**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 (2018), direct sales of fluid power components are estimated at $21 billion in the U.S. and $49 billion worldwide.

Fluid power is transmitted and controlled by means of a pressurized fluid, either liquid (hydraulics) or gas (pneumatics). Transmission of energy via fluid power has a number of important advantages over mechanical transmission. Forces generated by fluid power are rapidly transmitted, essentially at the speed of sound in the fluid, over considerable distances with small loss. These forces can be conveyed up and down or around corners with high efficiency and without complicated mechanisms, especially when extremely high force or torque is required. Properly constructed fluid power systems are unrivaled in their ability to deliver high forces to small areas and they eliminate the need for complicated systems of gears, cams, and levers for the transmission of power to perform specified functions. Fluid power systems also offer simple and effective control of direction, speed, force, and torque using simple control valves. And fluid power systems often do not require electrical power, which makes them less vulnerable to electrical shock, sparks, fire, and explosions.

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.

Twenty-four faculty, mostly from the U.S., attended and outlined ways in which industry and academia could work together and apply for grants to bolster fluid power research and education. 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, the NFPA established an industry-wide cooperative network in order to increase interest in fluid power within leading schools of engineering. Linda Western pointed out to Preston in 2018 that after the failure of the first ERC proposal, “NFPA went to plan B, and in 2004 we created the *Cooperative Network for Research in Motion Control through Fluid Power (CNR).* It consisted of a group of 17 NFPA members and 5 university researchers whose work these industry supporters had selected from a field of research applicants. The goal here was to get some collaborative research underway—for its own sake and as proof to NSF that the fluid power industry really was serious in its efforts. I will always be grateful to Andrew Alleyne[[3]](#footnote-3) (University of Illinois), who worked with me in drawing up a model for this network, and who came to NFPA meetings to help me effectively present the concept. Unlike in the original CCEFP proposal, the selected researchers from the five universities worked independently.” These 17 companies collectively pledged $600,000 to fund selected research projects over two years.

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.”[[4]](#footnote-4) 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.”[[5]](#footnote-5) 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. Lynn Preston, the Leader of the ERC Program at the time, remembers that with these four funded there would be a residual equal to one half of one year’s support for a fifth ERC in the Class of 2006. 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.’”[[6]](#footnote-6)

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.”[[7]](#footnote-7)

Numerous innovations 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 include, 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; pressures greatly exceeding the system pressure exist in the small, trapped volumes in hydraulic pumps and motors, and a surprising result of this work is the discovery of entrapped volumes of fluids within stationary contacts; this phenomenon 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, and this research led to significant knowledge in this area;
* Implementation of a full-sized, displacement-controlled excavator, with testing by Caterpillar demonstrating over 35% fuel savings and 50% productivity improvement;
* An open air accumulator that could be scaled up to utility-scale energy storage systems. The patents for the technology are currently licensed by two companies.
* 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:

**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.

Two other CCEFP-developed technologies that are recognized as especially valuable to NFPA members are:

* 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 that has been commercialized by Parker Hannifin. Parker Hannifin has established a new manufacturing division to produce the product. This achievement is largely attributable to Professor Monika Ivantysynova’s remarkable capacity to fulfill the full spectrum of an ERC—from fundamentals to full demonstration in a proof-of-concept testbed in partnership with industry, and transfer to industry.

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

**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). Elements of the various competitions include the design (creativity/novelty, functionality, presence of renewable energy systems), fabrication (quality, aesthetics), design process (design report, cost analysis), and a riding competition (e.g., efficiency, acceleration, and distance events). 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.

Since adoption and implementation of the program in 2009, CCEFP has offered 11 events at the University of Minnesota, Georgia Institute of Technology, and Purdue University. In total, over 2,000 middle school students have participated, including 35 teachers, and have been exposed to fluid power technology and applications

The student shown in the accompanying figure 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)

In addition, a fluid power curriculum was developed by teachers who participated in CCEFP’s Research Experiences for Teachers program and is available at TeachEnginering.com or ccefp.org.

In 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.

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 contribute 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 to a new giving and recognition society within the Foundation, named after Blaise Pascal, would be used to support research projects within the CCEFP, and 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.

**CCEFP Activity After NSF Graduation**

The Pascal Society support structure lasted for four years. At its peak, 82 industry partners were engaged, and it provided more than $2.9 million in research funding to the CCEFP. It 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 support of both its academic and industrial leadership, in 2016 the CCEFP began turning its attention towards new government funding opportunities.

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. 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.

