the system to present all relevant items – were 98.6 percent.

MICROELECTRONICS, SENSING, AND INFORMATION TECHNOLOGY

Chiral Symmetry Breaking Enables Deterministic Switching in Capacitors

Deterministic switching is a capability that allows designers to engineer technologically useful nanoscale devices that feature non-volatile magneto-electronics with low energy consumption. During the past year, researchers at the ERC for **Translational Applications of Nanoscale Multiferroic Systems** (TANMS) demonstrated field-free deterministic spin-orbit torque (SOT) switching, using the concept of chiral symmetry breaking (Figure 3-9). Employing a sliding scale of magnetic properties, the researchers introduced a non-collinear spin texture when SOT was applied. The interplay between the chirality (or "handedness") of the antisymmetric exchange and the induced non-collinear spin texture breaks the symmetry between up/down states and results in deterministic switching.

The work at TANMS shows that deterministic switching can be realized by a slight modification of cobalt-iron-boron/magnesium oxide (CoFeB/MgO)-based heterostructures, without the requirement of additional layers (Figure 3-10). Furthermore, the concept can be applied to multilayers with uniform thicknesses, promising high potential for applications on wafer scales.

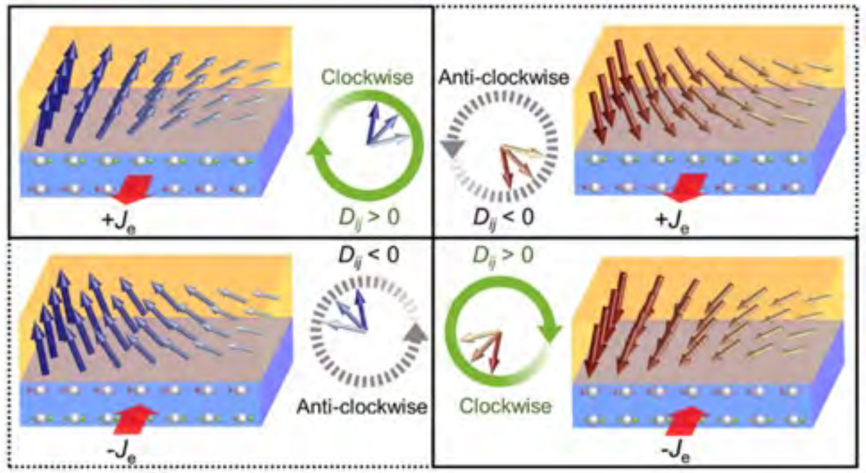


Figure 3-9: *Deterministic switching by chiral symmetry breaking (Credit: TANMS)*

Chiral symmetry breaking is also compatible with voltage controlled magnetic anisotropy—known as the VCMA effect. The VCMA effect occurs when an electrode in a capacitor is made of a thin ferromagnetic metal and the magnetic properties of that ferromagnetic metal change as a result of the voltage being applied to the capacitor. Current VCMA devices allow for lower power and higher speed in data writing mechanisms. Likewise, technologies equipped with VCMA-MRAM (magnetic random access memory) outperform other types of devices in terms of both energy consumption and instructions-per-cycle. Because the chiral symmetry breaking advance at TANMS enables deterministic switching of VCMA devices,

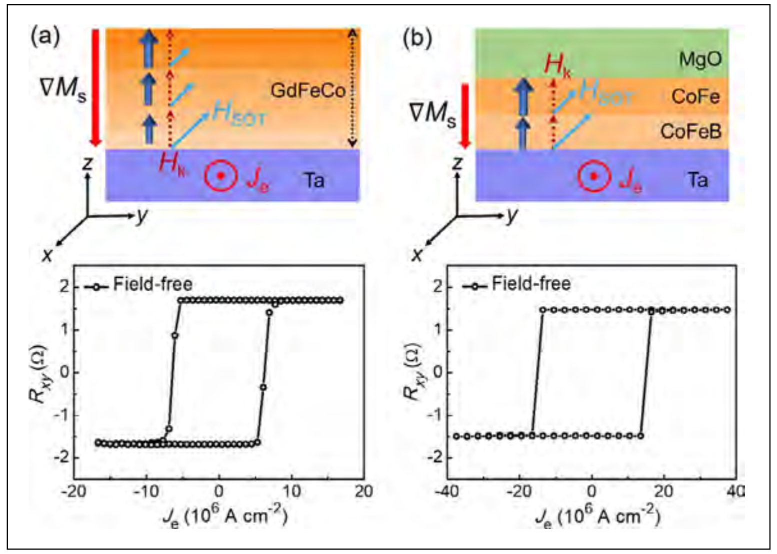


Figure 3-10: *Field-free spin-orbit torque switching in Ta/CoFeB/CoFe/MgO system (Credit: TANMS).*

Super-Thin Semiconductor Layer Allows Temperature Sensing

Researchers at the **Center for Power Optimization of Electro-Thermal Systems** (POETS) ERC, based at the University of Illinois, conducted the first-ever demonstration of a large temperature coefficient through a super-thin semiconducting layer. Temperature sensing is critical for many applications in electronics, including the suppression of thermal failures in integrated circuits.

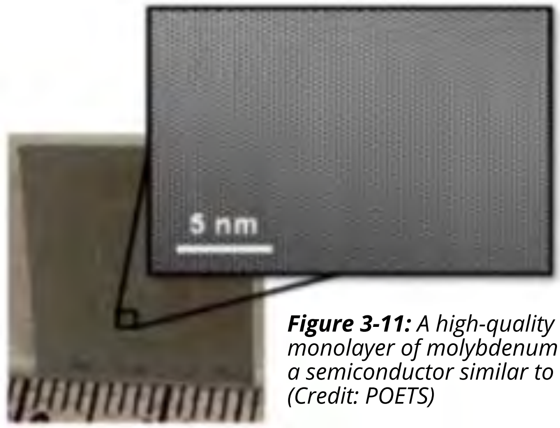


Figure 3-11: *A high-quality 0.6 nm monolayer of molybdenum disulfide, a semiconductor similar to silicon. (Credit: POETS)*

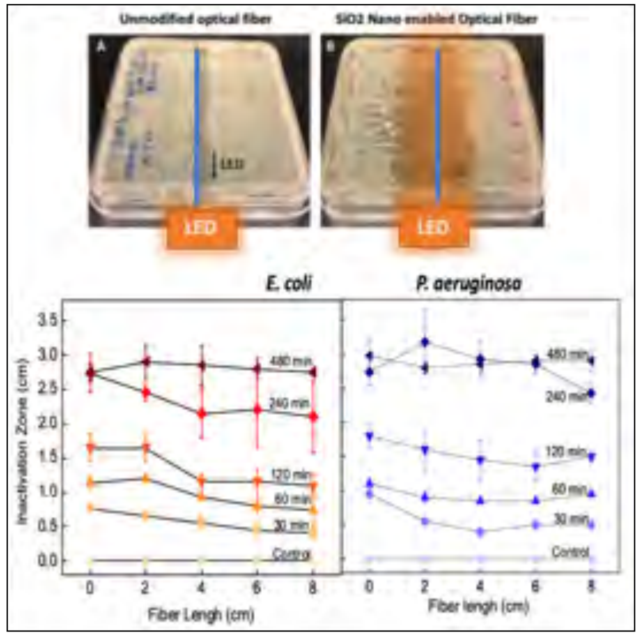
Traditional temperature sensors rely on thermocouples, resistors, or circuit-based sensors that can't be placed with microscale precision and cannot respond to ultrafast temperature changes. None of these commercial products can sense temperature changes with such atomically thin semiconducting materials. The POETS researchers demonstrated a novel transfer technique for two-dimensional semiconductor materials, resulting in a monolayer thickness of 0.6 nm (Figure 3-11). The technique incorporated contacts on polyimide substrates that will provide the basis for integration into power modules. The work at POETS could enable condition-based monitoring and diagnostics of critical electronic components and help meet the need for novel electrical and thermal component designs.

ENERGY, SUSTAINABILITY, AND INFRASTRUCTURE

Side-emitting Optical Fibers Create Germicidal "Glowstick" That Inhibits Biofilm Formation

Researchers with the **Nanotechnology Enabled Water Treatment** (NEWT) ERC, headquartered at Rice University, have successfully designed transparent, particle-modified polymer coatings that emit light to inhibit the growth of E. coli bacteria in water. The side-emitting-optical fibers (SEOFs) effectively create a flexible, germicidal "glowstick" that is stable in water and can be inserted into narrow-diameter channels such as piping or tubing, where bacteria-contaminated biofilms can form.

Commercially available light-emitting diodes (LEDs) that emit germicidal 265 nanometer (nm) light, known as UV-C, are known to be a disinfectant, but they afford only limited light emissions and can be difficult to deploy efficiently because the lights must be close to microbes in order to kill them. Flexible glass optical fibers offer a solution and are widely used in the telecommunication, medical, and other industries. However, when biofilm grows on wet surfaces, bacterial growth on the film may harbor pathogens or cause operational problems for water-based systems (Figure 3-12). NEWT's patent-pending nanotechnology-enabled SEOFs emit germicidal ultraviolet light along their entire length like a glowstick to eliminate biofilm growth and better protect both systems and organisms (Figure 3-13). SEOFs can also be woven into a fabric capable of disinfecting water at a closer range. This innovation is supported by NASA for potential use on the International Space Station.



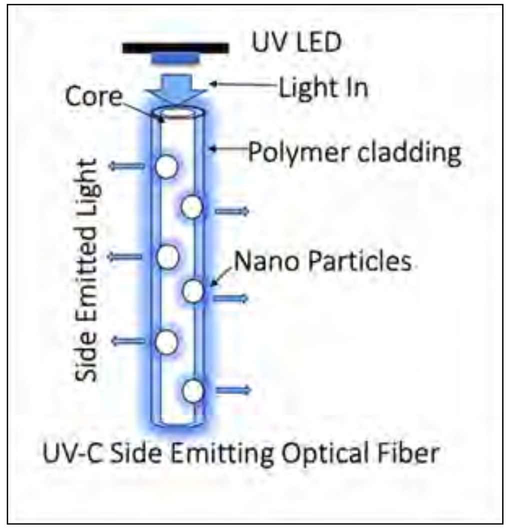


Figure 3-13: *Schematic diagram of the UV-C SEOF (Credit: NEWT)*

Figure 3-12: *(Top) An E. coli bacterial "lawn" on 8x10cm Lysogeny broth Agar plates after eight hours of exposure to an unmodified optical fiber (left) and a UV-C SEOF connected to a UV 265 nm LED (right). (Bottom) The SiO2 enabled SEOFs achieve a zone of inhibition of more than 3cm in tests of two different bacterial cultures (Credit: NEWT).*

New Tool Locates and Identifies Power Grid Problems

Oscillatory behavior in power systems has long been of great interest to engineers and researchers. Monitoring oscillation in power generation is essential for reliable system performance. In the past, most of the interest in this topic was focused on modal—i.e., natural—oscillations because of their relationship to system-wide events. A *forced* oscillation is an unintentional and forced periodic exchange of energy across different components of a power grid, which is symptomatic of the malfunction or mis-operation of equipment. That has received less research attention.

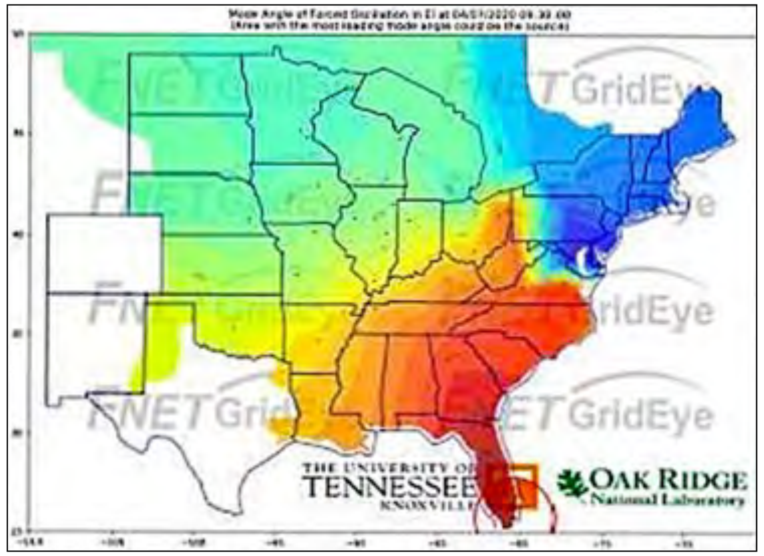


Figure 3-14: *The dark red area is the estimated source location of the forced oscillation. (Credit: CURENT)*

Researchers at the **Center for Ultra-Wide-Area Resilient Electric Energy Transmission Networks** (CURENT), an ERC headquartered at the University of Tennessee-Knoxville, have developed an online tool for locating the source of forced oscillation and deployed it in U.S. power grids (Figure 3-14). Upon detecting a forced oscillation, the CURENT tool can generate reports on events, visualize their evolution, alert system operators, and provide detailed event information. Further, the location estimation of the forced oscillation source helps pinpoint the event cause, accelerating resolution of the issue and assisting in post-event analysis.

Assessing the Relative Merits of Different Types of Power Plants

After assessing the techno-economics and environmental attributes of comparable power plants, **Quantum Energy and Sustainable Solar Technologies** (QESST) ERC researchers at Arizona State University concluded that alternating current (AC)-coupled photovoltaics systems (PVS) paired with Battery Energy Storage Systems (BESS) are a considerably better option for power generation than simple-cycle gas (combustion turbine, or CT) power plants. The study's findings show that aggregate lifetime costs are much less for AC-coupled PVS with BESS, even when environmental costs are not included.

The results make a compelling argument for adoption and investment in new solar power plant construction. QESST's assessment examined initial startup costs, lifetime costs of operation, fuel costs, tax credits, and environmental costs for comparable-output power plants. The study also explored how well AC-coupled PVS BESS plants perform in meeting peak capacity requirements (Figure 3-15).

