**CASE STUDY:**

**Environmentally Benign Semiconductor Manufacturing, Semiconductor Research Corporation (SRC)/NSF ERC (1996)**

In 1994, the Semiconductor Research Corporation (SRC) approached NSF with the proposition that the NSF and the SRC jointly develop a program solicitation for an ERC that would be focused on topics of interest to the SRC members, jointly funded, and jointly reviewed pre-award and post-award. This partnership represented an opportunity for the ERC Program to collaborate with an industrial organization representing the semiconductor industry. It would build on the strengths of the ERC construct and the strengths of the Program in soliciting proposals for new centers, managing a competitive pre-award review process, creating funding instruments that would ensure delivery on the goals of a center, and providing effective post-award oversight to strengthen a center and weed out failed centers. These would be joined with the strengths of the SRC in direct industry/university cooperation in research and technology development.

The process began with the development in 1994 of a Memorandum of Understanding (MOU) and its approval in March 1995. The MOU spelled out the basic principles of the partnership and the characteristics of an NSF/SRC ERC. Getting to that signature stage took some time and involved the development of a new understanding by the SRC staff and its industry members of how NSF functioned as well as a new awareness on the part of NSF of the SRC’s expectations regarding intellectual property and the strengths of the SRC’s industry-focused project-level oversight system.

* The initial point of contention between NSF and the SRC was SRC’s assumption that support of an ERC at a particular university would grant background intellectual property (BIP) rights to all semiconductor research previously funded at that university. NSF was wary of participating in the partnership because the SRC BIP policy applied through the ERC would have a strong ripple effect throughout the university community. However, the SRC was concerned that previously developed IP, or BIP, could block the use of research results from a given research program at the ERC. Preston brought the issue to NSF Deputy Director Joseph Bordogna’s attention He took over from there because the BIP issue was being raised by the SRC more broadly, as it provided research funding at major research universities across the country. A meeting was held with the leaders of these universities, Bordogna, and leaders of the SRC and a compromise was reached for fair treatment of BIP that balanced the needs and interests of universities and industry. This was achieved by using NSF’s standard policy regarding intellectual property rights, whereby IP developed under the shared base research programs of any funded project or center would be consistent with the Bayh-Dole Act. Under these terms, firms that were members of the ERC at the time a patent disclosure was received by the NSF and the SRC would be granted worldwide, non-exclusive, royalty-free licenses to all inventions or other IP developed under the shared base research programs of the center. The universities involved in the ERC would remain free to license patents commercially to non-sponsoring companies. Following this resolution, Preston proceeded with the MOU.

While the MOU was in negotiation, a program announcement was being drafted jointly by NSF and SRC staffs. The announcement scoped out the partnership in terms of review, funding, and oversight and stipulated four areas for proposals: lithography (patterning); interconnections; environmental safety and health considerations in the fabrication of semiconductors; and other technologies pointing to future generations of the (SRC) Roadmap. The announcement was released in 1995 (NSF 95-77).

Twelve proposals were submitted in July 1995, after the submission of 28 letters of intent. The review process followed the standard ERC review system, except that in each stage half of the reviewers selected were suggested by the SRC staff and the other half by NSF. The steps were:

* Formation of a12 members of the Technical Panel (TP)
* Initial mail review by the members of the TP
* TP met at the SRC headquarters in Research Triangle Park, North Carolina, managed by Preston and Holton, the SRC Vice President for Research Operations.
* Three proposals were recommended for site visit.
* Six-member “Blue Ribbon Panel” was formed, which would be responsible for final review and selection.
* Site visits in Septembe and October, 1995, each with a dedicated review team and two members of the Blue Ribbon Panel serving as observers.
* Blue Ribbon Panel met on October 18-20, 1995, at NSF were briefed by NSF/SRC, discussed each proposal and its reviews, proposals were rated and ranked
* Winning proposal was the ERC for Environmentally Benign Semiconductor Manufacturing (EBSM), submitted by Professor Farhang Shadman and his team from the University of Arizona, the University of California at Berkeley, the Massachusetts Institute of Technology, and Stanford University.