Currently, CCEFP has twenty-three industry members provided $377,000 in membership dues. This has allowed CCEFP to fund two research projects at $80,000 per year and support one full-time administrator, a student assistant and a fraction of the Director’s salary. Also, the Pascal Society has contributed $100,000 per year to provide $10,0000 supplemental grants to ten research projects. The supplemental grants allow faculty and students with research funding from other sources to attend the spring and fall Industrial Engagement Committee (IEC) Summits to present their research results. At the present time CCEFP has stable funding that allows it to continue indefinitely, but it is clear that additional research funding is needed from other sources if CCEFP is to continue to have meaningful impact.

**New Research Thrust Areas**

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. Three new deputy directors were assigned for these thrust areas, Zongxuan “Sunny” Sun of Minnesota for off-road vehicles, Eric Barth of Vanderbilt for human-scale fluid power and Tom Kurfess of Georgia Tech for fluid power manufacturing. Tom Kurfess was later replaced by Tequila Harris, also of Georgia Tech. Recognizing that we must initiate efforts on one thrust at a time to be effective, it was decided to pursue off-road vehicles first, human-scale fluid power next and manufacturing last.

**Off-road Vehicles**

A key insight for developing an off-road vehicle research program was found in a DOE report (Vyas *et al.,* 2013) on the non light-duty vehicle energy improvement strategy. This report stated that off-highway vehicles used in construction, agriculture, mining and forestry consume 8% of total transportation energy, more than marine or aviation transportation. In spite of its size and potential for energy improvement, there was no federal program for energy saving in this sector. Realizing that there was an obvious gap in our nation’s energy policy, we contacted the researchers at Argonne National Laboratory who had conducted the study. They confirmed the lack of understanding, the need for further research and the potential of off-road vehicle energy saving technology. Realizing that CCEFP needed help in identifying and gaining access to key people in the DOE and Congress, CCEFP and the NFPA jointly funded a lobbying firm, Strategic Marketing Innovations (SMI), to help. The CCEFP leadership team, along with industry supporters visited the Vehicle Technology Office (VTO) of the Energy Efficiency and Renewable Energy (EERE) program at DOE in Washington, D.C. Our presentation raised awareness of the energy saving potential of a program for off-highway vehicles and created a better understanding of the key role that hydraulics plays in improving energy efficiency. Industry participation added credibility to the visit.

To create a new program, enabling language was added to the FY17 Energy and Water Appropriations bill creating a $5 million program for energy saving technology for commercial off-road vehicles. Annual visits by industry and CCEFP are conducted to assure continuing congressional support. The program has been renewed in FY18 and FY19. We are now lobbying Congress to increase the funding to $10 million for FY20.

Research funding decisions have been made for FY17 and FY18 with CCEFP researchers receiving a total of $4.4 million for three three-year projects. Each project has industry partners and a 20% cost share requirement. The projects are: “Efficient, Compact, and Smooth Variable Propulsion Motor,” PI: James Van de Ven, Minnesota; “Individual Electro-Hydraulic Drives for Off-Road Vehicles,” PI: Andrea Vacca, Purdue; and “Hydraulic Electric Architectures for Mobile Machines,” PI: Perry Li, Minnesota. The remainder of the funding went to research on coatings, tribology and fluids at Argonne National Laboratory, Oak Ridge National Laboratory and Pacific Northwest National Laboratory and an engine research project at Caterpillar. The funding announcement for FY19 funds is expected in Spring 2019.

**Human-scale Fluid Power**

The human-scale fluid power thrust has also made progress. Sixteen university researchers and twenty-seven industry supporters attended a workshop on human-scale fluid power at Vanderbilt University on December 9, 2015. Topics discussed included MRI compatible devices, rehabilitation, human assist devices, industrial pneumatics, factory automation, robotics, exoskeletons and compact fluid power supplies. There was a clear consensus that the area should be pursued and a series of initiatives started.

Several initiatives have created opportunities for human-scale fluid power research in the aftermath of the workshop. CCEFP participated in initial planning meetings of the Advanced Robotics for Manufacturing (ARM) institute led by Carnegie-Mellon University (see arminstitute.org). Fluid power was recognized in the planning meetings as an essential technology for mobile untethered robots, but follow up with industry has thus far failed to put together a successful proposal team because of the large financial and time commitment involved. Future success will depend on recruiting a large sponsor for collaboration.

Another important initiative was the NSF Emerging Frontiers in Research and Innovation (ERFI) program on Continuum, Compliant, and Configurable Soft Robotics Engineering (C3 SoRo). More than thirty researchers from CCEFP and the Wearable Robotics Association (WearRA) submitted supporting letters for soft robotics research resulting in the creation of this program. Calls for proposals for 2017 and 2019 have been issued, but to date, no CCEFP researchers have been supported. Human-scale fluid power research remains active at several CCEFP universities and the potential for larger research initiatives remains, but has yet to be realized.

