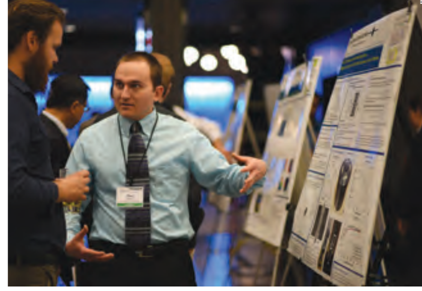
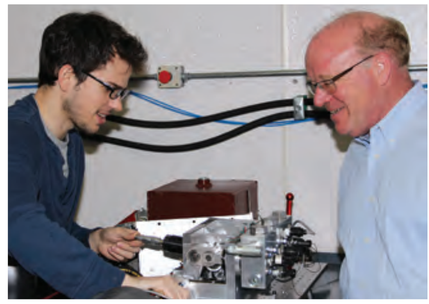
www.ccefp.org

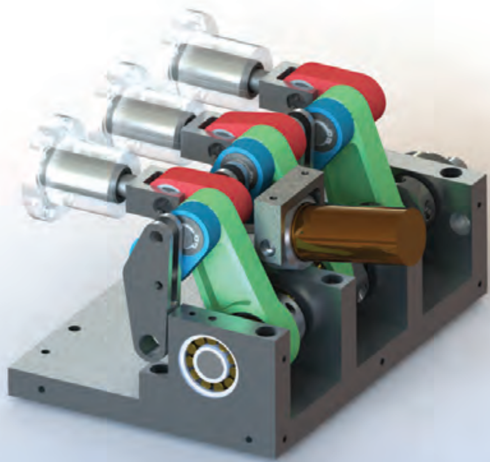




PRELIMINARY FINAL REPORT 2016

COOPERATIVE AGREEMENT #EEC 0540834

VOLUME 1



CENTER FOR COMPACT AND EFFICIENT FLUID POWER

A National Science Foundation Engineering Research Center

University of Minnesota
Georgia Institute of Technology
Milwaukee School of Engineering
North Carolina Agricultural & Technical State University
Purdue University
University of Illinois at Urbana-Champaign
Vanderbilt University

Dr. Kim Stelson, Director
Dr. Eric Barth, Co-Deputy Director
Dr. Zongxuan Sun, Co-Deputy Director

This page is intentionally left blank

Volume I Table of Contents — Page

PROJECT SUMMARY

The Center for Compact and Efficient Fluid Power (CCEFP) is a network of researchers, educators, students and industry working together to transform the fluid power industry—how it is researched, applied and studied. CCEFP research projects are organized in three thrusts that achieve the following societal benefits: creation of new fluid power technology that, with improved efficiency, will significantly reduce petroleum consumption, energy use and pollution; creation of new fluid power technology that, with improved effectiveness, will make fluid power clean, quiet and safe for its millions of users; and creation of new fluid power technology that, with improved compactness, will exploit its attributes in a new generation of human scale devices and equipment. The CCEFP's education and outreach program is designed to transfer this knowledge to diverse audiences—students of all ages, users of fluid power and the general public.

Intellectual Merit:
CCEFP research is demonstrated on four test beds spanning four orders of magnitude of power and weight. These test beds and the classes of equipment they represent are: excavator (mobile heavy equipment, 50 kW-500 kW), hydraulic hybrid passenger vehicle (highway vehicles, 10 kW-100 kW), patient transfer device (mobile human scale equipment, 100W-1kW), and the orthosis (human assist devices, 10W-100W). Although stationary applications will also benefit from CCEFP research, the test beds are mobile applications where the advantages of fluid power are most evident. The test beds will integrate research aimed at overcoming the nine technical barriers of fluid power: efficient components, efficient systems, control and energy management, compact power supplies, compact energy storage, compact integrated systems, safe and easy to use, leak-free and quiet. Three of the barriers are transformational, efficient components, compact power supplies and compact energy storage. Through its strategic planning process, CCEFP has identified the following important goals: 1) doubling fluid power efficiency in current applications and in new transportation applications, 2) increasing fluid power energy storage density by an order of magnitude, and 3) developing new fluid power supplies that are one to two orders of magnitude smaller than anything currently available. The CCEFP fills a void in fluid power research that existed for decades. Until the Center was established, the U.S. had no major fluid power research center (compared with thirty centers in Europe and five centers in Asia). Fluid power researchers, who were previously disconnected, are now linked through the CCEFP.