At this stage, Holton returned to the SRC to discuss the outcome with the SRC leadership and its Board of Directors from industry. As Holton later told Preston, there was some consternation since some of the member firms had assumed that the winner would be focused on either lithography or interconnects. An influential member of the SRC Board of Directors, Yoshio Nishi, who was a Senior Vice President and Director of Silicon Technology Development at Texas Instruments, made an impassioned plea for support of the winning ERC focused on environmentally benign semiconductor manufacturing because he believed the industry could not continue to manufacture with processes that consumed large amounts of water and resulted in high levels of pollution. His argument held and the SRC Board voted to join NSF in support of the ERC at the University of Arizona.

That was the first hurdle overcome in the partnership. The second reflected the difference in management styles between the NSF and the SRC. The SRC at that time was accustomed to funding research projects in universities with very tight controls over the research, almost in a contract mode. One of the reasons that Sumney wanted to join with NSF was to understand better how to fund fundamental research and provide oversight in a more flexible mode. However, the SRC administrative staffer sent to work with Preston to develop the cooperative agreement did not understand the implications of that new type of oversight for the SRC and insisted on a traditional SRC system of tight controls. Preston called Holton and explained the dilemma. As a result, a more flexible staff person was sent to NSF to work with Preston and the staff of the Division of Grants and Agreements, and a new joint cooperative agreement was developed. The award was recommended through the NSF process, approved by the Director, and the agreement was signed by NSF, the SRC, and the University of Arizona.

The new ERC began operation in 1996 with $1.0M from NSF and an additional $1.0M provided directly to the University of Arizona by the SRC. Post-award oversight was carried out by a cross-sector team: John Hurt, an NSF ERC PD with a materials background; and Dan J.C. Herr, who was responsible for the SRC’s Section on Environment, Safety, and Health Sciences. This team carried out joint post-award oversight in the ERC mode, with reviewers coming from NSF and SRC sources. In addition, the SRC carried out its project-level technical oversight in its traditional mode.

The vision of the NSF/SRC EBSM was: To create and develop the science, technology, and educational methods that will lead to future semiconductor manufacturing facilities with minimal consumables (e.g., water, energy, acids, solvents, gases) and minimum emission of environmentally harmful, unsafe, and unhealthy waste materials. This ERC established itself as the world leader in addressing issues of environment, safety, and health (ESH) relating to semiconductor manufacturing. The ERC and the SRC recognized that in the 21st century, material resources and energy will become scarce and environmental controls will become stricter; in response, semiconductor manufacture must utilize more benign “green” techniques to remain operational. For example, one of the most significant contributions of the EBSM during its time as an NSF ERC was in the area of ultrapure water (see sidebar).

**Energy and Water Savings in the Use of Ultrapure Water**

Millions of gallons of ultrapure water are used in modem semiconductor manufacturing plants during various stages of device fabrication. Ultra-purification of water requires using a lot of energy and a wide variety of chemicals. Therefore, the production of this amount of water and the disposal of an equally large volume of wastewater, which may contain hazardous contaminants, create various environmental, economic, and sustainability challenges.

The CEBSM has developed technologies for both *reduction* of the water usage as well as safe *treatment* of the corresponding wastewater. These technologies have been the result of coordinated collaboration among investigators from the ERC partner universities. For example, a novel sensor hardware (Electro-Chemical Residue Sensor) and its associated metrology software have been developed for real-time and on-line measurement of residual contaminants in the nano-features of the patterned wafers. This breakthrough has significant impact on surface cleaning process, which is one of the largest users of ultra-pure water. This technology together with a process simulator and control has reduced the water usage in some cleaning tools by over 70%.

Another group of integrated projects at the ERC resulted in the development of technologies for recovery and reuse of the water in semiconductor manufacturing plants. The technology uses a combination of on-line monitoring and process simulation for control of recycle loop to avoid contamination accumulation and surge issues that had previously been major obstacles in water recovery and reuse.