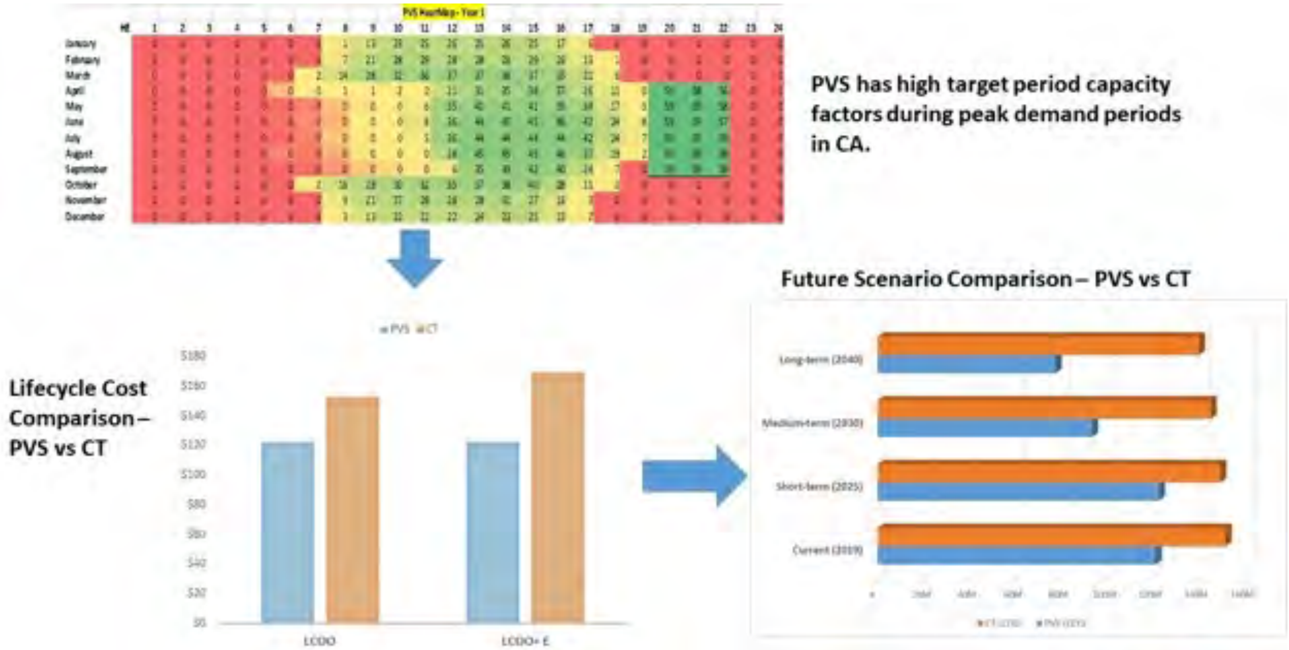
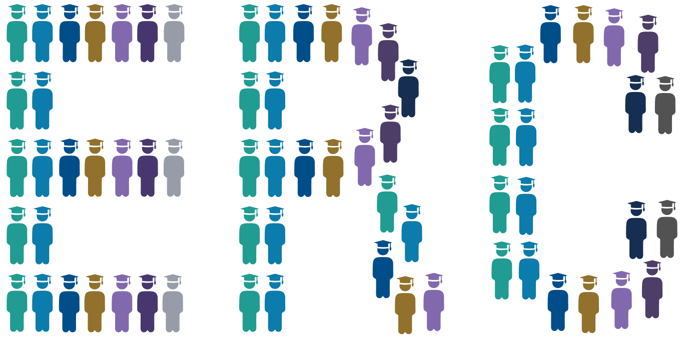


Figure 3-15: *(top) PVS heatmap showing high capacity factors during peak demand period; (bottom) Lifetime cost of operation (LCOO) comparison between PVS+BESS and CT power plants. (Credit: QESST and MDPI Energies)*

4. ENGINEERING WORKFORCE DEVELOPMENT

OVER THE PAST 35 YEARS, THE ERCS HAVE REVOLUTIONIZED ENGINEERING EDUCATION AND PRODUCED NEW GENERATIONS OF GRADUATES WHO ARE ADEPT AT INNOVATION AND PRIMED FOR GLOBAL TECHNOLOGY LEADERSHIP.

IN 2020, AN AVERAGE OF
160 students
participated in higher education and outreach programs at each center.



A major goal of the NSF's Engineering Research Centers program is to ensure that the education of engineering students prepares them to be leaders in innovation in industry as well as academe. The aim of engineering workforce development (EWD) efforts in ERCs is to produce engineering graduates who are able to apply their knowledge across disciplines to advance technology based on first-hand experience with research on engineered systems, which is vital for industrial innovation. Several facets of the ERC EWD environment contribute to the centers' success in achieving this aim.

First, ERC faculty, students, and industry partners integrate discovery and learning in an interdisciplinary innovation ecosystem that reflects the complexities and realities of real-world technology. Second, ERCs expose prospective students (both graduate and undergraduate) to industrial views in order to build competence in engineering practice and to produce engineering graduates with the depth and breadth of education needed for success in technological innovation and for effective leadership of interdisciplinary teams throughout their careers. Third, ERC innovations in research and education are expected to impact curricula at all levels, from precollege to life-long learning, and to be disseminated to and beyond their academic and industry partners.

Accordingly, ERCs also build programs of precollege outreach to help ensure that new generations of students understand what engineering is and have the opportunity to pursue careers in engineering. Further, outreach to population groups traditionally underrepresented in engineering helps to ensure that the nation draws its engineering talent from the broadest possible pool.

In 2020, across the 15 reporting ERCs, on average over 160 students at all levels (including precollege Research Experiences for Teachers participants but not precollege students) participated in education and outreach programs at each center. The total of 2,447 students in this one year alone represents a significant impact on engineering-oriented education in the United States. When the 59,120 K-12 and community college students and teachers impacted by ERC education activities are considered, it is evident that the ERCs have a far greater impact on engineering exposure and awareness.

ERC GRADUATES: DEGREES AND PLACEMENT

In 2020, as Table 4-1 depicts, all the ERCs together graduated 306 students, or an average of 20 degrees per center. The degrees are granted through the departments, but the students typically take numerous ERC-generated courses and conduct their research in Center labs with Center faculty and students.

Table 4-1: *ERC Student Degrees, FY 1985–2020*

	FY 2020 (15 ERCs)		**FY 2015-2019** Annualized		**FY 1985-2020** (65 ERCs)
Degree Type	**Total**	**Per Center**	**Total**	**Per Center**	**Total**
Bachelor's	100	7	105	6	4,607
Master's	65	4	92	5	4,379
Doctoral	141	9	155	9	5,221
Total	**306**	**20**	**352**	**20**	**14,207**

ERC graduates move into all sectors of engineering employment, as the chart in Figure 4-1 displays. Given their close association with industry during their education and the quality of the training they receive, ERC graduates are highly sought-after by industry. In 2020, 54% of all ERC graduates went into industry. It is also a testament to the value placed on interdisciplinary research and the capacity to lead in innovation in academe that 41% of the 2020 graduates of these cross-disciplinary research organizations entered faculty positions.

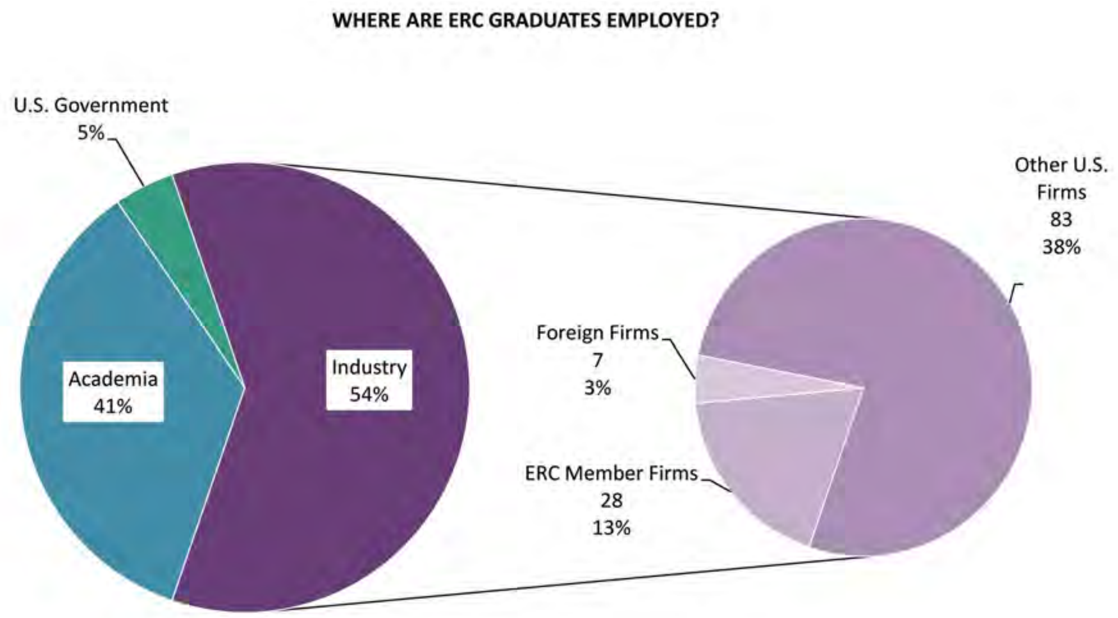


Figure 4-1: *Employment choices of ERC graduates*

UNDERGRADUATE EDUCATION

The ERCs were the first NSF-funded academic research units to routinely involve large numbers of undergraduates in the research, as members of the research team. By integrating them into the research team along with graduate students, postdocs, faculty, and even industrial partners, the ERCs are able to bring research and education together in powerful new ways, greatly impacting the quality and relevance of the undergraduate educational experience.

While every ERC conducted a variety of education programs focusing on undergraduate education in 2020, the following example helps to convey the innovative nature of these programs and their effectiveness.

A New Undergraduate Curriculum in Nanomechanics and Cellular Metamaterials

The **ERC for Cellular Metamaterials** (CELL-MET) developed an undergraduate core curriculum in nanomechanics and cellular metamaterials for Florida International University (FIU), a CELL-MET partner institution in Miami, Florida (Figure 4-2). The new curriculum at FIU is the first undergraduate-level concentration in nanomechanics and cellular metamaterials developed by CELL-MET, which was established in 2017.

FIU's advanced core curriculum, housed in the Department of Mechanical and Materials Engineering, is based on themes from the Center's research. With CELL-MET as a multi-institution partnership, the cross-institutional course "Integrated Leadership in Tissue Engineering" will be part of all concentrations in the new curriculum.

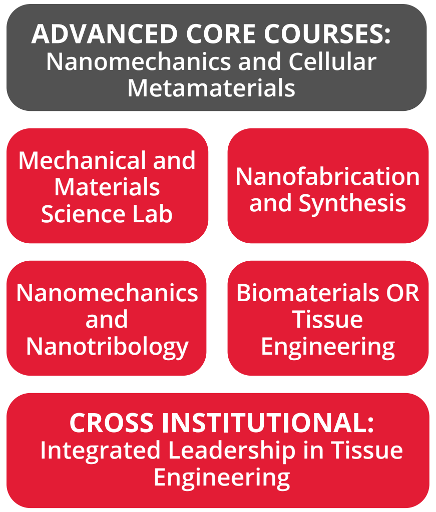


Figure 4-2: *Schematic showing approved course structure for undergraduate CELL-MET concentration. (Credit: CELL-MET)*

GRADUATE EDUCATION

Graduate education in ERCs, being oriented toward engineered systems, is both specialized and diversified. In addition to an immersion in the fundamental sciences underlying their systems focus, students gain a broad multidisciplinary perspective via the team approach to developing system testbeds. Through research on these testbeds and through collaboration with industrial researchers they gain real-world, hands-on experience in technology development. They acquire an understanding of what it takes to commercialize ERC innovations through the involvement with industry. ERC graduate students also gain leadership experience by working in significant project management roles, by mentoring undergraduate team members, by presenting engineering-themed programs to K-12 students, and by playing an active role in their Student Leadership Councils.

Some examples will serve to illustrate these unique features of an ERC graduate education.

Online Graduate Certificate Program Focuses on Nanotechnologies and Big Data

***Figure 4-3:** A student conducts an experiment for NASCENT's online certificate program (Photo credit: The University of Texas at Austin)*

The University of Texas at Austin's **Nanomanufacturing Systems Center** (NASCENT) ERC is offering an online graduate certificate program focused on experiential nanotechnologies and big data. The updated program enables experiential learning through portable nanolabs, a unique feature of the program.

The Experiential Nanotechnologies and Big Data Certificate Program provides students with a meaningful introduction to leading-edge and emerging trends in nano-enabled technologies and related data-analysis skills. In the program, which began in 2017, 60 students participate in three semester-long courses, which are available to corporate partners and partner institution undergraduates. A key feature of the updated program is the development of portable labs with automation– hands-on labs shipped to the students – enables enabling new experiments, such as a vacuum lab, and the collection of very large data sets for student analysis.

Training its fourth cohort of students in 2020, the program is designed to enable engineers in the semiconductor and other nanotech-related industries to engage more deeply and comprehensively in their careers through online course instruction, real-time office hours, hands-on experiments, and associated computational projects.

Grad Students Display "Wonders of Wattage" to K-12 Students

Ten graduate students from the University of Arkansas (UA) impacted more than 3,000 K-12 students through informal activities sponsored by the **Center for Power Optimization of Electro-Thermal Systems** (POETS) ERC in 2020. The graduate students from the UA, a POETS partner, helped expose younger students to engineering and science at the "Wonders of Wattage," an annual event at the Scott Family Amazeum in Bentonville, Ark.