Broader Impact:
The CCEFP's Education and Outreach Program is intentionally ambitious. It is designed for many audiences—pre-college and college students, fluid power industry stakeholders and customers, and the general public—in recognition that hydraulics and pneumatics is neither well-understood nor often taught. Given the scope of this challenge, the CCEFP maximizes the impact of its education and outreach projects, along with additional related initiatives, through three strategic approaches: partnering with effective and broadly distributed education and outreach networks, focusing on projects that can be replicated and/or adapted by others for audiences outside the Center's reach, and selecting its program menu in such a way that the accomplishments of a given project will bolster the progress and chances of success for another. Informed by the CCEFP's research, the Center's Education and Outreach programs enrich understandings of fluid power technology. But its projects share in a broader goal: to heighten interests in technology and engineering among an increasingly diverse student population.

The CCEFP's 71 corporate supporters as well as a number of other sponsors and participants are key contributors to its success; the partnerships that continue to develop between industry and academia are among the most important of the CCEFP's legacies. Industry will ensure that research results are commercialized and members' interest in and support of the CCEFP's education and outreach programs assure that channels for effective knowledge transfer in fluid power will continue to flourish.

This page is intentionally left blank

Participants Table

PARTNERING INSTITUTIONS

Name of Institution	City	State
University of Minnesota, *Lead University*	Minneapolis	Minnesota
Georgia Institute of Technology	Atlanta	Georgia
University of Illinois at Urbana-Champaign	Urbana - Champaign	Illinois
Milwaukee School of Engineering	Milwaukee	Wisconsin
North Carolina Agricultural and Technical State University	Greensboro	North Carolina
Purdue University	West Lafayette	Indiana
Vanderbilt University	Nashville	Tennessee

LEADERSHIP TEAM

Title of Position	Name	Department	Institution
Director	Kim Stelson	Mechanical Engineering	University of Minnesota
Co-Deputy Director	Eric Barth	Mechanical Engineering	Vanderbilt University
Co-Deputy Director	Zongxuan Sun	Mechanical Engineering	University of Minnesota
Industrial Liaison Officer	Mike Gust	ERC Staff	University of Minnesota
Education & Administrative Director	Alyssa Burger	ERC Staff	University of Minnesota
Sustainability Director	Brad Bohlmann	ERC Staff	University of Minnesota
Contracts and Finance Manager	Jaylee Engebretson	ERC Staff	University of Minnesota
Communications Specialist	Don Haney	ERC Staff	University of Minnesota
Thrust Area 1 Leader	Monika Ivantysynova	Agricult. / Biological Eng.	Purdue University
Thrust Area 2 Leader	Andrew Alleyne	Mechanical Engineering	University of Illinois at UC
Thrust Area 3 Leader	Wayne Book	Mechanical Engineering	Georgia Institute of Technology

THRUST 1: EFFICIENCY

Faculty Researcher	Randy Ewoldt	Mechanical Engineering	University of Illinois at UC
Faculty Researcher	William King	Mechanical Engineering	University of Illinois at UC
Faculty Researcher	David Kittleson	Mechanical Engineering	University of Minnesota
Faculty Researcher	John Lumkes	Agricult. / Biological Eng.	Purdue University
Faculty Researcher	Paul Michael	Fluid Power Institute	Milwaukee School of Engineering
Faculty Researcher	Andrea Vacca	Agricult. / Biological Eng.	Purdue University

THRUST 2: COMPACTNESS

Faculty Researcher	Douglas Adams	Mechanical Engineering	Vanderbilt University
Faculty Researcher	Eric Barth	Mechanical Engineering	Vanderbilt University
Faculty Researcher	Tom Chase	Mechanical Engineering	University of Minnesota
Faculty Researcher	Will Durfee	Mechanical Engineering	University of Minnesota
Faculty Researcher	Vito Gervasi	Applied Technology Center	Milwaukee School of Engineering
Faculty Researcher	Michael Leamy	Mechanical Engineering	Georgia Institute of Technology
Faculty Researcher	Zongxuan Sun	Mechanical Engineering	University of Minnesota
Faculty Researcher	Jun Ueda	Mechanical Engineering	Georgia Institute of Technology
Faculty Researcher	Pietro Valdastri	Mechanical Engineering	Vanderbilt University
Faculty Researcher	Jim Van De Ven	Mechanical Engineering	University of Minnesota
Faculty Researcher	Robert Webster	Mechanical Engineering	Vanderbilt University