Since industry tends to focus upon short-range solutions to pressing problems and leaves long-term issues to academia, this ERC was and is looked upon by industry as providing many long-range ESH solutions. That fact is evidenced by an average of 15 firms supporting the EBSM annually throughout its life under joint support from NSF and the SRC, through 2005. At the time of writing, the SRC and 21 individual firms support the ERC.

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**CASE STUDY:**

**Compact and Efficient Fluid Power (CCEFP) ERC Catalyzed and Sustained by the National Fluid Power Association.*[[1]](#footnote-1)***

In 2006, an Engineering Research Center (ERC) for Compact and Efficient Fluid Power (CCEFP) was awarded to the University of Minnesota, as the headquarters for a seven-university effort to transform fluid power relevant to hydraulics and pneumatics through an infusion of new research, education, and technology. While fluid power may not be the most “sexy” ERC topic, it is one of the most industrially far-reaching. Fluid powered devices are employed in nearly all complex mechanical devices and machines and are used extensively in airplanes, automobiles, trucks, trains, earth-moving equipment, machine tools, manufacturing lines, and medical devices, and in agriculture, construction, and mining. In 2005, at the time of the submission of the winning CCEFP proposal to NSF, it was estimated that over half of all industrial products had fluid power components, with direct sales of $12 billion in the U.S. and $33 billion worldwide; the total sales volume of systems using fluid power components was 10 to 100 times higher. Today, direct sales of fluid power components are estimated at $21 billion in the U.S. and $49 billion worldwide.

In 1953, manufacturers engaged in fluid power technology formed a trade association, the National Fluid Power Association (NFPA). The association began broadening its membership base fifty years later, and today NFPA members represent the industry’s entire supply chain—more than 180 manufacturers of fluid power systems and components, their distributors and suppliers. The association has also established partnerships with more than 150 schools and universities with programs relevant to this technology.

Although improvements in fluid power devices have been made since their invention, the wider application of fluid power has been hindered by a number of shortcomings, including: (1) inefficient components for switching and control; (2) excessive weight and size of systems for generating high pressure fluid; (3) noise and leakage; and (4) awkward operator interfaces. While industry understood that research would help solve these shortcomings, the NFPA saw that the lack of interest in fluid power in academia had resulted in few engineering faculty and graduates who understood fluid power or were positioned to contribute to solutions to these shortcomings in current technology and innovations in fluid power technology. Because the field had been largely neglected in academia for generations, the NFPA sought the formation of an ERC to help solve these issues.

To pursue this goal, as chronicled by Linda Western, who was the Executive Director of the NFPA between 2000 and 2007, the NFPA began a campaign in 2001 to generate interest in fluid power in academia.[[2]](#footnote-2) In launching this effort, the Association hosted an Educators’ Summit that fall to:

* Create a community of interest in fluid power,
* Provide a forum where industry leaders and educators with research interests in and teaching responsibilities for fluid power and motion control technology could learn from one another, and
* Launch discussions about the future of fluid power—its technology and the interest this industry holds for students.

From this convocation, NFPA initiated a strategy to apply for an ERC. The first proposal was submitted in 2003 but it was not successful. So as not to lose the momentum, as Linda Western pointed out to Preston in 2018, the NFPA established an industry-wide cooperative network, the *Cooperative Network for Research in Motion Control through Fluid Power (CNR).*

Meanwhile, with NFPA’s support a second team of researchers filed for the next round of NSF/ERC funding to start the CCEFP ERC. That proposal was led by Kim Stelson, of the University of Minnesota, who also participated in the CNR. According to Western, “Given the competitive nature of this grant, everyone agreed that it was a long shot.”[[3]](#footnote-3) She pointed out that they were jubilant to hear that of the 109 pre-proposals submitted to the ERC competition, the CCEFP proposal was one of 29 invited to submit a full proposal. That proposal met with strong support from the review community, as represented by a comment from the final review panel: “The strongest element of the (CCEFP) proposal is the unprecedented level of industrial support extended to it by the North American Fluid Power Industry.”[[4]](#footnote-4) Finally, in the spring of 2006, NSF announced that the CCEFP was one of five centers to receive the ERC Program approval for an award of multi-millions dollars.