The ERC students and staff help organize the annual activity as part of Engineering Week at the Amazeum, Northwest Arkansas' hub for fun, creativity, and discovery through hands-on activities. The grad students guided youngsters through hands-on electrical demonstrations that included making an electric motor, sending an arc of electricity rising between two rods, and completing an electrical circuit that spurred a pair of plastic legs to start kicking. The planning and teaching activity broadens the educational experience of the grad students while it broadens the horizons of the young students.

***Figure 4-4:** An ERC electrical engineering student from the University of Arkansas, right, completes a circuit that gets legs kicking at the "Wonders of Wattage." (Credit: Northwest Arkansas Democrat-Gazette)*

OUTREACH

ERCs reach out to *undergraduate students* across the country to involve them in the excitement of research in an interdisciplinary team culture. NSF's Research Experiences for Undergraduates (REU) summer program was inaugurated in 1985, and from its beginning nearly all ERCs have offered REU opportunities to university and community college students, either under their own ERC Program-funded programs or under NSF-wide REU Site supplements. These efforts stimulate interest in the ERC's field of research among a wider spectrum of students, often including students from population groups traditionally underrepresented in engineering, such as African Americans, Native Americans, Hispanic Americans, women, and persons with disabilities. There were 173 REU participants across the ERCs in summer 2020. Of these, 57% were female; 27% were members of racial minorities; and 24% were Hispanic.

The aim of outreach programs focused on *precollege students* is to raise their awareness of engineering and their potential interest in pursuing an engineering career—whether at the ERC or elsewhere. In 2020, 54,175 K-12 students participated in ERC outreach programs. Through the Research Experiences for Teachers (RET) program, ERCs also involve *precollege teachers* in workshops and laboratory experiences to inform them about engineering research and design challenges. These teachers are then able to incorporate engineering concepts in their classroom lessons to stimulate students' awareness of engineering as a field of endeavor and a possible career choice. In 2020, the ERCs directly impacted 158 precollege teachers through the RET program, and impacted 4,054 K-12 teachers though a range of other outreach activities.

The purpose of outreach programs mounted for the *general public*, such as museum exhibits, is to increase public awareness of science and engineering and of the field in which the ERC is active. Finally, ERCs disseminate their research advances and new knowledge to the *academic and professional engineering* worlds through a variety of means, including hosting conferences and symposia and offering short courses.

Some outreach examples from 2020 follow.

Engineering Pathways for High School Teachers and Students

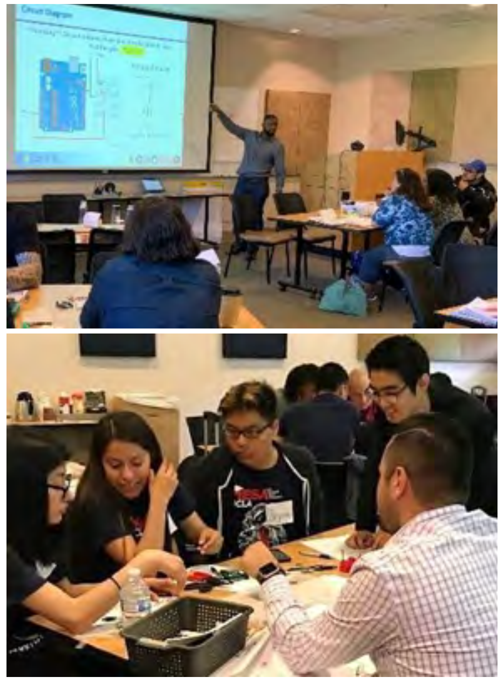


***Figure 4-5:** TANMS Graduate Fellows Introduce an Ardulno Electromagnetic Nanomotor activity, included in the MESA Course, to Institute Teachers (Credit: TANMS)*

The **Center for Translational Applications of Nanoscale Multiferroic Systems** (TANMS), based at the University of California at Los Angeles (UCLA), has developed a highly integrated approach to K-12 course development focused on its innovations in electromagnetic nanomotors and mechanical systems. The novel method, which combines new science learning with research experiences and mentoring projects, is successfully introducing TANMS ideas to thousands of high school students across California under the TANMS High School Science Initiative (HSSI); an associated Math, Engineering, and Science Achievement (MESA) Schools course; and its NSF-funded education programs such as RET.

By engaging both new and established teachers in jointly creating engineering pathways for students at multiple learning levels, the TANMS ERC facilitates professional teacher development while also writing and introducing new STEM course materials. The ERC leverages its RET program towards project-based curriculum development in order to promote and simultaneously achieve science engagement and learning. This significantly speeds the spread of key concepts and discoveries from TANMS advanced research while also gaining hands-on participation from students and educators at various education levels, leading to greater STEM persistence and interest in TANMS research experience opportunities. The new method also includes a Research Experience and Mentoring (REM) program that pairs TANMS undergraduate students with high school students exposed to the electromagnetic nanomotors curriculum as "near-peer" mentors, allowing participants at both levels to gain greater STEM efficacy through their own educational growth. As a result of this approach, REM students tend to demonstrate ongoing TANMS interest and experience by going on to pursue REU programs or by applying themselves towards four-year engineering degree programs. Finally, this method achieves important gains in authentic diversity and inclusivity; the TANMS/MESA Course is expected to have an initial statewide reach of approximately 350 MESA schools serving low-income, underrepresented minority students.

High School Students Design and Build "Infant Incubators"

Students at an Illinois high school designed and prototyped infant incubators that could help poorer regions where electricity is neither affordable nor reliable. The exercise was supported by graduate students from the the **Center for Power Optimization for Electro-Thermal Systems** (POETS) ERC. The high school students worked as 10 different teams of five or six each in conceptualizing, designing, and building prototypes of the devices. They learned engineering concepts, how to work together as a group, and how to present their work in posters and short videos.

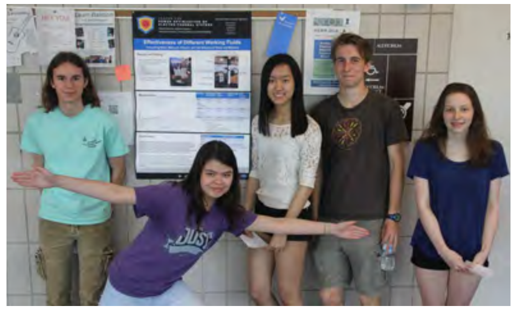


Figure 4-6: *University Laboratory High students displaying their poster for a POETS-supported project in which they gained experience in engineering design and presentation. (Credit: POETS)*

The program began when an Illinois high school teacher consulted on a POETS Research Experiences in Teaching curriculum about infant incubators. The teacher adapted it for his high school chemistry class as an end-of-semester design challenge. Students then presented their posters and videos to a group of POETS graduate students in a seminar, where awards were given to the best design, best poster, and best video.

Outreach to Community College Veterans and Minorities Aids Recruiting

Veterans and minority students at a community college conducted summer research in a new mentoring program launched by the **ERC for Re-inventing the Nation's Urban Water Infrastructure** (ReNUWIt), headquartered at Stanford University. The new program, called Research Experience in Water-Environment Science & Technology (REinWEST), aims to encourage interest in science and engineering for students studying at a community college. Mentors lead the research during the summer and continue to work with the students to facilitate their transfer to four-year degree programs.

Participants in the REinWEST program get a broad exposure to studying science and engineering, helping to conduct research and touring other ReNUWIt testbeds. Participants also attended the annual conference of the New Mexico Alliance for Minority Participation, where they participated in workshops and presented posters on their ReNUWIt research. Of five participants the first year, three enrolled in a four-year college and one continued as an undergraduate researcher with ReNUWIt.

Figure 4-7: *REinWEST participants conduct research, present posters, and tour ReNUWIt testbeds. (Credit: NM Alliance for Minority Participation)*

ERC Team Pivots to Virtual Model for 2020 RET Program

In summer 2020 the **Center for Bio-mediated and Bio-inspired Geotechnics** (CBBG), an ERC headquartered at Arizona State University (ASU), presented a completely virtual version of its Research Experience for Teachers (RET) program due to COVID-19 restrictions on in-person programming.

Figure 4-8: *CBBG researchers deliver RET Program material remotely using Zoom. (Photo Credit: CBBG)*

The Center developed a new five-week remote course using the online platforms Canvas and Zoom. Participating teachers were supported by researchers from ASU, Georgia Tech, and Lafayette College in adapting STEM-focused and lab-based engineering lessons for online and remote delivery to their students during the academic year. Other ASU programs used the remote format as a model, and the 2021 RET Program included some components of the online program in a hybrid mic of remote and in-person formats.

CURRICULUM DEVELOPMENT

One of the most effective and highly leveraged ways for ERCs to disseminate the "culture change" in engineering education that they have always represented is through the development of innovative new curricula ranging from textbooks to course modules to new courses, to minors and certificates, to entirely new degree programs. With their cross-disciplinary systems focus, ERCs throughout the years have had a major impact on engineering curricula across the nation. 2020 was no exception, as table 4-2 displays.

Table 4-2: *ERC Influence on Curriculum, FY 1985-2020*

	FY 2020 (15 ERCs)		FY 2015-2019 Annualized		FY 1985-2020 (65 ERCs)
Degrees	**Total**	**Per Center**	**Total**	**Per Center**	**Total**
New Full-Degree Programs Based on ERC Research	2	<1	2	<1	57
New Degree Minors Based on ERC Research	2	<1	0	<1	34
New Certificate Programs Based on ERC Research	2	<1	2	<1	43
Courses	**Total**	**Per Center**	**Total**	**Per Center**	**Total**
New Courses Based on ERC Research	32	2	28	2	1,085
Ongoing Courses With ERC Content	246	16	291	16	3,483
Course Modules Based on ERC Research	44	3	28	2	746
Textbooks	**Total**	**Per Center**	**Total**	**Per Center**	**Total**
New Textbooks Based on ERC Research	5	<1	4	<1	187
New Textbook Chapters Based on ERC Research	5	<1	6	<1	109

Some interesting examples of ERC curriculum development in 2020 follow.

Accelerated Engineering and Public Health Degrees

New courses and fast-track Bachelors-to-Masters curricula have been developed by educators from institutions participating in the **Precise Advanced Technologies and Health Systems for Underserved Populations** (PATHS-UP) ERC, headquartered at Texas A&M University (TAMU), including PATHS-UP partners the University of California at Los Angeles (UCLA), Rice University, and Florida International University (FIU). The coursework provides students with essential knowledge and tools to prepare them for careers in the development of enabling technologies and advanced engineered systems leading to better healthcare.

Figure 4-9: *PATHS-UP now offers new five-year combination degree options that allow students to earn a B.S. in industrial Engineering while also earning a Master of Public Health in Occupational Safety and Health. (Credit: TAMU)*

PATHS-UP faculty at TAMU gained approval for two new five-year combination degree options that allow students to earn a Bachelor of Science in Industrial Engineering while also earning a Master of Public Health in Occupational Safety and Health. Students who complete this program graduate with both degrees in just five years. This program helps satisfy the need for engineers with formal education in industrial engineering and health, to improve the quality of life for the public in underserved areas. Graduates of the program will be immersed in practical health-related issues and help to design technologies that can overcome the barriers usually faced in the use of point-of-care devices. The degree plans were first presented in the 2020-2021 catalog, and the first recruitment cycle opened in Spring 2021.

Since its inception in 2017, PATHS-UP faculty and graduate students have also created three new courses, a one-year capstone design project, modules for six existing courses, a PATHS-UP Overview, and modules about the four main research thrusts that are used to on-board summer REU participants at all partner institutions.

Textbook Empowers Engineers for Power Engineering Careers

Among the most critical engineering accomplishments advancing human well-being in the 20th century was the construction of power grids and their associated infrastructures all over the world. Preparing people for careers in power engineering is vital to sustaining and advancing the generation, transmission, distribution, and use of electric power. A new textbook on *Power System Modeling, Computation and Control*, developed by research educators working with the **Center for Ultra-Wide-Area Resilient Electric Energy Transmission Networks** (CURENT). headquartered at the University of Tennessee-Knoxville (UTK), now supports two semesters of graduate coursework on essential power engineering topics.

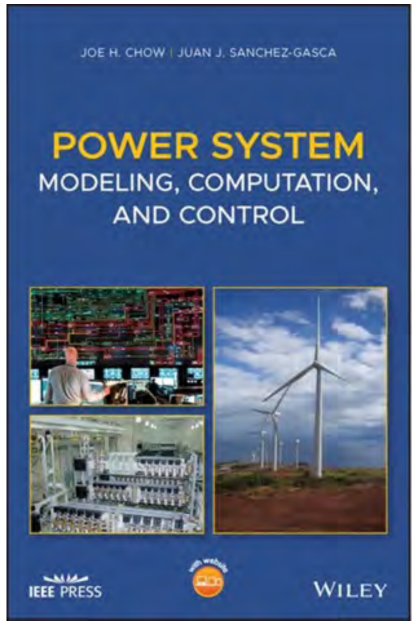


Figure 4-10: *Front cover of the new textbook. (Credit: CURENT)*

The two courses supported by this book address the dynamic aspects of components and how they interact with each other in the enormously complex, continuously operating electric power systems using the prevailing central station model of power generation. The courses and book provide power students with an understanding of the practices in power system stability analysis and control design and the computational tools being used and provided by commercial vendors. This background will also prepare power engineers to deal with anticipated future power systems, in which most households will be equipped with solar panels and every town will have a few wind turbines.

SolArt Competition for Professional Training in Solar Design

Students with the **Quantum Energy and Sustainable Solar Technologies** (QESST) ERC designed and organized a competition to train future professionals in interdisciplinary solar design. The 2020 SolArt competition, hosted by the student-led group Green Engagement Specialists (G.E.S.), inspired student teams to design beautiful, useful, solar-powered spaces and places for people to live and work outdoors at Arizona State University, where QESST is based.

The 2020 SolArt competition also helped students explore the social value of energy. QESST students posit that social values are often subtly embedded throughout energy infrastructures, but that these choices can be seen more readily in arrangements that produce renewable energy—particularly those that provide services or bring people together outdoors. Organized events associated with the competition actively demonstrated the production and flow of energy while supporting teams in intentionally creating more sustainable social spaces for the campus community.