THRUST 3: EFFECTIVENESS

Faculty Researcher	Scott Bair	Mechanical Engineering	Georgia Institute of Technology
Faculty Researcher	Ken Cunefare	Mechanical Engineering	Georgia Institute of Technology
Researcher	J.D. Huggins	Mechanical Engineering	Georgia Institute of Technology
Faculty Researcher	Steven Jiang	Industrial and Systems Eng.	North Carolina A & T
Faculty Researcher	Zongliang Jiang	Industrial and Systems Eng.	North Carolina A & T
Faculty Researcher	Thomas Kurfess	Mechanical Engineering	Georgia Institute of Technology
Faculty Researcher	Eui Park	Industrial and Systems Eng.	North Carolina A & T

Faculty Researcher	Richard Salant	Mechanical Engineering	Georgia Institute of Technology
Faculty Researcher	Andrea Vacca	Agricult. / Biological Eng.	Purdue University

TEST BEDS

Test Bed Leader, TB1	Monika Ivantysynova	Agricult. / Biological Eng.	Purdue University
Test Bed Leader, TB3	Perry Li	Mechanical Engineering	University of Minnesota
Test Bed Leader, TB4	Wayne Book	Mechanical Engineering	Georgia Institute of Technology
Test Bed Leader, TB6	Liz Hsaio-Wecksler	Mechanical Sci. and Eng.	University of Illinois at UC
Visiting Scholar, Associated Wind Power Test Bed	Feng Wang	Mechanical Engineer	University of Minnesota

NON-UNIVERSITY PARTNERS

Name	City	State
Science Museum of Minnesota	St. Paul	Minnesota
National Fluid Power Assoc.	Milwaukee	Wisconsin
The National GEM Consortium	Alexandria	Virginia

EDUCATION AND OUTREACH PERSONNEL

Name	Title	Department	Institution
Brad Bohlmann	Capstone Project Advisor	ERC Staff	University of Minnesota
Alyssa Burger	Education Outreach Director	ERC Staff	University of Minnesota
William Durfee	Faculty Researcher	Mechanical Engineering	University of Minnesota
Jenifer Helms	Engineering Education Researcher	Evaluation and Assessment	Quality Evaluation Designs
Elizabeth Hsiao-Wecksler	Faculty Researcher	Mechanical Sci. and Eng.	University of Illinois at UC
Marcus Huggans	Education Partner	External Relations	The National GEM Consortium
Medhat K. Bahr Khalil	Dir. Prof. Ed. & Rsch. Dev.	Mechanical Engineering	Milwaukee School of Engineering
Gary Lichetenstein	Principal Investigator	Evaluation and Assessment	Quality Evaluation Designs
John Lumkes	Faculty Researcher	Agricult. / Biological Eng.	Purdue University
J. Newlin	Education Partner	Physical Sciences & Tech.	Science Museum of Minnesota
Eui Park	Faculty Researcher	Industrial and Systems Eng.	North Carolina A & T
Josh Cummins	SLC President	Mechanical Engineering	Vanderbilt University
Andrea Vacca	Faculty Researcher	Agricult. / Biological Eng.	Purdue University
James Van De Ven	Education Director	Mechanical Engineering	University of Minnesota

SCIENTIFIC ADVISORY BOARD

Name	Title	Organization
Dr. Hans Aichlmayr	Physicist, Weapons & Complex Integration	Lawrence Livermore National Lab
Prof. Richard Burton	Professor, Dept. of Mech. Engineering	Univ. of Saskatchewan, Canada
Dr. Robert Cloutier	Associate Professor, School of Systems and Enterprises	Stevens Institute of Techology
Prof. Frank Fronczak	Professor, Dept. of Mech. Engineering	University of Wisc. - Madison
Mr. Steven Herzog	Global Product Manager (Retired)	Evonik RohMax USA, Inc.
Prof. Toshiharu Kagawa	Professor, Dept. of Mech. Engineering	Tokyo Institute of Technology
Dr. Joseph Kovach	Vice President of Technology & Innovation - Hydraulic Group (Retired)	Parker Hannifin
Dr. Lonnie J. Love	Sr. Research Scientist, Robotics and Energetic Systems	Oak Ridge National Laboratory
Prof. Hubertus Murrenhoff	Professor, Inst. for Fluid Power Transmission & Control	RWTH-Aachen
Prof. Jan-Ove Palmberg	Professor, Division of Fluid Power Technology	Linköping University
Prof. Andrew Plummer	Professor, Dept. of Industrial and Systems Engineering	University of Bath, U.K.
Mr. Sohan Uppal	Vice President, Technology and Chief Technology Officer (Retired)	Eaton Corporation
Prof. Lu Yong Xiang	President (Retired)	Chinese Academy of Sciences