Unbeknownst to the CCEFP team, this award almost didn’t happen. The review panel ranked the highly recommended final proposals and funds were available in the FY 2006 ERC budget to support fully the first year of the first four of them. However, Lynn Preston, the Leader of the ERC Program at the time, remembers that there was a residual in funds reserved for new ERCs sufficient to support one half of one year’s support for a fifth ERC. Given the quality of the research and education, the pledged support from 50 firms and the NFPA, and the strong support of a contingent of panelists who were concerned that there weren’t enough ERCs underway in fields that would support manufacturing industries, she went in search of additional funds to support the CCEFP start-up. She found them with the help of the Deputy Assistant Director for Engineering, Michael Reischman. The needed funds were added to the ERC budget, enabling the support of CCEFP as the fifth ERC in the Class of 2006. The proposal was led by the University of Minnesota with six core partners (Georgia Institute of Technology, the University of Illinois at Urbana-Champaign, Milwaukee School of Engineering, North Carolina A&T University, Purdue University, and Vanderbilt University) and 50 industry supporters.

The NFPA was ecstatic; as Linda Western said in 2006, “the words of Steve Demster, chair of NFPA’s Board in 2004-2005 (NFPA *Reporter*, May, 2006), are prescient: ‘In every industry there are major events that change the destiny of that industry. Often these ‘inflection points’ happen without us even being aware of them until they are virtually a *fait accompli*. The achievement of an NSF-funded Engineering Research Center for Compact and Efficient Fluid Power will be one of those major events.’”[[5]](#footnote-5)

Because Kim Stelson had years of experience in taking his knowledge of controls and applying it to problems in manufacturing and fluid power, he understood that addressing the challenging problems and opportunities in fluid power would require him to lead teams of researchers to work outside their disciplinary comfort zones—to break down disciplinary boundaries and university boundaries and work closely with industry. As chronicled in an analysis of ERC leaders as boundary breakers, “Stelson had a vision to transform fluid power and he energized his colleagues to join in a quest to lend their skills and perspectives to address that vision—to transform an ostensibly ‘dull’ field to one with exciting possibilities to double fluid power efficiency in transportation, jump fluid power systems to increase energy storage by a factor of 10, and shrink the size of new hydraulic and pneumatic technology by 10 to 20 times.”[[6]](#footnote-6)

The engineered systems focus for the ERC’s original research program was motivated and integrated by four systems testbeds:

* Mobile Heavy Equipment (50 kW-500 kW): Excavator
* Highway Vehicles (10 kW-100 kW): Hydraulic Hybrid Passenger Vehicle
* Mobile Human Scale Equipment (100W-1kW): Patient Handling Robot
* Human Assist Devices (10W-100W): Orthosis.

Later, research initiatives also addressed new fluid power applications in the larger and smaller scales: wind power (megawatts) and medical micro devices (less than one watt).[[7]](#footnote-7)

Numerous advances in the fundamentals underlying fluid power and in fluid power technology and education resulted from this joint investment by NSF and the NFPA members. These included, by the end of the 10th year:[[8]](#footnote-8)

* Development of a multi-domain model of positive displacement pumps that is sufficiently predictive to be useful in the design of efficient pumps
* Fundamental understanding of lubricant behavior through the elucidation of a self-consistent model of high-pressure films providing an understanding that pressures greatly exceeding the system-level pressure exist in the small, trapped volumes in hydraulic pumps and motors, leading to the discovery of entrapped volumes of fluids within stationary contacts, which could be exploited to lower the required starting torque for motors
* Development of the first comprehensive seal model that includes heat transfer, deformation analysis, viscoelastic and rod surface roughness effects; micro-texturing is known to greatly reduce friction, with reduction of 80% observed experimentally, leading to significant new knowledge in this area
* A compressed air open accumulator that could be scaled up to utility-scale energy storage systems, using the high power density of hydraulics (liquid fluid power) and the high energy density of pneumatics (gas fluid power) in a single architecture that allows the system to operate at near constant pressure, regardless of the energy content, so that efficiency and power capability can be maintained at all times
* An elastomeric accumulator where the energy is stored as strain, which increases the energy density of the accumulator by three to four times over traditional bladder energy storage, an improved design that could achieve the goal of an order of magnitude increase in storage.
* Demonstration of the pneumatic orthosis for mobility impaired patients;
* New silencer for fluid power systems that is effective, light weight and ready for commercialization.