**Fluid Power Manufacturing**

The manufacturing thrust has also been actively pursuing follow on research funding opportunities. Two manufacturing planning grants helped to formulate the strategy. One planning grant, Fluid Power Advanced Manufacturing Consortium, was from the NIST AMTech program. Two manufacturing road-mapping workshops were held at Georgia Tech in July, 2015, and January, 2016, with eleven university and twenty-eight industry participants in the first session and seven university and twenty-two participants in the second session. Between and after the workshops extensive planning was done off-line by industry and university participants resulting in detailed roadmaps for ten critical fluid-power manufacturing technologies. These were: coatings, micromachining, composites and engineering plastics, sintered metals, additive manufacturing, batch free heat treating, robotics, hybrid manufacturing, metrology, and in-process sensing, feedback and control. The findings of the study were presented to industry in October 2017, at Sun Hydraulics in Sarasota with six university and twenty-three industry representatives attending. Further details are available in the final report (Stelson, 2018). The second planning grant was from NSF with a different focus. The goal was to identify critical research needs for NSF funding to enable capabilities identified in the NIST roadmap. A workshop was held at the University of Minnesota in May 2016, with eight university and fifteen industry representatives. Recommendations were made in three areas: material properties and process relations, factory automation and control, and system modeling and software tools. Further details are available in the final report (Stelson and Sun, 2017). The planning reports provide a blueprint for fluid power manufacturers and researchers to participate in future National Network for Manufacturing Innovation (NNMI) initiatives.

Based on the insight from the NIST and NSF planning awards, it was decided that coatings and the related areas of tribology and fluids would be the first priority of the manufacturing thrust. With her expertise in this and related areas, Tequila Harris is the ideal leader for this area. Through the DOE off-road vehicle research program, communication on collaboration with Argonne coating researchers has begun. Emerging teams with industry, government and university researchers are being formed. Also, a proposal has been submitted by Argonne to the DOE Technologist in Residence (TIR) program. This program would facilitate connections for future research collaborations between the DOE labs and CCEFP industry members.

**Education, Outreach, and Engagement After Graduation**

The CCEFP continues to create impact across the fluid power research and technology communities through leadership, innovation, advocacy, education, and engagement.  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.

Since 2016, the CCEFP brings hands-on fluid power research experiences to graduate and undergraduate students at 12 institutions.  Each summer and through 2019, the CCEFP is host to visiting undergraduates sponsored by the National Science Foundation's REU Site Award.  CCEFP has sponsored over 250 domestically diverse REUs in its 11-year program.  Over 57% of CCEFP REUs continue into graduate school, 25% of those pursuing PhDs.

On an on-going basis, CCEFP offers *Fundamentals of Fluid Power,*a massive open online course (MOOC) offered through Coursera.  Since 2016, over 15,000 participants, of which 54% are engineering professionals, have enrolled in the MOOC.

CCEFP provides value to its industry and academic stakeholders by providing the means to connect, engage, and disseminate results of CCEFP's work.  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.

**References**

(Vyas, et. al, 2013) Vyas, A. D.; Patel, D. M.; Bertram, K. M. “Potential for Energy Efficiency Improvement Beyond the Light-Duty-Vehicle Sector,” *Transportation Energy Futures Series,* (February 2013). Prepared for the U.S. Department of Energy by Argonne National Laboratory, Argonne, IL. DOE/GO-102013-3706, 82 pp, Available online at [https://www.nrel.gov/docs/fy13osti/55637.pdf](about:blank).

(Stelson, 2018) Stelson, K. A., “Fluid Power Advanced Manufacturing Consortium (FPAMC),” *Final Report for NIST AMTech Planning Grant,* Federal Award ID # 70NANB15H061, August 3, 2018.

(Stelson and Sun, 2018) Stelson, K. A. and Sun, Z. X., “Workshop on Fluid Power Advanced Manufacturing,” *Final report for NSF Award No. 1634216,* May 1, 2017.

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 L Western] [↑](#footnote-ref-2)
3. Andrew Alleyne became one of the co-PIs on the successful CCEFP ERC proposal. [↑](#footnote-ref-3)
4. Ibid. p. 2. [↑](#footnote-ref-4)
5. Ibid. [↑](#footnote-ref-5)
6. Ibid. p. 3. [↑](#footnote-ref-6)
7. 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-7)
8. Center for Compact and Efficient Fluid Power (2018).CCEFP HIGHLIGHTS: Research, Technology, Education, Infrastructure, Sustainability, Special Initiative, 2006–2017. [↑](#footnote-ref-8)
9. Stelson, KA (2013). “The Center for Compact and Efficient Fluid Power.” *Mechanical Engineering*, Vol. 135, No. 6, June 2013. [↑](#footnote-ref-9)
10. http://nfpahub.com/fpc/robotics-challenge/ [↑](#footnote-ref-10)