INDUSTRIAL ENGAGEMENT COMMITTEE

Name	Title	Organization
Brian Rhode	OEM Liaison Manager	Afton Chemical
Kent Sowatzke	Vice President of Operations	Bimba Manufacturing
Gunter Matt	Design Engineer	Bobcat
Bill Durr	Engineering Manager	Caterpillar Inc.
Aleksandar Egelja	Engineering Manager	Caterpillar Inc.
Navneet Gulati	Senior Manager - Electro-Hydraulic Controls	CNH
Gary Kassen	Engineering Director - Hydraulic Competency Center	CNH
Eric Bretey	Manager, Advanced Systems Engineering	Danfoss Power Solutions
Kevin Lingenfelter	Senior Integrated Solutions Engineer	Danfoss Power Solutions
Marcus Royal	Engineering Manager	Deltrol Fluid Products
Marty Barris	Director, Hydraulic Products	Donaldson Company
Qinghui Yuan	Manager, Advanced Technology, Industrial Sector	Eaton Corp.
Jonathon Gamble	Director of Engineering	Enfield Technologies
Don Smolenski	OEM Liaison Manager	Evonik RohMax USA, Inc.
David Holt	Senior Research Scientist	ExxonMobil Research
David Scheetz	Senior Equipment Builder Engineer	ExxonMobil Research
Rajeev Kumar	Senior Researcher at ExxonMobil	ExxonMobil Research
Rick Hill	Project Development Engineer	Gates Corp.
Marcia Bolesky	Finance Executive	HYDAC/Schroeder Industries
Gordon Shellhaas	Executive Vice President	Hydraquip Distribution
Scott Lane	Engineering Manager	Linde Hydraulics Corp.
Shubhamita Basu	Technology Manager, Industrial	Lubrizol
Dan Foster	Director of Engineering	Moog Inc.
Eric Lanke	Executive Director	National Fluid Power Assoc.
Paul Gangopadhyay	Vice President, Business Development	Netshape Technologies, Inc.
Zach Holt	Product Manager	Netshape Technologies, Inc.
Paul Paluszewski	Director Product Development - Machinery & Equipment	Pall Corporation
Ray Collett	Manager, Innovation & Technology	Parker Hannifin Corp.
Nic Copley	Vice President of Technology and Innovation	Parker Hannifin Corp.
Matt Simon	Principal Engineer	Parker Hannifin Corp.
Howard Zhang	Chief Engineer	Parker Hannifin Corp.
Markus Rauchhaus	Managing Director	Poclain Hydraulics
Gilles Lemaire	Prospective Head & Scientific Support	Poclain Hydraulics
Brent Archer	Vice President	Proportion Air
Jon Goreham	Sales and Marketing Manager	Quality Control Corp. - QCC
Sujan Dhar	Developer and Project Engineer	Simerics Inc.
Sam Lowry	President	Simerics Inc.
Larry Castleman	Technical Director of Product Development	Trelleborg Sealing Solutions
John Tysver	Vice President and General Manager	Woodward HRT

This page is intentionally left blank

1. SYSTEMS VISION, VALUE ADDED AND BROADER IMPACTS OF THE CENTER

Fluid power has been broadly used for many years; in some applications for centuries. It has been the dominant method of energy transmission in applications ranging from off-road vehicles, such as agricultural, construction and mining equipment to manufacturing systems for more than half a century. These machines are examples of complex fluid power systems. Fluid power is typically used for propulsion, steering and to perform the work activities of the vehicle.

By definition, an entity's vision is *a compelling, but realistic future state*. For most of its first eight years, the vision of the Engineering Research Center for Compact and Efficient Fluid Power (CCEFP) was to **transform fluid power by making it more compact, efficient and effective**. As the Center has matured, we have come to recognize that while the "compact, efficient and effective" attributes represent means to achieve the envisioned future state, the vision to "transform fluid power" is quite ambiguous. Therefore, in 2014 the vision statement was changed to something that better describes the compelling and realistic future state we are working to create. The new CCEFP vision statement is "***Fluid power is the technology of choice for power generation, transmission, storage, and motion control***".

The Center's work continues to make progress towards reducing our Nation's energy usage and increasing the ways in which fluid power will improve our quality of life, such as in human-scale applications. Realization of the Center's vision will expand the use of fluid power in current applications and spawn entirely new industries.

As it nears completion of its tenth year, the Center's research and people continue to transform fluid power. The Center has become the catalyst in energizing the U.S. fluid power industry and research community. For the first time in decades, the fluid power industry in the U.S. is undertaking significant numbers of university-industry collaborations on research. U.S. universities are emerging as international leaders in fluid power research, as evidenced by best paper awards presented to Center researchers and their students at recent prominent international conferences. In addition, CCEFP is recognized as a thought leader in the fluid power research community internationally.