CCEFP and the NFPA are especially proud of the following technology achievements:

*Energy Efficient Hydraulic Hybrid Excavator:* In 2011, CCEFP researchers at Purdue, led by Monika Ivantysynova, filed a patent for a hydraulic hybrid system for an excavator. The novel hydraulic hybrid system, called displacement control (DC), combines hydraulic hybrid technology with energy-efficient displacement-controlled actuation. Hydraulic accumulators are used to store and reuse brake energy, which helps to further reduce fuel consumption. Novel control and power management concepts allow effective power flows between actuators, engine, and accumulator. The basis for the advantages of DC actuation resides in the complete elimination of resistance control. DC actuation uses a variable-displacement pump to control actuator motion. An additional advantage is the ability to recapture energy from overrunning and breaking loads. As a consequence of the displacement-controlled actuation improved efficiency, the average engine power required for the mobile machine is dramatically reduced. The world’s first 22-ton DC excavator prototype was built at Purdue in collaboration with an industry partner in 2013. A fuel consumption reduction of 35% and more than a 50% productivity improvement were documented in independent testing by a major equipment manufacturer. Caterpillar launched its first production hydraulic hybrid excavator in 2013. In 2014, Caterpillar commercialized the hydraulic hybrid excavator as model 336EH. In contrast to competing electric hybrid excavators, the 336EH was a commercial success, having captured 15% of the excavator market in its class by 2016.

**RunWise**

In 2015, Parker Hannifin pointed to the impacts of hydraulic hybrid drive systems: *RunWise® hydraulic technology reduces fuel consumption by an average of 43 percent*

There are more than 200 refuse haulers equipped with the RunWise hydraulic transmission that have on average reduced fuel consumption by 43 percent compared to conventional diesel fuel refuse haulers. The reduction is nearly double the proposed requirements from the EPA. Additionally, the California Air Resources Board has also certified the RunWise transmission, paired with Cummins Engine Co.’s 2015 model-year engine, as a validated technology to help improve fuel economy and efficiency in California refuse fleets by up to 50 percent.)\*

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*MarketScreener 09/21/2015. https://www.marketscreener.com/PARKER-HANNIFIN-CORP-13997/news/Parker-Hannifin-Hydraulic-Transmission-Outperforms-Proposed-EPA-Emissions-Regulations-for-Heavy-du-21074277/*

*Strain Energy Accumulator.* Current accumulators use either compressed gas or springs to store energy. Conversely, this new carbon nanotube elastomeric accumulator safely stores energy as strain. Energy savings greater than 25% have been demonstrated over existing pneumatic systems.

*Free Piston Engine/Pump.* Precise piston motion control is necessary for reliable operation of a free piston engine pump that can directly convert liquid fuel combustion into hydraulic power. The demonstration of this technology merges the engine and pump into one compact assembly.

*Fluid Power Transmission for Hydraulic Hybrid Powertrains:* An associated project of the CCEFP, funded by Parker Hannifin, extends the displacement control approach to a patented fluid power transmission for hydraulic hybrid powertrains resulting in significant fuel consumption savings that have been commercialized by Parker Hannifin, which created a new division, Hybrid Drive Systems (HDS), located in Columbus, Ohio for the design and manufacture hydraulic hybrid systems.