Creating innovative solar technologies requires learning to work in teams of interdisciplinary specialists in design, engineering, sustainability, and societal impacts. All SolArt participants were mentored by local design, architecture, construction, engineering, and cultural professionals to maximize cross-functional and intergenerational insights while promoting shared, experiential learning.

Figure 4-11: *Interdisciplinary students present designs for a tree-inspired solar shade structure during the 2020 SolArt competition at ASU (Credit: QESST).*

5. DIVERSITY & CULTURE OF INCLUSION

ERCS FULFILL NSF'S STRATEGIC GOAL TO INCREASE THE DIVERSITY OF THE SCIENTIFIC AND ENGINEERING WORKFORCE BY INCLUDING ALL MEMBERS OF SOCIETY, REGARDLESS OF RACE, ETHNICITY, OR GENDER, IN EVERY ASPECT OF THE CENTERS' ACTIVITIES; THEY ALSO FOSTER A CULTURE OF INCLUSION THAT ACCEPTS AND VALUES THAT DIVERSITY AS A SOURCE OF STRENGTH IN ALL THE CENTERS.

STARTING WITH GEN-4 ERCs

In FY 2020,

strengthening Diversity and a Culture of Inclusion is one of the four foundations of all ERCs

For many years one of the key features of the NSF's ERC program and of all the ERCs has been a determination to strengthen the diversity of the scientific and engineering workforce by encouraging members of population groups traditionally underrepresented in technical fields to pursue engineering studies. As long ago as 2004 this expectation was formalized in an official ERC Program Diversity Policy that set forth requirements for ERCs. By 2011, the emphasis had expanded beyond viewing diversity efforts as simply increasing headcounts of ERC participants from underrepresented groups, to an expectation that each ERC will promote Diversity and a Culture of Inclusion (DCI) through the center. The emphasis on strengthening the culture of inclusion is very visible in the Gen-4 ERCs, with the first class awarded in 2020. DCI is one of the four "foundational components" of a Gen-4 ERC, as shown in Figure 1-1.

NSF ERC Program leaders prepared a "kickoff" presentation to brief the newly awarded Gen-4 ERCs on expectations in a range of areas, including DCI. Figures 5-1 and 5-2 show two of the kickoff slides.

THE DATA REFLECT GROWING SUCCESS IN ACHIEVING DIVERSITY

On the diversity side, the general aim is for ERCs to exceed nationwide averages in academic engineering programs. This goal is pursued in many ways by individual ERCs and is now routinely achieved across the ERCs as a whole, as illustrated in the following series of charts.

As shown in Figure 5-3, in 2020 ERCs exceeded by a considerable margin the percentage of women involved nationally in academic research and education. For example, 26% of all ERC faculty are women compared to about just under 20% (est.) nationwide. And about 53% of all ERC undergraduate students are women, compared to about 25% nationally.

What is *Diversity*?

A collection of individual attributes that together help agencies pursue organizational objectives effectively. Examples:

language, national origin, race, color, disability, ethnicity, gender, age, religion, sexual orientation, gender identity, socioeconomic status, veteran status, educational background, experiences, and family structure.

Source: NSF ODI 2012 Strategic Plan

Figure 5-1: *"What is Diversity?" from NSF Kickoff presentation to Gen-4 ERCs. (Credit: NSF and freepik.com)*

What is a *Culture of Inclusion*?

An **environment** in which **all members feel valued and welcomed**, **creatively contribute**, and **gain mutual benefit** from participating.

- ➢A research and educational space where everyone feel that they and their work are **respected and supported.**
- ➢Policies and behaviors **recognize and celebrate differences and equity** prevails, with everyone having the same access to opportunities.

Figure 5-2: *"What is a Culture of Inclusion?" from NSF Kickoff presentation to Gen-4 ERCs.*

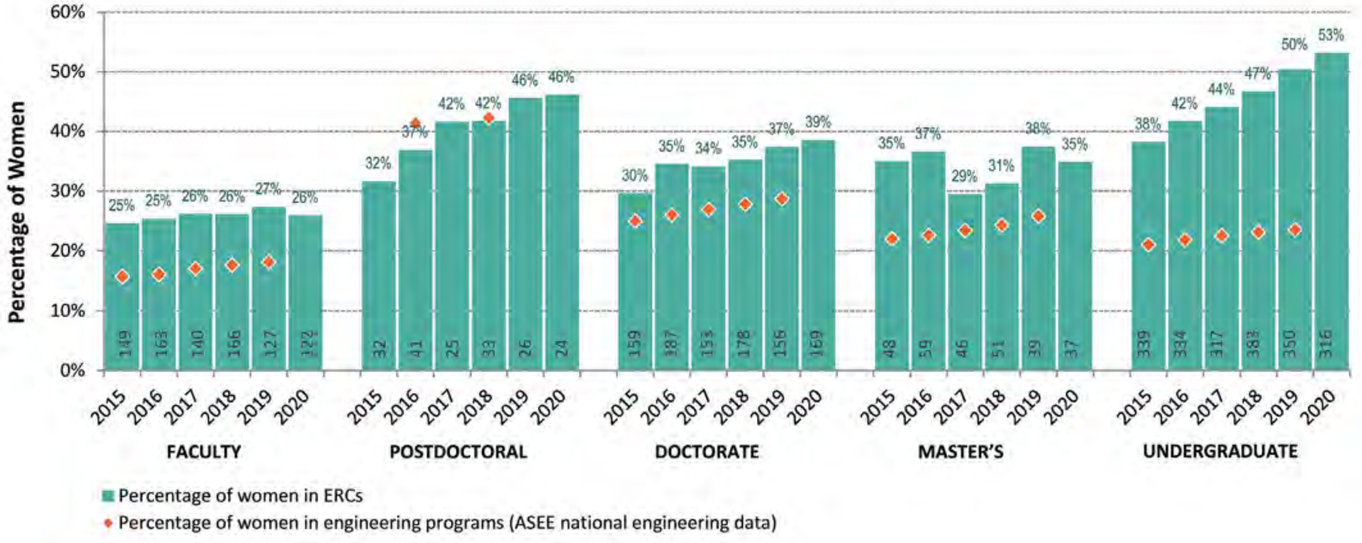


Figure 5-3: *Percentage of Women Personnel in ERCs vs. Percentage of Women in Engineering Programs Generally. (ASEE data were not collected for 2020.).*

Minority groups traditionally underrepresented in engineering, including African Americans and American Indians, are better represented in ERCs than in other academic engineering programs nationwide (see Figure 5-4). For example, about 9% of those seeking a doctoral degree at an ERC in 2020, and 17% of the undergraduates, are in these population groups, compared to only 5% and 6% (respectively) nationwide. And nearly 6% of ERC faculty are in these underrepresented groups, compared to about 3% nationally.

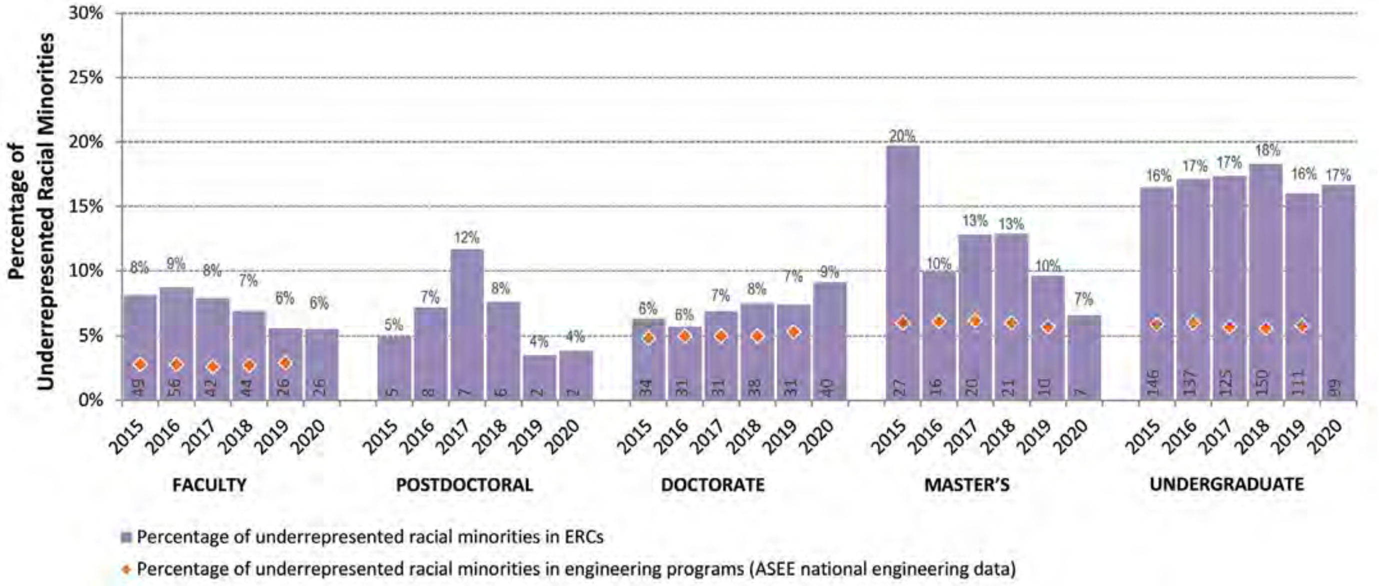


Figure 5-4: *Percentage of Underrepresented Racial Minority Personnel in ERCs vs. Percentage of Underrepresented Racial Minorities in Engineering Programs Generally*

ERC PROGRAM FOCUS ON DCI

Similarly, as shown in Figure 5-5, Hispanics and Latinos* were better represented in the ERCs in 2020 than in academic engineering programs nationally—e.g., 11% of ERC faculty vs. about 4% nationally; and 24% of all ERC undergraduates vs. about 16% nationwide.

** Hispanics and Latinos/Latinas are documented separately from racial minorities because they are an ethnic group consisting of several races.*

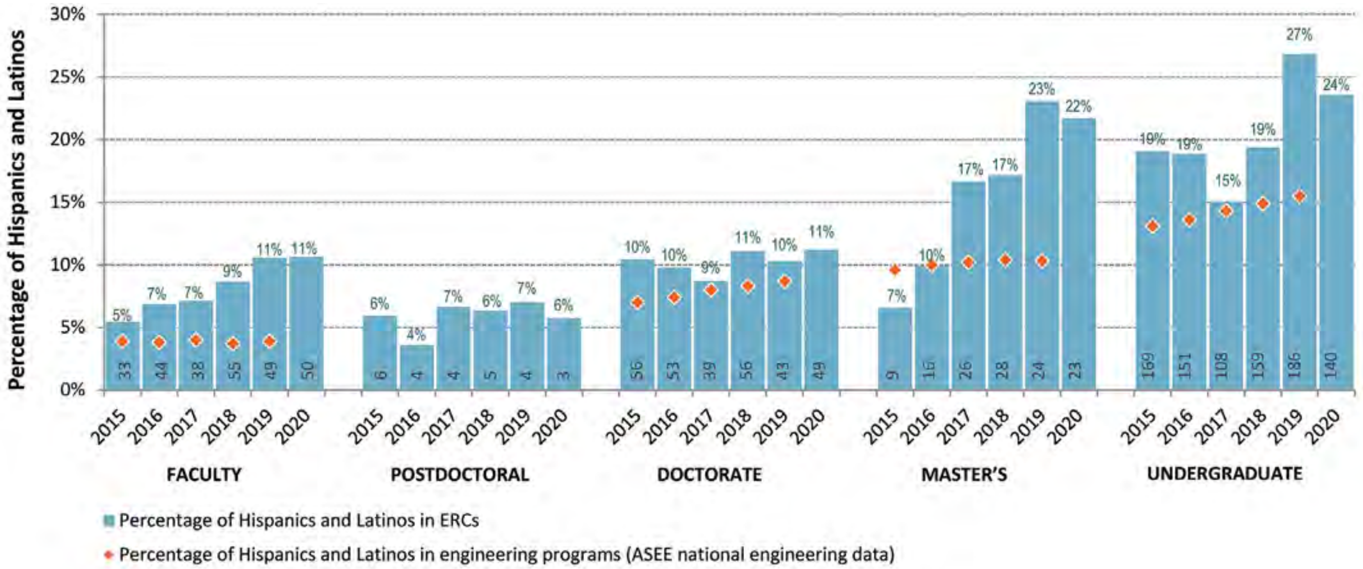


Figure 5-5: *Percentage of Hispanic and Latino Personnel in ERCs vs. Percentage of Hispanics and Latinos in Engineering Programs Generally*

Several of the supplemental programs available to ERCs—such as REUs and RETs (see "Education and Outreach" section)—are aimed at helping to achieve greater diversity and inclusion. The NSF-wide Louis Stokes Alliances for Minority Participation (LSAMP) and Alliances for Graduate Education and the Professoriate (AGEP) programs are among several that are focused on increasing the number of underrepresented minority students in NSF-funded activities. A number of ERCs are actively involved in these programs.

During FY 2020, a new chapter of the ERC Best Practices Manual (chapter 7) on "Diversity and Culture of Inclusion" was begun. ERC DCI leaders Pam McLeod (ReNUWIt), Tricia Berry (NASCENT), and Roy Charles (ASSIST) supported NSF ERC Program communications contractor Court Lewis in preparing an outline and draft of the chapter, which was completed in FY 2021 and posted on the ERC Association website. The chapter includes sections on program planning and direction, recruitment and retention, fostering a culture of inclusion, assessment and evaluation, and sustaining DCI after center graduation.

At the 2019 ERC Program Biennial Meeting (held in late October of that year, early in FY 2020), DCI was a major emphasis, with breakout sessions focusing on how to strengthen the culture of inclusion in ERCs.

CENTER-LEVEL DCI PROGRAM EXAMPLES

While every ERC conducted in 2020 a variety of programs aimed at improving DCI, the following examples help to convey the diversity and creativity of these programs and their effectiveness.