An important new initiative in response to the interests of our industry members is broadening the focus of the Center's research to include not only fluid power components and systems, but also how these are manufactured. To that end, CCEFP submitted a proposal for and was awarded an Advanced Manufacturing Technology Consortia (AMTech) planning grant award. AMTech is a program at the National Institute of Standards and Technology to incentivize the formation of and provide resources to industry-led consortia that will support basic and applied research on long-term, pre-competitive and enabling technology development for the U.S. manufacturing industry. The objective of AMTech is to establish and strengthen technology consortia, driven by industry, to identify and prioritize research projects addressing long-term U.S. industrial research needs.[1] The deliverables for the planning grant are primarily an advanced manufacturing roadmap for the fluid power industry and the creation of a sustaining collaboration of industry and academia focused on implementing and expanding the roadmap.

As is the case with CCEFP's vision, the Center's research strategy has continued to evolve and mature based on input from our industry supporters. Our leadership position in the international fluid power research community and the close relationships we have with most of the major companies in the fluid power industry have allowed us to gain an ever-improving understanding of the industry's critical needs. The relevance of the Center's strategy and research agenda is validated by the strong industry support it continues to enjoy and by the adoption of similar strategies in the international fluid power research community.

[1] http://www.nist.gov/amo/

1.1 EVOLUTION OF THE SYSTEMS VISION AND VALUE ADDED FOR CCEFP

Mission, vision and strategy

The mission of the Center for Compact and Efficient Fluid Power (CCEFP) has been consistent, "Changing the way fluid power is researched, applied and taught." The initial vision of the CCEFP was "Fluid power is the technology of choice for power transmission and motion control." The vision was later extended to "Fluid power is the technology of choice for power generation, transmission, storage and motion control." This evolution reflects the importance of power sources and energy storage in enabling a complete systems perspective of fluid power. The strategy of the CCEFP involves both improving fluid power in existing applications and creating new markets for fluid power. This is done in close partnership with industry. Education of the next generation of leaders for fluid power is one of the most important elements of the strategy. As our understanding of how to have greatest impact became more refined, we came to understand that educating the future workforce of fluid power researchers and practitioners was our most important task.

Research Trusts

The CCEFP has three research thrusts: efficiency, compactness and effectiveness. Efficient means saving energy; compactness means making fluid power smaller and lighter with the same capability; effectiveness means making fluid power clean, quiet, safe and easy to use. Although the focus of individual research projects within the thrusts has continually changed, the research thrusts have remained consistent through the life of the Center.

Test Beds

The CCEFP test beds have continually evolved over the life of the center. The there were initially six test beds as listed below:

Test Bed 1: Excavator

Test Bed 2: Injection-molding machine

Test Bed 3: Hydraulic hybrid passenger car

Test Bed 4: Rescue robot

Test Bed 5: Fluid power hand tools

Test Bed 6: Ankle foot orthosis

Fluid power has a broad range of applications with varying requirements, and it was understood that the test beds must represent this broad range. Furthermore, it was recognized that test beds were create excitement for the research teams. For this reason, the test beds were shared among the CCEFP universities.

The evolution of the test beds began almost immediately. Early in the life of the Center test beds 2 and 5 were discontinued. The Site Visit Team criticized the large number of test beds and strongly recommended a reduction. Since one of the key advantages of fluid power is its high power density and power density is a more important advantage for mobile applications it was decided to discontinue the injection-molding machine, the only stationary test bed. Since the fluid power hand tools were deemed simpler and thus had fewer interesting systems issues, this test bed was also discontinued. This caused an inconsistency in the overall research strategy since the miniature free-piston engine compressor was now an orphaned project with no test bed for demonstration. Nevertheless, the project was continued, and the result was the creation of the smallest internal combustion engine ever made. Because of noise and emissions, this engine is unsuitable for the orthosis test bed. The search for a suitable power source for the orthosis test bed was long and tortuous, but ultimately the Stirling engine thermo-compressor was discovered as a silent alternative to the free-piston engine compressor.

The four test beds (1, 3, 4 and 6) are representative of typical fluid power applications. But it soon became evident that two emerging applications, wind power and precision pneumatics for MRI guided surgery, were new opportunities worthy of investment. Two new associated test beds were added; test bed α, wind power, and test bed β, precision pneumatics for MRI guided surgery. Also, a patient-handling robot replaced the rescue robot since patient handling was a neglected area and far more resources were being given to rescue robots by other research groups. This led to the final configuration of test beds listed below ranked by power and weight from largest to smallest.