*Dynamic Systems and Control:* CCEFP research in fluid power was featured in the June 2013 issue of the ASME*’s Mechanical Engineering* magazine. CCEFP’s work on the control of hydraulic hybrid powertrains, the piston-opposed cylinder free-piston engine, the liquid free-piston compressor, and miniature MRI-compatible fluid-powered medical devices were highlighted in the ASME publication.[[9]](#footnote-9)

*Fluid Power Challenge:* The NFPA and its sponsors manage a program of fluid power education activities to challenge middle school, secondary school, and college students to design and fabricate devices and systems using fluid power. These programs range from the use of simple devices at the middle school level (the Fluid Power Action Challenge), to robotics devices and systems at the secondary school level (the Fluid Power Robotics Challenge), to human-powered vehicles at the college level (the Fluid Power Vehicle Challenge). The goal of the overall program is to provide students with an opportunity to learn about fluid power, apply their knowledge to a real-world, open-ended design project, and compete in a national competition to demonstrate their work.

The students shown in the photo competed in the NFPA Robotics Challenge, which is a scholarship program that launched with the 2016-17 school year. “In support of the missions of *FIRST®* Robotics and the National Robotics League (NRL),NFPA will offer one merit-based scholarship, for $40,000 ($10,000 per year for four years)**,** to a high school senior who demonstrates the use of fluid power as part of a 2018 *FIRST®* Robotics or NRL Competition Team. This scholarship may be used to study engineering at any accredited technical college or university in the United States.”[[10]](#footnote-10)

Plans for Self-Sufficiency

By 2012, the CCEFP was a highly productive ERC in both research and education. The NFPA had achieved its mission to raise the visibility of fluid power challenges in academia resulting in this wide range of achievements in fundamental knowledge and technology. However, as an outcome of its sixth-year renewal review where renewal is based on past productivity, the potential for future new innovations, and the quality of the plans for self-sufficiency after year 10, the ERC was not initially renewed. The reason was that the plans for self-sufficiency looked more like the configuration of the original CNR—a loose network of university partners working rather independently. During the site visit, in the private meeting between the industry members and the site visit team, Preston and the site visit team voiced their concern that the plan for self-sufficiency had the potential to cancel out the gains that had been made in the past that had resulted from integrating the work of the faculty across university lines to address the challenges facing fluid power. She made a passionate plea for the NFPA to once again step in to help the faculty prepare a plan that would preserve the CCEFP and prepare it to remain an integrated platform as it moved to self-sufficiency, able to address concerns raised by the NFPA and new opportunities that might arise in new fields, like wind power. The site visit team recommended that the ERC be given a second chance for renewal by preparing a new renewal proposal, which would be reviewed near the end of the seventh year.

***NFPA Robotics Challenge participants***

The NFPA and CCEFP faculty team met to reconfigure their plans for the center post-NSF support. A major change in the membership structure would begin after Year 8. At that time, the previous membership agreement would be terminated. Instead, companies would be invited to join the Pascal Society by contributing to the NFPA Education and Technology Foundation – a tax-exempt, charitable foundation, aligned with the NFPA, and dedicated to meeting the technology and workforce needs of the fluid power industry. Donations would be used to support research projects within the CCEFP. Donors, based on their giving level, would be invited to serve on a series of industry advisory committees responsible for helping to shape CCEFP’s overall research strategy, providing project-level guidance, and conducting cyclical road-mapping exercises.

A second renewal proposal was submitted to NSF and a second renewal site visit was held with the same site visit team. This time the renewal was successful and the CCEFP completed its ten years of NSF support using the Pascal Society industrial partnership configuration.

CCEFP Activity in Preparation for Graduation and Beyond

The Pascal Society support structure lasted for four years, through the 12th year of the center’s life. At its peak, 82 industry partners were engaged, and it provided more than $2.9 million in research funding to the CCEFP. The level of support did not, however, replace the funding provided by the ERC program for administration, or for the number of projects thought necessary to address CCEFP’s diverse research agenda.