Diversity and Inclusivity Training for Mentors in Cell Manufacturing Technology

Diversifying the nation's science, technology, engineering, and mathematics (STEM) workforce is a continuing challenge, despite programs and strategies aimed at addressing the shortage of women and minorities in STEM fields. On June 10, 2020, the **Cell Manufacturing Technologies** (CMaT) ERC at Georgia Institute of Technology participated in the nationwide #ShutDownSTEM movement, with activities spearheaded by the American Association for the Advancement of Science (AAAS). Participants developed and hosted a Center-wide Diversity and Inclusion (D&I) Training entitled, "Conversation that Motivates Allies to Take ACTION" (CMaT Training).

Figure 5-6: *CMaT Trainees, REUs, REMs, faculty and staff at the Emerging Researchers National (ERN) Conference in STEM, Washington DC, February 2020 (Credit: CMaT).*

The center-wide mentor training program was made available to all Research Experience and Mentoring (REM), Research Experience for Undergraduates (REU), and Research Experience for Teachers (RET) mentors at each of the four primary CMaT partner universities. #ShutDownSTEM invited researchers and scientists to pause their work for the day in order to create specific action plans for ending racism in scientific communities. By interrupting "business as usual" for the day, the students, faculty, and other scientists hoped to foster awareness that would help increase the representation, retention, and recruitment of Black scientists to academia and industry.

Of CMaT's 20 virtual REU participants, representation includes students of whom 75% are female; 20% are African American; 30% are Hispanic; 1 is Native American; and 1 is a student with a disability. Of the Center's 11 virtual REM students, 62.5% are women; 12.5% are Hispanic; 37.5% are African American; and 12.5% are students with a disability. By acting as mentors to other scientists in the community, CMaT's highly inclusive, D&I-trained groups will both leverage and further best practices that can be adapted to the recruitment, admission, and retention of underrepresented students – including gender and ethnic minorities, low-income students, and first-generation college students as well as subsequent cohorts of teachers and mentors.

ERC Engages Physically Challenged Students Through Science and Engineering Outreach


Figure 5-7: *NASCENT graduate students presenting at the Center's STEM Fest at the Texas School for the Blind and Visually Impaired. (Credit: The University of Texas at Austin)*

In 2020 the University of Texas at Austin's **Nanomanufacturing Systems Center** (NASCENT) ERC, engaged with 28 deaf and hearing-impaired and 24 blind and visually impaired high school students through outreach programs. NASCENT graduate students work monthly with hearing-impaired students at the Center's Texas School for the Deaf Science Club, offering hands-on activities and experiments that allow them to explore all aspects of science. This has included areas such as nanoscience, sustainable energy, and the electric grid with the help of an American Sign Language interpreter.

For the blind and visually impaired students, NASCENT hosted the 4th annual STEM Fest at the Texas School for the Blind and Visually Impaired (TSBVI) in Austin, Texas.

Students Outline Strategies to Increase Equity in Admissions

As part of an ongoing effort to promote diversity at the ERC for **Re-Inventing the Nation's Urban Water Infrastructure** (ReNUWIt), based at Stanford University, students from the Center's four partner campuses drafted a report of best practices for increasing equity in graduate admissions. The literature-based resource enables faculty on admissions committees to better advocate for practices that help mitigate bias and inequalities and thereby admit a more diverse student cohort.

The student report contributes to a multi-year effort at ReNUWIt to build an inclusive climate, recruit a more diverse population of students and researchers, and expand the pipeline for underrepresented minorities. It outlines five key actions that departments can implement to ensure an equitable, consistent, and efficient admissions process. The student effort reflects ReNUWIt's unique organizational structure leading its diversity, equity, and inclusion (DEI) efforts—a structure that has resulted in student-led change. Center leaders have facilitated student leadership within DEI, and the actions they urge toward more equitable admissions comprise one example of the students' substantive contributions.

Figure 5-8: *Conceptual model of systematic, holistic review for graduate admissions. (Credit: Kirin Furst)*

Neuroscience for Neurodiverse Learners

The **Center for Neurotechnology** (CNT), based at the University of Washington (UW), partnered with the UW's DO-IT Center and received NSF funding for a 4-year, $1.5M project called Neuroscience for Neurodiverse Learners (NNL) that began in January 2020. Initially expected to be an in-person program for students on the UW campus, with the onset of the COVID-19 pandemic, the UW NNL team had to quickly pivot to an online model.

Funded under NSF's Innovative Technology Experiences for Students and Teachers (ITEST) program, NNL is providing hands-on experiences in neuroscience disciplines, networking opportunities, and resources to high school and early post-secondary students identified as "neurodiverse" learners and will disseminate findings to teachers of courses related to neuroscience and, more broadly, to science, technology, engineering, and mathematics (STEM).


Figure 5-9: *Serena, an NNL participant, holds up a model of a neuron that she fashioned at home based on instructions provided to NNL students by the CNT's leader for study activities. NNL staff made a special effort to include hands-on activities like these as part of the NNL online program. (Credit: CNT)*


Figure 5-10: *TANMS students in the lab (Credit: TANMS)*

6. INNOVATION ECOSYSTEM

SINCE THE FIRST ENGINEERING RESEARCH CENTERS WERE FOUNDED IN 1985, THESE PIONEERING ORGANIZATIONS HAVE TRANSFERRED A CONTINUOUS STREAM OF CUTTING-EDGE TECHNOLOGIES TO THEIR INDUSTRIAL PARTNERS ACROSS A BROAD SPECTRUM OF TECHNOLOGY FIELDS, WHILE PROVIDING ACCESS TO A LARGE CONTINGENT OF HIGHLY QUALIFIED GRADUATES AS EMPLOYEES PRIMED FOR TECHNOLOGY LEADERSHIP.

EVERY ERC ESTABLISHES AN INNOVATION ECOSYSTEM with industry partners at its core.

One of the key features of every ERC is the mutually beneficial partnership it establishes with its industrial members in the context of a strong innovation ecosystem. The primary goals of this partnership—and the means by which each side of the partnership benefits—are a two-way exchange of information and knowledge, multi-faceted technology translation, and the impact on students, both in terms of shaping their education through the contact with industry and through their employment and the impact that brings to the company. Figure 6-1 lists the main benefits reported by industry for ERC membership, which have remained consistent over time.

There is strong industrial involvement by industry partners in planning an ERC's research program and directions as well as the direction and shape of its education programs. This collaboration necessarily involves maintaining a careful balance between the longer-term strategic vision of the ERC and the nearer-term needs of industry. That continual interplay of needs and perspectives in turn helps keep the ERC grounded, vigorous, and relevant. The financial and other (e.g., in-kind equipment) support that an ERC's industrial members provide demonstrate their commitment to the ERC and help leverage NSF funding for the center.

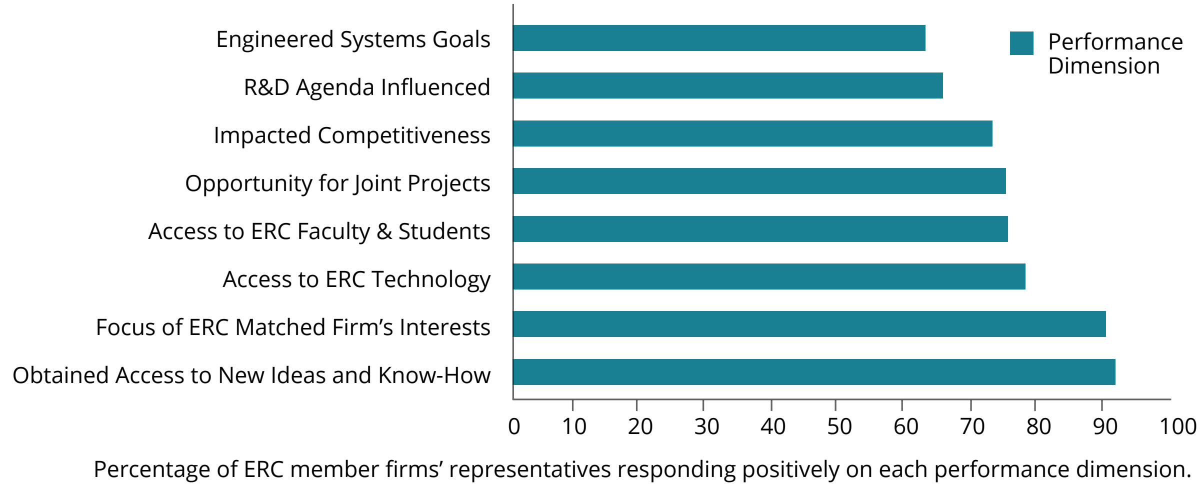


Figure 6-1: *Benefits to industry of ERC membership (Source: SRI International, 2004)*

INDUSTRIAL INTERACTION BY THE NUMBERS

In FY 2020 there were 278 total industrial members (domestic and foreign) of the 15 ERCs. Taking into account all other funding and supporting organizations, the total number of industrial participants was 520, for an average of 35 organizations per center (see Table 6-1). They provided a total of $6.58 million in direct support for the ERCs. This support comprised membership fees ranging from $5,000 to $100,000, depending on the center and its fee structure for different levels of membership. In addition to direct cash support and project sponsorship, industry also provided $1.1 million in in-kind support such as equipment, software, and research personnel on loan to the centers.

Table 6-1: *ERC Industrial/Practitioner Members and Supporting Organizations, FY 2014–2020 (does not include data for Earthquake ERCs)*

	FY 2014	**FY 2015**	**FY 2016**	**FY 2017**	**FY 2018**	**FY 2019**	**FY 2020**
Organization Type							
Contributing Organizations	30	50	85	72	93	100	<1
Funders of Associated Projects	218	199	171	144	157	108	<1
Funders of Sponsored Projects	10	9	13	12	28	11	<1
Foreign Industrial/Practitioner Members	81	69	69	45	45	31	2
U.S. Industrial/Practitioner Members	345	333	301	249	274	234	16
Total Number of Organizations	**684**	**660**	**639**	**522**	**597**	**484**	**520**
Total Number of Centers	**20**	**17**	**19**	**16**	**19**	**19**	**15**
Total Number of Organizations per Center	**34**	**39**	**34**	**33**	**31**	**25**	**35**

ERC graduates move into all sectors of engineering employment, as the chart in Figure 4-1 displays. Given their close association with industry during their education and the quality of the training they receive, ERC graduates are highly sought-after by industry. In 2020, 54% of all ERC graduates went into industry. It is also a testament to the value placed on interdisciplinary research and the capacity to lead in innovation in academe that 41% of the 2020 graduates of these cross-disciplinary research organizations entered faculty positions.

Some interesting trends notable in the table are: (1) a decline in the overall number of industrial members since 2014—partly a result of reduced R&D expenditures by U.S. companies, but mainly due to a drop in the number of ERCs (the average number of members per center only declined from 21.3 to 18.5 in that period); (2) a sharp increase in the number of contributing organizations[1]; and (3) a steady decrease in participation of foreign firms—which seems counterintuitive in an increasingly globalized economy, but probably reflects a lessened emphasis by the NSF ERC Program on foreign academic and industry partners as well as the emergence of strong research centers in other countries. Also, the table does not include "Innovation Partners," a new category of organizations that participate in the ERC with a mission to stimulate entrepreneurship and innovation but do not provide financial support to the ERC. In FY 2020 there were 169 Innovation Partners across the ERCs, so that the total number of organizations (including Innovation Partners) was 689.

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[1] A contributing organization provides non-project-specific support to the ERC through grants, equipment, or other real donations but does not satisfy all criteria for full membership.

As Figure 6-2 shows, in recent years the percentage of small businesses among ERC member companies has seen a small but steady increase, with a concomitant small decline in the percentage of large companies. This trend reflects the interest on the part of ERC Program leadership in engaging the innovative drive of small companies and startups.

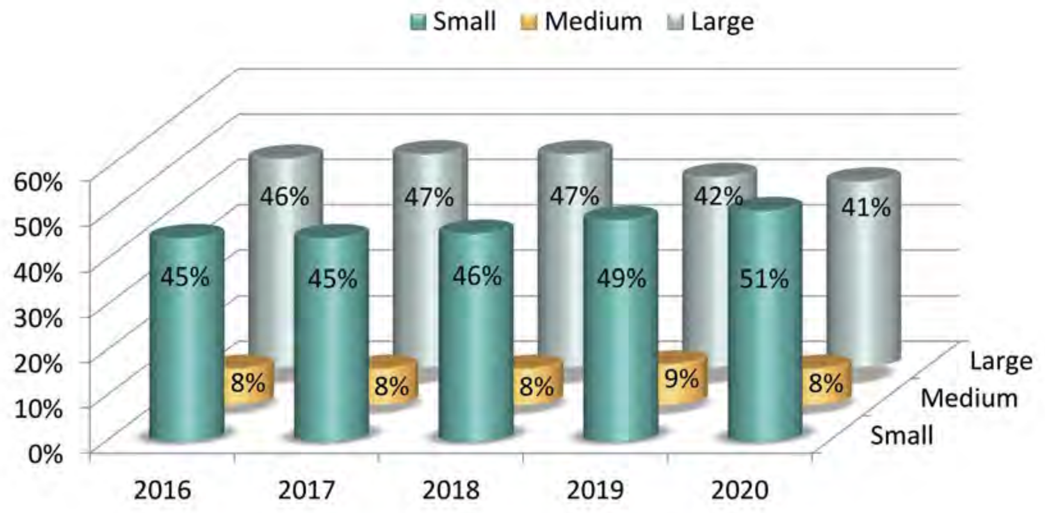


Figure 6-2: *Distribution of Industrial/Practitioner Members by Industry Size, FY 2016–2020*

Industrial members generally enjoy early and even real-time access to ERC discoveries, inventions, and technologies. Therefore, the intellectual property (IP) generated by the centers is a major incentive for industrial involvement. One important means of technology translation for ERCs is the spinning off of new companies formed by ERC faculty, graduates, and students. Table 6-2 summarizes the various IP outputs of ERCs in 2020 and over the 35-year life of the program. Each ERC's Membership Agreement specifies in detail the types of access to center-developed IP according to level of membership, type of IP, and special funding arrangements. It can be seen that these outputs have remained quite consistent across the decades, especially when taking into account the effects of COVID-19 restrictions during FY 2020.