Test Bed α: Wind power

Test Bed 1: Excavator

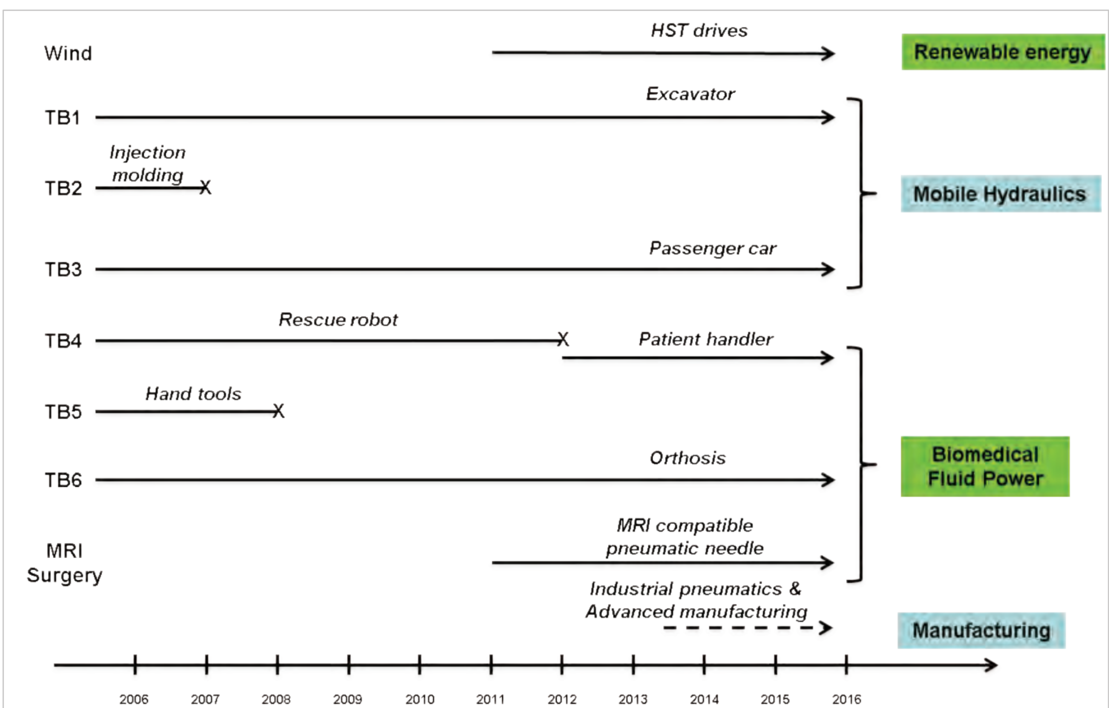
Test Bed 3: Hydraulic hybrid passenger car

Test Bed 4: Rescue robot

Test Bed 6: Ankle foot orthosis

Test Bed β: Precision pneumatics for MRI guided surgery

The history of test bed evolution is shown on the figure below. The current test be configuration supports are sustainability plan with research in renewable energy, mobile hydraulics and biomedical fluid power. We are currently initiating research in fluid power manufacturing. Our recent NSF supplemental funding will support research in the use of additive manufacturing. This will be demonstrated on AME, the Additive Manufacturing Excavator, to be demonstrated at the CONEXPO-CON/AGG exposition in Las Vegas on March of March 7-11, 2017.



CCEFP Test Bed Evolution

Research

The CCEFP test beds were strategically chosen to span the power and weight range of existing and potential future fluid power applications. The primary purposes of these test beds are:

- Test Bed 1, the hydraulic excavator, demonstrates efficiency improvements in existing fluid power applications.
- Test Bed 3, the hydraulic hybrid passenger vehicle, demonstrates a cost-effective competitive alternative to electric hybrids.
- Test Bed 4, the patient transfer device, demonstrates a human-scale device capable of providing the needed force and power in a small package with precise and intuitive control.
- Test Bed 6, the ankle-foot orthosis, demonstrates the practical limits of miniature fluid power systems, both pneumatic and hydraulic.

Test Bed 1

The compact excavator test bed has employed throttle-less hydraulic actuation technology from the inception of the Center through spring 2012. In February 2012, the test bed began transitioning to being a demonstrator of a novel hydraulic hybrid configuration, called series-parallel hybrid displacement control (DC) system. The series-hybrid architecture introduces secondary controlled actuation for the swing drive in combination with the implementation of an energy storage system in parallel to the other DC actuators for the remaining working functions. Such architecture enables energy recovery from all actuators, the capture of swing braking energy and the potential for 50% engine downsizing. The goals for the project are 50% fuel savings over current state-of-the-art excavator systems, while meeting current exhaust emission standards and with no degradation in machine performance.