With the funding structure of the Pascal Society, industry funding was dedicated to a combination of education, research and outreach activities where CCEFP was just one of the recipients. According to input from Kim Stelson, this caused confusion on the part of industry. Some companies wanted to support the education and outreach activities, some wanted to support CCEFP research, and others wanted to support both. For this reason, beginning in 2018, the CCEFP launched an independent industry consortium. With the separation of funding sources, industry could more clearly choose want they wanted to support. This change also allowed CCEFP to have better communication with a smaller, but more committed group of companies.

Stelson indicated that after the second renewal, the CCEFP strategic efforts focused almost exclusively on sustainability. This was a large challenge since none of the mission oriented federal agencies had programs that directly dealt with CCEFP research areas. The original three thrust areas: efficiency, compactness and effectiveness, were replaced with thrusts more closely aligned with funding sources: off-road vehicles, human-scale fluid power and manufacturing. CCEFP decided to pursue off-road vehicles first, human-scale fluid power next and manufacturing last.

Since 2016, CCEFP has sponsored over $2,000,000 in fluid power research and education projects and leveraged $6,910,378 in affiliated fluid power research initiatives. The Center continues to engage the original core universities through sponsored activity as has negotiated new partnerships at Marquette University, Iowa State University, University of California-Merced, University of Wisconsin-Madison, Texas A&M University, Oak Ridge National Laboratory, and Argonne National Laboratory. CCEFP ‘s education efforts continue to impact across the fluid power research and technology communities through leadership, innovation, advocacy, education, and engagement, including an NSF-funded REU site award, that has sponsored over 250 domestically diverse REUs in its 11-year program. Finally, each Fall and Spring, the CCEFP hosts a Summit at a partnering institution where attendees learn of progress and results of sponsored and affiliated research, tour local laboratory and teaching facilities, and participate in special programmatic features (such as a workshop, social event, etc.). The Summits are also the opportunity for members of the Industry Engagement Committee (IEC) to meet face-to-face during closed-door sessions. Since 2016, over 435 attendees have participated in CCEFP events.

This history demonstrates the significant benefits to the fluid power industry from the formation and operation of the CCFP and the challenges posed to the NFPA and the CCEFP faculty from the ERC Program’s self-sufficiency policy. These challenges were creatively met by the NFPA and CCEFP leadership to continue support for research and education important to so many industries.

1. Collaboratively written by Eric Lanke, President and CEO, National Fluid Power Association (NFPA); Lynn Preston, Leader of the ERC Program (1985–2013, retired NSF 2014); Linda Western, Executive Director of NFPA, 2000–2007, NFPA consultant, 2007–2010; and Kim Stelson, Director of CCEFP, 2006–2018. [↑](#footnote-ref-1)
2. Western, Linda (2012). *Understanding the CCEFP: Knowing Where We Are by Knowing Where We’ve Been.* National Fluid Power Association. Milwaukee, WI. p. 1. [link to file] [↑](#footnote-ref-2)
3. Ibid., p. 2. [↑](#footnote-ref-3)
4. Ibid., p. 3. [↑](#footnote-ref-4)
5. Ibid. p. 3. [↑](#footnote-ref-5)
6. Curral, Steven C., Ed Frauenheim, Sara Jansen Perry, and Emily M. Hunter (2014). New York, Oxford University Press. p.90 and pp. 81-97, Chapter 6, Boundary-Breaking Collaboration. [↑](#footnote-ref-6)
7. Stelson, Kim A. and Perry Y. Li (2013). The Center for Compact and Efficient Fluid Power, *Mechanical Engineering,* *135*(06), S2-S3, June 1, 2013. doi:10.1115/1.2013-JUN-4. [↑](#footnote-ref-7)
8. Center for Compact and Efficient Fluid Power (2018). *CCEFP Highlights: Research, Technology, Education, Infrastructure, Sustainability, Special Initiatives: 2006-2017.* University of Minnesota. [↑](#footnote-ref-8)
9. Stelson, Kim A. and Perry Y. Li (2013). Op. cit. [↑](#footnote-ref-9)
10. http://nfpahub.com/fpc/robotics-challenge/ [↑](#footnote-ref-10)