Table 6-2: *ERC Products of Innovation, FY 1985–2020 (does not include data for Earthquake ERCs)*

	FY 2020 (15 ERCs)		**FY 2015-2019** Annualized		**FY 1985-2020** (65 ERCs)
Intellectual Property Transaction	**Total**	**Per Center**	**Total**	**Per Center**	**Total**
Inventions Disclosed	57	4	80	5	2,564
Patent Applications Filed (Provisional and Full)	69	5	96	5	2,242
Patents Awarded	22	1	31	2	883
Licenses Issued	11	1	8	<1	1,379
Economic Development	**Total**	**Per Center**	**Total**	**Per Center**	**Total**
Spinoff Companies	12	1	10	1	240
Spinoff Employees	139	9	76	4	1,604

INNOVATIONS MOVING INTO INDUSTRY

Advances made at the ERCs are often at the fundamental level but in many cases are then developed at the center to the point of precompetitive technology that can be transferred to industry. Very often the process of development is collaborative with industry researchers, and many times leads to startups spinning off from the center with center faculty and students as principals. The 75 ERCs and Earthquake ERCs established since 1985 have produced literally thousands of technological innovations that have made their way into new industrial products and processes—not just within their member companies, but in many cases across entire industries. A few examples from 2020 will serve to illustrate the impact that leveraging ERC-developed technologies into industry can have.

ERC Partners with Stakeholders on Technology for Treating Agricultural Waters

The removal of nitrogen and phosphorus from wastewater is an emerging worldwide concern. Excessive amounts of these elements can lead to toxic algae blooms, harming water quality, food resources, and natural habitats. The **Center for Bio-mediated and Bio-inspired Geotechnics** (CBBG), an ERC headquartered at Arizona State University, is partnering with industry and community stakeholders to test a new technology to reduce phosphorus and nitrate levels in ground and surface water on agricultural lands.

The Center demonstrated in the lab a proof of concept for removing nitrogen and phosphate using steel slag. A new industry partner, Geo-Logic Associates, joined CBBG to advance development of this biogeotechnology toward testbed deployment. The Center led the design and implementation of a full-scale testbed at a field site in Beaver Dam, Wisconsin, and Geo-Logic Associates provided substantial in-kind civil design services (Figure 6-3).

Figure 6-3: *Design of field-scale testbed with in-kind support from local industry partners. (Photo credit: CBBG)*

Local farmers, field specialists, and college students have provided the demonstration site, field services, and data collection for the project. The project also engages local community groups, such as the Fox Lake Protection & Rehabilitation District, and has attracted the attention of the Wisconsin Department of Natural Resources.

Company Founded by ERC Graduate Wins Grants to Pursue Advanced Manufacturing Technology

SandBox Semiconductor, an Austin, Texas-based company founded by an alumna of the University of Texas at Austin's **Nanomanufacturing Systems Center** (NASCENT), secured two Small Business Innovation Research (SBIR) awards. The awards will further SandBox Semiconductor's work in the development of next-generation manufacturing technologies for semiconductor devices.

Figure 6-4: *Sandbox Semiconductor founder and SBIR award winner Meghali Chopra. (Photo credit: The University of Texas at Austin)*

SandBox Semiconductor was founded in 2016 by NASCENT alumna Meghali Chopra and University of Texas at Austin Professor Roger Bonnecaze (Figure 6-4). The company's mission is to accelerate advanced manufacturing process development through the application of physics-based and artificial intelligence/machine learning-based models. Their work helps process engineers working towards creating the next generation of semiconductor, petrochemical, and biopharmaceutical applications. SandBox Semiconductor has eight employees, who have collaborated on more than 10 patents and publications and presented at numerous domestic and international conferences.

Engineering Improvements to Deep-Brain Stimulation

Deep-brain stimulation has been shown to improve the tremors and other symptoms of Parkinson's and other neurological diseases. Implanted electrodes can deliver the healing stimulation deep in the brain, but serious challenges remain in knowing how much current should be delivered and when. Researchers at the **Center for Neurotechnology** (CNT), an ERC based at the University of Washington, are developing methods of collecting feedback from the brain itself.

In the long term, analysis of data derived from the deep-brain stimulators and monitors could give researchers at the CNT and elsewhere insight into how to make devices that not only suppress tremors but actually engineer changes in the brain for healing and restoration of function.

Figure 6-5: *A close-up view of the Activa PC+S, an implantable device provided by Medtronic, which provides a basis for much of the team's research work. (Credit: Mark Stone, CNT)*

CNT industry affiliate Medtronic, known for innovation and among the largest medical device companies in the world, is working with CNT researchers on the issue. Medtronic provided the research team with the Activa PC+S, an implantable prototype (Figure 6-5), which enables collection of a large amount of data and advanced research into closed-loop neuromodulation.

PARTNERSHIP

One of the strongest features of the ERC-industry partnership is the access that industry provides academic researchers with to state-of-the-art facilities large and small, often through direct in-kind donations. Three examples from 2020 will illustrate this type of collaboration.

High-Value Nanomanufacturing Tools from Industry Empower Research at an ERC

The University of Texas at Austin's **Nanomanufacturing Systems Center** (NASCENT) is collaborating with U.K.-based Emerson & Renwick and the Massachusetts-based Bruker Corporation to bring high-value nanomanufacturing tools to the Center's Nanodevice Manufacturability Fabrication (nm-Fab) facility. The Center's partnerships with Emerson & Renwick and the Bruker Corporation facilitate the manufacture of nanometer-scaled patterns on materials that become the basis for making semiconductor devices and other flexible electronics. The nm-Fab facility utilizes a variety of nanofabrication capabilities with the aim of making production of these devices less expensive.

NASCENT's partnership with engineering company Emerson & Renwick center around jointly developing roll-to-roll (R2R) nanofabrication systems and processes. R2R manufacturing creates electronics on a roll of flexible plastic or metal foil, and is a key process for making more mundane products such as Scotch tape and paper towels. In the nm-Fab facility, Emerson & Renwick upgraded a reactive ion etch tool (Figure 6-6), which is used to engrave a variety of inorganic materials and metals, enabling reliable pattern transfer to web-based substrates. The company also plans to deliver to the Center R2R and roll-to-plate nanoimprint lithography tools, capable of fabricating large-area nanometer patterns.

Figure 6-6: *NASCENT's roll-to-roll (R2R) nanofabrication line can etch a variety of inorganic materials and metals. (Photo credit: The University of Texas at Austin)*

The Bruker Corporation installed at the Center a laser direct-write patterning tool (the SF-100 Lightning Plus) that can create a pattern with only a computer-generated image of the design, without the need for hard or soft lithography tools. This technology enables template writing for R2R fabrication of flexible electronics.

Revolutionary Water-Treatment Plant is a Joint ERC-Government-Industry Testbed

In building their innovation ecosystem, ERCs reach beyond industry to form partnerships with any stakeholder—such as regional and even local government agencies—that can contribute to the achievement of the ERC's research goals. This is particularly true of the new Gen-4 ERCs, but it has been a feature of earlier ERCs as well.

Figure 6-7: *The bioreactor, shown here under construction at Silicon Valley Clean Water, will assess the benefits and performance of mainstream, full anaerobic treatment to facilitate energy savings and water reuse. (Credit: Eric Hanson, SVCW)*

Most water-treatment plants today use aerobic microbes in a process, unchanged for more than a century, that requires a startling 1% of the nation's energy—largely to inject oxygen to keep the microbes alive. Now, a number of public agencies and private companies have partnered to build an innovative water treatment plant in Silicon Valley, and conduct a pilot study to test technology developed with support from ReNUWit. Using anaerobic microbes, the new facility promises to consume less energy and perhaps be a net-energy producer through methane captured from the new process.

Able to process 20,000 gallons per day for non-potable uses, the new facility uses grains of activated carbon to keep the anaerobic microbes alive and uses membranes to filter solids from the water. The Staged Anaerobic Fluidized-Bed Membrane Bioreactor (SAF-MBR), shown in Figure 6-7, is the world's largest test facility of its kind and builds on knowledge gained from the **ERC for Reinventing the Nation's Urban Water Infrastructure** (ReNUWIt) testbed at Stanford.

Besides the support from ReNUWIt, the facility's partners include the facility's host, Silicon Valley Clean Water, as well as the Santa Clara County Water District, U.S. Bureau of Reclamation, PG&E, seven private companies, and the Water Research Foundation, among others. Funding for the four-year pilot study includes a $2 million grant from the California Energy Commission.

Testbed Reactors Donated by Center's Industrial Member

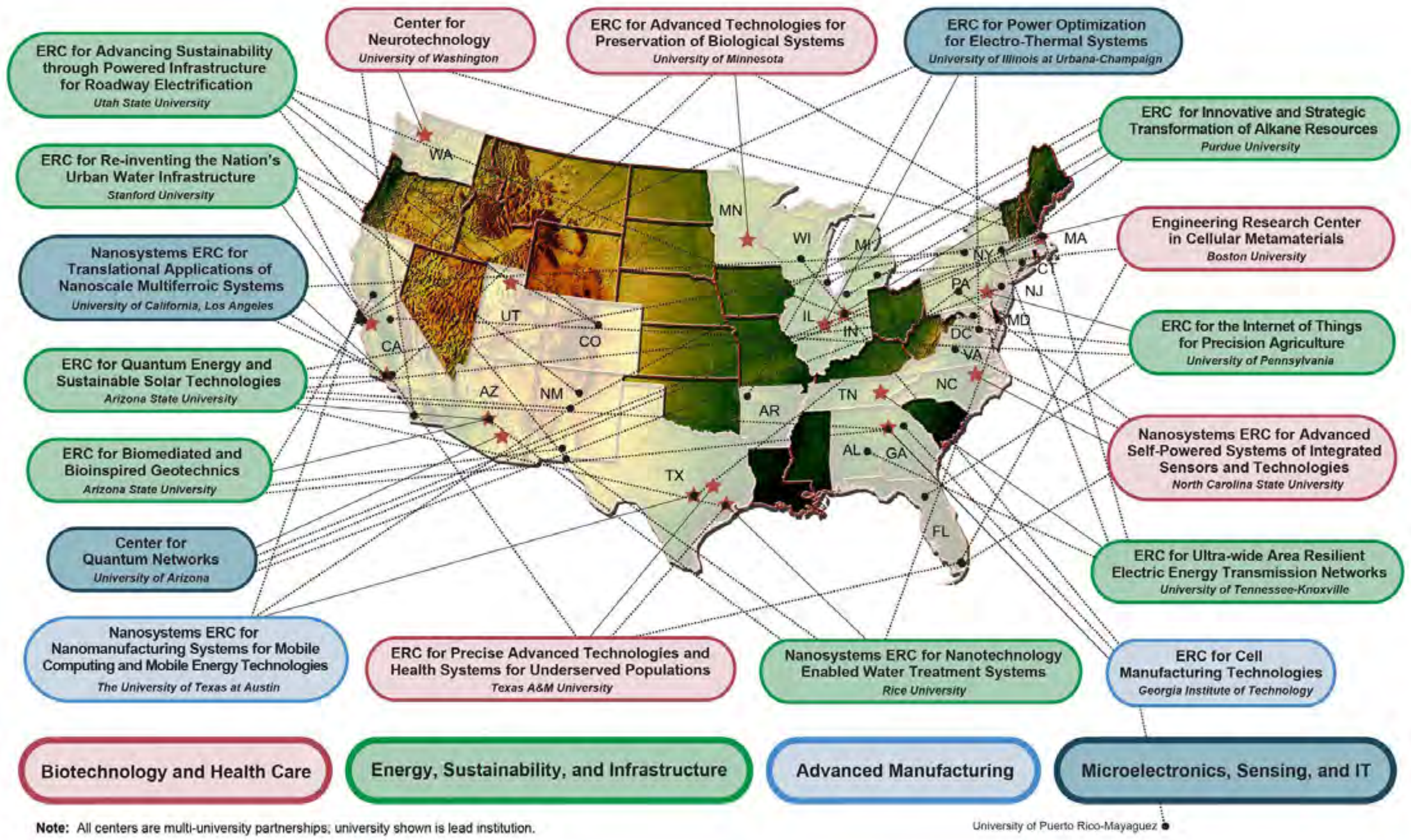
Two automated testbed reactors were installed to support two research thrusts at the **Center for Innovative and Strategic Transformation of Alkane Resources** (CISTAR), an ERC based at Purdue University. One reactor is a Micro-BTRS (Boron Thermal Regeneration System) with eight parallel reactor tubes for simultaneous testing of eight catalyst samples. The other, an Effi reactor, is highly modular and can be configured to perform nearly any reaction desired within the scope of CISTAR. (See Figure 6-8.) The testbed reactors allow for testing of catalysts at industrial conditions on a benchtop scale and are automated for greater efficiency and faster data collection.

CISTAR industrial consortium member Micromeritics provided the equipment through in-kind donations. The testbeds will further CISTAR's technical vision of creating transformative engineered system to convert light hydrocarbons from shale resources to chemicals and transportation fuels in smaller, modular, and highly networked processing plants.

Figure 6-8: *The Microactivity Effi reactor (top left) and Micro-BTRS reactor (top right), donated by Micromeritics, with Evan Sowinkski of Purdue University overseeing installation of the testbeds (below). (Credit: CISTAR)*

7. ACADEMIC PARTNERSHIPS: GLOBAL COLLABORATION

CLOSE COLLABORATION AMONG MULTIPLE UNIVERSITY PARTNERS IS ONE OF THE MANY WAYS IN WHICH ERCS HAVE REDEFINED THE CONCEPT OF AN ACADEMIC RESEARCH CENTER OVER THE PAST THREE DECADES, SERVING AS A MODEL AND AN INSPIRATION FOR OTHER CENTERS PROGRAMS IN THE U.S. AND AROUND THE WORLD. THEY CONTINUE THAT PATH-BREAKING ROLE TODAY.