This test bed primarily addresses the efficiency thrust of the Center. A key role of the test bed is to demonstrate the energy savings that are possible in multi-actuator machines, through efficient system architectures (utilizing throttle-less actuation, enabling energy recovery and storage) and through advanced power management strategies. These concepts were investigated in project 1A.2 from 2006-2012 and the test bed draws upon theoretical results achieved to meet these goals. The test bed has also been used for demonstration of a novel human-machine interface as part of project 3A.1. It has plans to use and validate the potential of the energy-efficient fluids researched from Project 1G.1 and for evaluation of high efficiency, virtually variable displacement pump/motors from projects 1E2 and 1E3. With the transition of the test bed to a series parallel hybrid DC system, it will also open the door for testing new accumulator technologies researched within the Center (e.g. the advanced strain energy accumulator, Project 2C.2).

Since the conception of secondary-controlled drives, many advances in the control of the actuator position, velocity and torque have been developed. Efforts in this area for TB1 focused on determining a control strategy that would maximize performance and achieve conventional drive operability, which is a challenging control problem due to the large and rapidly-changing inertial load s to which the machine is subjected to. For this purpose, two linear control strategies, a PI controller and a robust multi-input multi-output controller (developed in the previous reporting period) were compared to a newly developed nonlinear adaptive robust technique.

The proposed hydraulic hybrid supervisory controller comprises two parts, (1) an instantaneous optimization for the minimization of fuel consumption and maximization of actuator performance and (2) a feedforward controller for the hydraulic hybrid primary unit based on the system power flows. In conjunction, these two parts optimize the usage of engine power and allow the hybrid to provide complementary power to the common shaft. Measurement results of TB1 with a stock-sized engine show that the control strategy maintains the engine at or below the prescribed engine power for a truck-loading cycle and the derived algorithms demonstrate that the hydraulic hybrid architecture in combination with DC actuation allows engine downsizing by up to 55% for an excavator.

As demonstrated in project 1A2, pump switching has the potential to minimize the number of pumps in a DC hydraulic system. A priority-based supervisory controller was developed. The advantage of using a priority-based approach is that the controller will select certain actuators by default and, using predefined joystick signal weights, allow the operator to switch to lower priority actuators in a seamless manner.

Test Bed 3

The overall goal of Test Bed 3 is to demonstrate hydraulic hybrid powertrains for passenger vehicles that provide both dramatic improvements in fuel economy and good performance. As a test bed project, it also drives associated projects by identifying the technological barriers to achieving that goal and integrating those project technologies into the test bed. The design specifications for the vehicle include:

- fuel economy of 70 mpg in the US Federal Test Procedure
- an acceleration rate of 0-60 mph in 8 seconds
- the ability to climb a continuous road elevation of 8%
- meeting California emissions standards
- size, weight, noise, vibration and harshness (NVH) comparable to similar passenger vehicles on the market

Test Bed 3 directly supports the goal of improving the efficiency of transportation. Efficiency is achieved by utilizing fluid power to create novel hybrid powertrains for passenger vehicles. The powertrains integrate high efficiency components and hydraulic fluids (thrust 1), compact energy storage (thrust 2) and methodologies for achieving quiet operation (thrust 3) from related CCEFP projects.

In this reporting period, changes to the high level energy management strategy were implemented. The three level control program for the vehicle has been modified to allow for the testing of different high level energy management strategies other than CVT. Dynamic Programming (DP) and Modified Lagrangian Multiplier (MLM) control programs have been created for testing.

When testing the vehicle in CVT mode, a consistent difference between the expected torque and the measured vehicle torque was observed. Investigation revealed that significant friction existed within the drive train that was not included in the system model. Extensive tests were done to characterize the friction at different output shaft speeds, vehicle torques, and pump/motor speeds and directions to enable modeling it.

After the friction was characterized, the output torque of the Speeder pump (pump S) was observed to be significantly less than that estimated by the pump/motor map. The map for pump S was then updated to account for the friction and further close the gap between the expected and measured vehicle torques. The new pump map is accurate to within 1-2 Nm over the range of normal Pump S displacements.