Note: All centers are multi-university partnerships; university shown is lead institution.

Figure 7-1: *FY 2020 ERCs Lead Institutions (★) and Core Partners*

Since 1998, all newly funded ERCs have been multi-institutional. That is, they have in addition to the lead institution several core partners (most often three but sometimes four or more). They also have active affiliations with outreach institutions, including female and minority-serving institutions and NSF diversity awardees (LSAMPs, etc.). The core partners participate as full partners in pursuing the strategic goals of the center in research, education, and technology transfer. Although they may be geographically quite dispersed, the collaboration is continuous and multifaceted, including shared curriculum and graduation requirements, regular student and faculty exchanges, joint meetings, etc. Interactions with outreach institutions can involve research collaborations, hosting students, and joint projects of various kinds.

A BROAD NETWORK OF PARTNERSHIPS

The map in Figure 7-1 shows the wide distribution of lead and core partner institutions across ERCs in FY 2020—54 across the 18 ERCs. There were a total of 739 participating institutions at all academic levels and locations worldwide.

Over the past two decades it has become common for ERCs to collaborate in both research and education with foreign universities and research facilities—although in recent years, with greater restrictions on the use of NSF funds for foreign travel and foreign students support and especially with the impact of COVID-19, this trend has moderated. Often, the research collaboration takes the form of cooperation in a highly defined area in which the foreign institution has recognized expertise. Or a testbed might be set up at the foreign institution that is useful for extensive testing of concepts developed by the core partners, with students and researchers going in both directions.

As of the end of FY 2020, the ERC participating institutions included a total of 54 foreign institutions in 26 different countries. There were 75 individual participants associated with these institutions. The map in Figure 7-2 shows the distribution of these participating institutions.[1]

	🏛	👤
Australia	2	2
Brazil	2	1
Canada	5	4
China	29	19
Denmark	1	0
Egypt	1	0
France	1	1
Georgia	2	0
Germany	6	5
Greece	1	0
Hong Kong	1	1
India	1	0
Ireland	4	10
Israel	1	0
Italy	1	0
Japan	6	5
Jordan	1	1
Mexico	4	0
Netherlands	1	0
Qatar	1	1
Russia	1	5
Saudi Arabia	1	0
Serbia	1	0
Singapore	1	0
South Africa	2	0
South American Countries, Other	1	0
South Korea	2	1
Sweden	2	1
Switzerland	3	5
Taiwan	1	0
United Arab Emirates	1	0
United Kingdom	12	3

Figure 7-2: *Locations of Foreign Participating Institutions, FY 2020 (Source: CBS)*

During FY 2020 NSF undertook an expansion of the existing Center-to-Center (C2C) mechanism for collaboration between ERC and foreign research institutions. Following an earlier pilot test case, the mechanism was expanded to several other collaborations. In FY 2020 the expanded model was further broadened to encompass a worldwide "open call" for proposals for C2C collaboration. Working with a content contractor, VentureWell, and web database and programmer contractor Creative Business Systems, Inc., NSF built an extensive new area of the ERC Association website for this purpose. Figure 7-3 is an outline of the planning for the C2C site.

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[1] Institutions in countries showing fewer participants than institutions are retained on the table for ease of year-to-year reporting.

Figure 7-3: *An outline of the planning for launch of the new Center-to-Center (C2C) program website.*

The NSF's ERC Program's evolution into Gen-4 ERCs, with their emphasis on convergent research, workforce development, collaborative team-building, and societal impact brings into even greater focus the importance of multi-institutional academic partnerships. The networks that ERCs have to build to achieve their goals must function more smoothly and seamlessly than ever to succeed.

8. CENTER KEY EVENTS

WITH FOUR NEW GEN-4 ERCS BEING ADDED TO THE PROGRAM IN FY 2020, THIS FLAGSHIP NSF PROGRAM CONTINUES TO EVOLVE AND GROW.

The Gen-4 ERCs are here!

1
ERC for Advanced Technologies for Preservation of Biological Systems
(ATP-Bio)

2
ERC for Advancing Sustainability through Powered Infrastructure for Roadway Electrification
(ASPIRE)

3
ERC for the Internet of Things for Precision Agriculture
(IOT4AG)

4
ERC for Quantum Networks
(CQN)

NEW ERCS: THE CLASS OF 2020

In the summer of 2020, a lengthy process of selection of the first cohort of Generation-4 ERCs culminated in the establishment of four new ERCs. Gen-4 ERCs build on the features of Gen-3 ERCs but with an emphasis on “convergent research” and innovation through inclusive partnerships and workforce development. Informed by a 2017 report of the National Academies entitled *A New Vision for Center-based Engineering Research*, the Gen-4 ERC program places greater emphasis on high-risk/high-payoff research leading to societal impact through a deeply collaborative, team-based approach to problem solving that cuts across disciplinary boundaries.

The four new ERCs are:

ERC for Advanced Technologies for Preservation of Biological Systems (ATP-Bio)

In pursuit of its vision of dramatically advancing the field of biopreservation, ATP-Bio aims to "suspend biological time" and radically extend our ability to bank and transport cells, micro-physiological systems (MPS or "organs-on-a-chip"), aquatic embryos, tissue, skin, whole organs, and even whole organisms through a team approach to building advanced biopreservation technologies.

The Center plans to accomplish this by engineering technologies that will be applied to biological systems before cooling, during cooling and stasis at subzero temperatures, and during rewarming to normal biological temperatures. At each stage, engineering will aim at eliminating or controlling ice, mitigating toxicity from cryoprotective agents, and eliminating thermal and mechanical stress (which are the prime causes of biological damage at subzero temperatures).

They envision a world in 10 years in which a broad spectrum of biological systems are preserved in a high-throughput manner for a wide range of benefits to humankind and the natural environment. They also anticipate that the core technologies developed by ATP-Bio will be the foundation for advances in nanotechnology, 3D printing, genetics, and numerous other fields that will be merged to improve biopreservation.

ATP-Bio is based at the University of Minnesota in partnership with Massachusetts General Hospital, the University of California, Berkeley, and the University of California, Riverside.

ERC for Advancing Sustainability through Powered Infrastructure for Roadway Electrification (ASPIRE)

Electric vehicles (EVs) have arrived, and are expected to be the future of transportation. They offer tremendous opportunity to both reduce emissions and stabilize and reduce costs. But significant challenges remain in the pursuit of widespread adoption of EVs; these challenges are centered around range and the supporting charging infrastructure.

The ASPIRE ERC is the first of its kind in the world to take a holistic approach to eliminating range and charging as barriers for electrifying all vehicle classes, from passenger cars to heavy duty trucks. ASPIRE's vision is of widespread electrification of all vehicle classes with shared charging infrastructure, leading to equitable reductions in greenhouse gas emissions, improved air quality, reduced cost to move people and goods, and increased domestic job growth.

The Center's approach is to pursue innovative wireless and plug-in charging and infrastructure technology solutions that bring the power to the vehicles—where they drive and park. The result will be smaller and longer-lasting batteries on vehicles, effectively unlimited EV range, and a seamless charging experience. EV users will no longer be concerned with when, where, or how they will charge, and EVs will be less expensive to purchase and operate than their gasoline and diesel counterparts. EVs will become a resource to decarbonize the electric grid and a perfect match with autonomous and connected vehicles.

ASPIRE is based at Utah State University, in partnership with Purdue University, the University of Colorado, and the University of Texas at El Paso.

ERC for the Internet of Things for Precision Agriculture (IoT4Ag)

By 2050, the US population is estimated to grow to 400 million and the world population to 9.7 billion. Current agricultural practices account for 70% of global water use; energy use is one of the largest costs on a farm; and inefficient use of agrochemicals is altering Earth's ecosystems. With finite arable land, water, and energy resources, meeting the goal of ensuring food, energy, and water security will require new technologies to improve the efficiency of food production, create sustainable approaches to supply energy, and prevent water scarcity.

The mission of the IoT4Ag ERC is to create and translate to practice Internet of Things (IoT) technologies for precision agriculture and to train and educate a diverse workforce that will address the societal grand challenge of food, energy, and water security for decades to come. The Center will pursue its technological mission by creating novel, integrated systems that capture the microclimate and map a variety of stresses for early detection and intervention to result in better outcomes in agricultural crop production. It will create IoT technologies to optimize practices for every type of plant, wherever grown. These will range from sensors, robotics, and energy and communication devices to data-driven models constrained by plant physiology, soil, weather, management practices, and socio-economics.

Ultimately, IoT4Ag aims to deliver more crop for every drop of water and joule of energy to ensure a food, energy, and water-secure future. IoT4Ag is led by the University of Pennsylvania, in partnership with Purdue University, the University of California, Merced, and the University of Florida.

ERC for Quantum Networks (CQN)

One of the great engineering challenges of the 21st century will be to lay the technical and social foundations of the quantum Internet. This is the challenge that the CQN is taking on. The Center brings together experts with a wide variety of backgrounds to develop the device technology and theoretical research needed to realize the vision of a scalable quantum Internet. The quantum Internet will surpass the capabilities of today's Internet because of the unique advantages of "entanglement"—a coordination of the quantum states of particles serving as computational bits in a way that is not possible in the realm of classical physics.

The quantum Internet will provide the new service of quantum communication that is not possible today—that is, the act of transmitting quantum bits (qubits) reliably at high rates among multiple users simultaneously, supporting a range of new applications that will have far-reaching impacts for technology and society. Quantum communication will improve the Internet in at least two important ways. First, it will enable physics-based communication security that cannot be compromised by any amount of computational power. Second, the quantum Internet will create a global network of quantum computers and processors, as well as ground- and space-based sensors, that are fundamentally more powerful than today's technology. This will bring unprecedented advances in distributed computing and the Internet of Things, and it will enable secure access to cloud-based quantum computation for the public.

In pursuit of this mission, CQN aspires to become an idea-generation hub and epicenter driving the maturation of the new discipline of Quantum Information Science and Engineering (QISE). CQN's closely intertwined research and educational missions will prepare the quantum-trained engineering workforce of the 21st century.

CQN is based at the University of Arizona, in partnership with Harvard University, Massachusetts Institute of Technology, and Yale University

CENTER LEADERSHIP

Executive management positions in the existing ERCs (Center Director/Deputy Director and Managing/Executive Director levels) saw no changes in FY 2020—an indication of the health and stability of the centers. At the four new Gen-4 ERCs, top leadership was as follows:

ATP-Bio:	Center Director– Dr. John Bischof Deputy Director– Dr. Mehmet Toner Integration Director– Dr. Rhonda Franklin
ASPIRE:	Center Director– Dr. Regan Zane Campus Directors (Co-PIs)– Dr. Konstantina "Nadia" Gkritza (Purdue U.), Dr. Qin "Christine" Lv (U. of Colorado-Boulder), Dr. Soheil Nazarian (U. of Texas-El Paso), Dr. Christopher Fawson (Utah State U.), and Dr. Grant Covic (U. of Auckland, New Zealand)
IoT4Ag:	Center Director– Dr. Cherie Kagan Site Directors– Dr. David P Arnold (U. of Florida), Dr. David J Cappelleri (Purdue U.), Dr. Catherine M H Keske (U. of California-Merced), and Dr. Kevin T Turner (U. of Pennsylvania)
CQN:	Center Director– Dr. Saikat Guha Co-Deputy Directors– Dr. Jane Bambauer and Dr. Dirk Englund

The broad distribution of leadership across these centers, as part of an executive team led by the Center Director, reflects the Gen-4 ERCs' increased emphasis on convergent research and collaborative team-building.

MAJOR CONFERENCES HOSTED

The COVID-19 pandemic sharply curtailed planned conferences during FY 2020. However, ERCs still found ways to interact creatively with their peers.

International Workshop on Energy Harvesting

The **Center for Advanced Self-Powered Systems of Integrated Sensors and Technologies** (ASSIST) was selected to host the Second International Energy Harvesting Workshop, EnerHarv 2022, to be held on the Centennial Campus of North Carolina State University in in April 2022. Originally planned for June 2020, the workshop was rescheduled due to COVID-19. EnerHarv 2022 will bring together experts from around the world working on all technical areas relevant to energy harvesting, power management, and its IoT applications. Planning for the workshop, sponsored by the Power Sources Manufacturers Association (PSMA), continued throughout FY 2020.

Center Promotes National Capacity-Building

Figure 8-1: Participants in the national capacity-building institute (Credit: CNT)

In FY 2019 the **Center for Neurotechnology** (CNT) was awarded an INCLUDES supplement to its base ERC grant to build a collaborative infrastructure for broadening participation in NSF-funded research and practice. As part of the Center's existing AccessERC program, the new ERC-INCLUDES project responds to NSF's call to create opportunities among currently funded NSF projects by fostering collaborations between the ERCs and the broader

NSF INCLUDES National Network. Goals of ERC-INCLUDES are:

- To integrate evidence-based broadening participation practices of INCLUDES into the ERCs.
- To share ERC diversity activities and outcomes to inform research/practice of INCLUDES projects.
- To build a durable collaborative infrastructure for broadening participation in NSF-funded research through the engagement of ERCs with the NSF INCLUDES National Network.

In April 2019 the project kicked off with a national capacity-building institute, hosted by the CNT. At the conference, representatives from ERCs and NSF-funded INCLUDES projects promoted best practices for engaging women, racial and ethnic minorities, first-generation college students, individuals with disabilities, and other groups underrepresented in STEM education.

In FY 2020, proceedings of the conference were published online and an online Community of Practice was formed. The Community consists of individuals who work at NSF-funded projects across the United States, especially ERCs and INCLUDES initiatives, members:

- discuss broadening participation and how to recruit participants with diverse characteristics into their programs and activities;
- recruit participants with diverse characteristics into mentoring, internships, and workshops to complement their activities;
- discuss best practices and resources identified at capacity-building institutes;
- discuss the implementation of universal design to make facilities, products, and activities more welcoming and accessible to individuals with disabilities; and
- share ideas about seed grants, new initiatives, and lessons learned.

National Workshop on Multiferroic Antennas

In January 2020, just before the start of the pandemic that halted many planned meetings worldwide, the **Nanosystems ERC** (NERC) **for Translational Applications of Nanoscale Multiferroic Systems** (TANMS) hosted a research and strategy workshop focused on multiferroic based antennas. This was TANMS' 6th Annual Research Strategy Meeting (ARSM). This annual event has been generating growing interest in the potentials of multiferroic applications since its first meeting in 2014. The 2020 workshop gathered the leading researchers throughout the country representing academia, industry, and government agencies along with program managers from the three main military services, focusing on new antenna developments. The workshop was extremely successful at advancing the fundamental engineering and science efforts on this topic and was equally important in generating interest within governmental agencies. As a result of this meeting, TANMS Center Director, Professor Greg Carman, organized a committee of leading experts in the field to propose a potential topic for the Department of Defense Multidisciplinary University Research Initiative (MURI), potentially providing new funding for ensuring that multiferroic technology continues to grow within the U.S.

***Figure 8-2:** TANMS's 6th Annual Research Strategy Meeting was highly successful in focusing research attention on multiferroic antennas.*

9. PROGRAM MANAGEMENT

ENLIGHTENED, CONSISTENT PROGRAM MANAGEMENT IS ONE OF THE KEYS TO THE SUCCESS OF THIS LANDMARK PROGRAM.

DURING COVID-19, THE ERC PROGRAM continued to survive and thrive under innovative management.

Engineering Research Centers

Gen-4 ERC:
Pre-recorded Program Overview

NSF 19-503

Kickoff Meeting
October 14-15, 2020
Deborah Jackson, ENG/ERC Program Director

PROGRAM EVOLUTION

FY 2020 was an eventful year for the NSF's ERC program. In response to a Program Solicitation issued in FY 2019 for the first cadre of Gen-4 ERCs, a large number of proposals were received and site visits were conducted. At the end of the process, in August 2020, four of the finalists were selected to form the new Class of 2020. These new ERCs are described in the preceding section on "Center Key Events." In addition to the awarding of the first cadre of four Gen-4 centers, a Program Solicitation was issued in January 2020 for the next cohort of new centers.

The Gen-4 Program Solicitation clearly describes the nature and goals of Gen-4 ERCs: *The ERC program supports convergent research that will lead to strong societal impact. Each ERC has interacting foundational components that go beyond the research project, including engineering workforce development at all participant stages, a culture of diversity and inclusion where all participants gain mutual benefit, and value creation within an innovation ecosystem that will outlast the lifetime of the ERC.*

This mandate is at once broader and more defined than those of earlier generations of ERCs. Convergent research is a new concept in the organization and work of ERCs. The 2017 National Academies study that informed much of the Gen-4 model, "A New Vision for Center-Based Engineering Research," recommended that NSF place "greater emphasis on forming research centers focused on convergent research and education approaches that address challenges with significant societal impact." Complex societal problems, the report asserted, require a convergent approach for the deep integration of knowledge, tools, and ways of thinking across disciplinary boundaries. Achieving it requires a change in emphasis.

Accordingly, while the Program continues as in the past to focus on advancing an engineered system through inclusive cross-disciplinary and cross-sector partnerships, it now also places greater emphasis on research with high-risk/high-payoff ideas that lead to societal impact through convergent approaches, engaging stakeholder communities, and using team science concepts for their team formation. In addition, while ERCs have sought increasingly over the years to improve the diversity of their students, faculty, and staff by engaging women and minorities traditionally underrepresented in engineering—and thereby helping to strengthen the diversity of the Nation's engineering workforce—the culture of Gen-4 ERCs is expected to demonstrate an environment of inclusion in which all members feel valued and welcomed, creatively contribute, and gain mutual benefit from participating.

In order to achieve the goal of strong societal impact, Gen-4 ERCs are expected not only to create fundamental knowledge and technology, but also to impact the broader engineering community, preparing students and researchers by emphasizing these new engineering approaches and best practices for engineering workforce development, diversity and inclusion, and academic-industrial partnerships. To that end, Gen-ERCs will be exemplars of how cohesive, high-performing teams engage in convergent research and innovative approaches so as to achieve these major impacts on engineering research and practice.

PROGRAM LEADERSHIP

The NSF ERC Program team consists of the Program management, with (in FY 2020) Dr. Kon-Well Wang as Director of the Division of Engineering Education and Centers (EEC) and Dr. Don Millard as Deputy Division Director, with primary responsibility for leading the ERC Program;[1] Program professionals and support staff with responsibilities ranging from education programs to program evaluation and reporting, to communications including websites and publications; and ERC Program Directors and Co-Directors in four broad technology areas or "clusters." These personnel comprise the "ERC Family" and are depicted in the ERC Association website.

EEC ERC Program staff and supporting staff leaving in FY 2020 were: ERC Program Director Junhong Chen and Engineering Education Program Director Julie Martin. Arriving as a new EEC ERC Program Director in FY 2020 was Ralph Wachter (detailee). ERC Program Co-Directors from other divisions in the Engineering Directorate assisted with ERC oversight as part of their overall duties.

MANAGING IN THE PANDEMIC

In early March 2020 a COVID-19 pandemic was declared nationwide, triggering extensive changes in the way that business was conducted in government, academe, and industry. Virtual meetings, which had been occasional using online platforms like Zoom and Microsoft Teams, now became universal. NSF staff no longer came in to the office and instead began working entirely from home.

Engineering Research Centers

ERC

Gen-4 ERC:
Innovation Ecosystem

NSF 19-503

Kickoff Meeting
October 14-15

Deborah Jackson, ENG/ERC
Program Director

Figure 9-1: *A slide from the "Kickoff" meeting for the new FY 2020 ERCs, held virtually with faculty and staff of all four centers*

It took some time to become acclimated to the new work and meeting protocols—especially with complex in-person meetings like ERC site visits, which had to be postponed to allow for a total change in format. The schedule of proposals for the FY 2021 ERC solicitation had to be extended indefinitely. By the end of FY 2020, in late September, COVID-19 cases were just peaking in much of the Nation, vaccines had not yet been approved, and there was no end yet in sight.

In the face of that unexpected and unparalleled challenge, NSF ERC Program staff organized to continue doing their work and pursuing their mission. They coordinated with the ERCs, whose staff had undergone similar major adjustments, to establish new ways of sharing information and maintaining their working relationships. For example, the "Kickoff" meeting for the new centers awarded late in FY 2020, normally conducted on-site, was planned virtually and then held in mid-October 2020, and was conducted via Zoom (see Figure 9-1). "Wellness Supplements" were made available to the centers to award to students on a need basis to facilitate their ability to work and study remotely.

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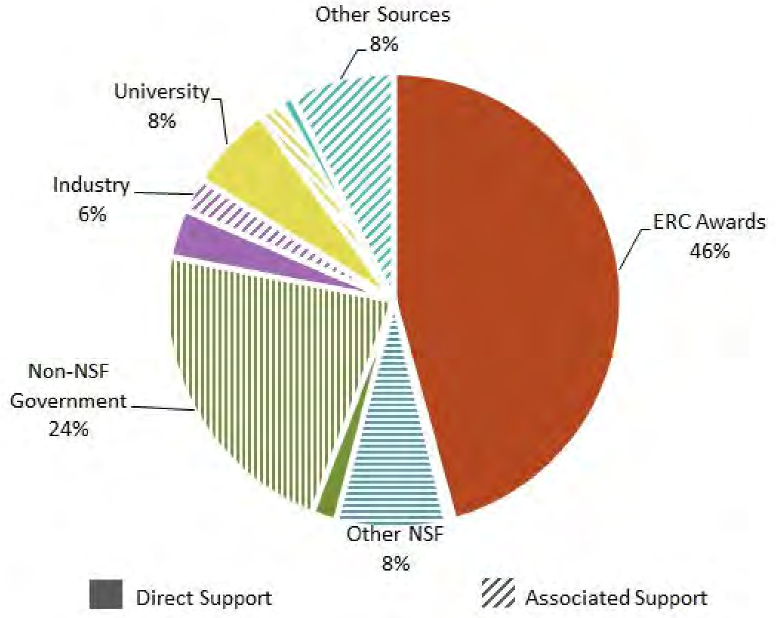
[1] In October 2020 Lynn Preston, longtime Leader of the ERC Program who had retired from NSF in 2014, passed away after a lengthy illness.

ERC BUDGET AND LEVERAGED SUPPORT



Total Value of Support: $117 million

Figure 9-2: *Total ERC New Cash Support, FY 2020 (15 ERCs)*

The ERC Program budget at NSF in FY 2020 was $54.61M. Most of those funds ($49.7M) supported the ERCs' base budgets and growth. The remaining funds were used for special-purpose supplements such as REUs and RETs ($3.28M) and operating cost for the program ($1.63M), such as program review and evaluation costs. Operating cost were lower than usual due to the impact of the pandemic in most of 2020.

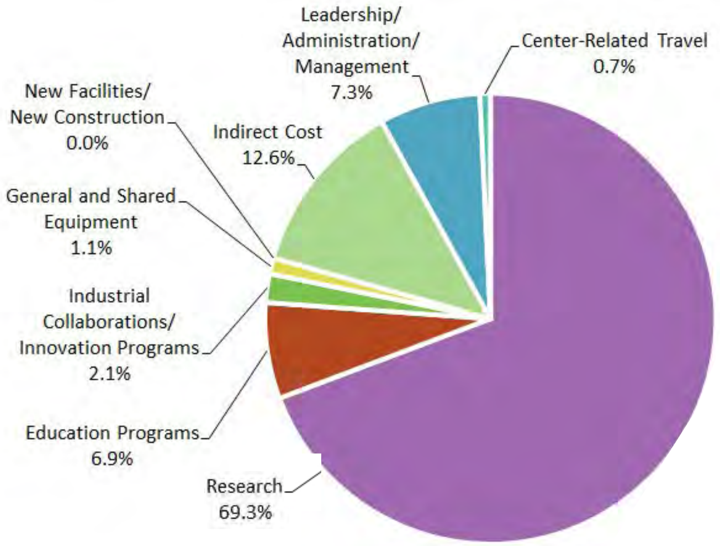
Total direct cash support for the 15 reporting ERCs from all sources in FY 2020 was $117M. Figure 9-2 shows the breakdown of this support by source. In addition to direct support (funds that are provided to the ERC and flow from its budget for expenditures), ERC faculty also directly receive support for associated projects that are under the scope of the ERC's strategic plan.

In FY 2020, total support for associated projects, including in-kind support, was $91.7M (see Table 9-1). The table also shows the number of participants in ERC research and education activities.

Table 9-1: ERC Estimates for Centers Participation - 2020

Number of Participating Institutions	739
Number of Industrial Members*	278
Number of Core University Partners	41
Total Leveraged Support**	$91,711,010
Number of Participants***	3320

* Includes Domestic and Foreign Industrial/Practitioner Members
** Includes Total Non-ERC Program Cash, Total Unrestricted Cash Sources, Total Restricted Cash Sources and Total in-kind Support
*** Includes All Personnel and Young Scholars



Direct Support Total $123,196,745

Figure 9-3: *Functional Budgets of ERCs in the Aggregate, FY 2020*

Figure 9-3 shows the allocation of the ERC's direct support (including in-kind and other noncash support) for different functions. Note that the majority (69.3%) of the funding was allocated to research.

WEBSITE AND BEST PRACTICES

During FY 2020 the ERC Program's prime support contractor, Creative Business Solutions (CBS, Inc.) migrated the ERC Association website to Amazon Web Services (AWS), the server platform on which the nsf.gov website operates. Working with another contractor who supplied the content, CBS also built the subdomain for a new international portal for the expanded center-to-center (C2C) program (see chapter 7).

The ERC Best Practices Manual consists of nine chapters covering all aspects of organizing and operating an ERC. These chapters are written by ERC faculty and staff. The various chapters are periodically revised to reflect the evolution of practices and new features of the program. A new Best Practices chapter on Diversity and Culture of Inclusion (Ch. 7) in ERCs was in preparation in 2020 and completed in FY 2021 (see section 5).

ERC HISTORY PUBLISHED

AGENTS OF CHANGE: NSF'S ENGINEERING RESEARCH CENTERS
A HISTORY

Figure 9-4: *A book-length history of the NSF's ERC Program was completed and published in FY2020. (Credit: NSF)*

In August 2020 a book-length history of the NSF ERC Program entitled *Agents of Change: NSF's Engineering Research Centers—A History* was completed. Written by Lynn Preston, who led the Program almost from its inception until 2013, and Courtland Lewis, the Program's long-time communications consultant, the 700-plus page history was published as an e-book on the ERC Association website and disseminated by email notice to hundreds of organizations and key individuals in academe, industry, and government throughout the U.S. and the world. The book is easily navigated and searched and also provides links to hundreds of supporting resource and reference materials.

Shortly after the book was completed and published, Ms. Preston succumbed to a year-long illness and passed away. The History is a fitting culmination of a professional lifetime of service in shaping and leading the ERC Program.

DIVERSITY STATEMENT

During FY 2020 an NSF ERC Program Statement on DCI was being prepared. This document, published in 2021, is the first formal ERC Program position on DCI to be published since 2004. It is intended to provide greater clarity among NSF Program Directors, and ERC leadership and personnel regarding expectations for ERC Diversity and Culture of Inclusion programs. It is available for download via the ERC Program website.

NSF

ERC ENGINEERING RESEARCH CENTERS

Engineering Education and Centers Division, Directorate for Engineering
National Science Foundation
http://www.nsf.gov/div/index.jsp?div=EEC
ERC Association: http://www.erc-assoc.org

Report No. NSF 22-104