Test Bed 4

The goal of Test Bed 4 is to demonstrate a mobile fluid powered patient transfer device (PTD), an example of a portable, un-tethered human scale fluid power application. The PTD occupies the power range from approximately 100 W to 1 kW. This range is poorly addressed by fluid power today due to barriers, including a lack of compact power supplies, lack of miniature components, and difficulty in control. The test bed provides a system for testing component technologies, as well as developing intuitive control and expanding the use of fluid power systems into the healthcare sector. The PTD will create a novel class of hydraulic controllers suited to human amplified machines needed to solve the unique control challenges of patient transfer. The PTD has large force requirements that must be balanced with the limits of the person being assisted. Effectiveness research in such areas as safety, noise, and leakage are also important areas for the new test bed. The PTD is intended to transfer mobility-limited patients, including bariatric patients, from bed to wheelchair, wheelchair to shower chair, or wheelchair to car. Patient lifts in the market today are typically electrically actuated, or have a manual hydraulic pump. They provide only one actuated degree of freedom and are antiquated and insufficient for current patient needs. Our goal is to develop a highly maneuverable, powerful, compact patient transfer device that can be easily operated by a single caregiver. It should be able to operate for a reasonable time without charging (e.g., all day), produce sufficient force to transfer bariatric patients (up to 500 lb), and have precise, safe and intuitive control. An additional factor in the decision to migrate Test Bed 4 to the PTD is the opportunity to collaborate with the Quality of Life Technology ERC. This will help us enable broader multi-disciplinary research opportunities. This test bed will help the CCEFP create critical mass in fluid power medical devices attracting biomedical companies, researchers and students.

The current first prototype hardware system has four actuated degrees of freedom (DOFs), a main lifting scissor, a horizontal boom extension, and two differential drive wheels. The focus of the work has been on the actuation, control and operator interface design; the overall mechanical design is not yet optimized. A test cart was built for implementing and evaluating various wheel control designs. The cart included the full actuation and control system, force sensing operator input, wheels, ultrasonic sensors for obstacle avoidance, and a National Instruments single board Rio for control. After the wheel control testing on the test cart was complete, the cart was disassembled in order to be transferred to the main machine.

The control and caretaker interface design has been the main research focus in the past year. Several versions of advanced algorithms to manage any potential environment interaction while also controlling motion have been implemented on all four degrees of freedom of the machine.

To help ensure safety and effective control with such a powerful device working in a relatively delicate and unstructured environment, and with both the caregiver and patient in the workspace, a form of interaction control to manage external interaction forces is needed. Several types of interaction control have been investigated. Forms of impedance control were implemented and tested on the current prototype PTAD. In systems with such high intrinsic stiffness, such as hydraulics, feedback of external forces is needed, but in high speed collisions, using this control approach means that control of interaction forces is limited by the speed of response to measured external forces. To eliminate this limitation, an additional virtual force term based on a proximity measurement was added to the impedance control framework to provide earlier information about potential collisions. Sensing both force and proximity provides redundancy and gives the operator the ability to maximize utilization of the restricted environment, and even push lightly against obstacles.

This impedance control framework with an additional proximity-based virtual force feedback term was implemented and tested on the horizontal boom extension, with software and human inputs. Experiments were performed with a stiff obstacle in the path of the boom, and the resulting collision forces were measured. The experiment was performed four times with the same controller, with the following forms of force feedback: none, only proximity-based virtual force, only measured external force, and both proximity and measured external force. The collision force is reduced by more than 60% using either measured external force or measured proximity and by more than 85% using both measurements, all while maintaining sufficient tracking performance in free space. Implementation of a similar form of impedance control is underway on the main lifting scissor.

Test Bed 6

The goal of Test Bed 6 is to develop enabling fluid power technologies to miniaturize fluid power systems for use in novel, human-scale, untethered devices that operate in the 10 to 100 W range. The results will help determine whether the energy/weight and power/weight advantages of fluid power continue to hold for very small systems operating in the low power range, with the added constraint that the system must be acceptable for use near the body.

Human assist devices developed in Test Bed 6 provide functional assistance while meeting these additional requirements: (1) operate in the 10 to 100 W target power range, (2) add less than 1 kg of weight to a given segment of the body, excluding the power supply, and be designed to minimize physical interference during use, and (3) provide assistance from 1 to 8 hours. The focus of this test bed is the development of novel ankle-foot-orthoses (AFOs) to assist gait. An AFO with its stringent packaging constraints was selected because the ankle joint undergoes cyclic motion with known dynamic profiles, and requires angle, torque, and power ranges that fit within the test bed goals. This test bed facilitates the creation of miniature fluid power systems by pushing the practical limits of weight, power and duration for compact, untethered, wearable fluid power systems. The test bed benefits society by creating human-scaled fluid power devices to assist people with daily activities and is creating new market opportunities for fluid power, including opportunities in medical devices.

Significant progress was made on both the portable pneumatic AFO at UIUC and the hydraulic AFO at Minnesota.

Pneumatic AFO: To address increased torque output, we further optimized the Gen 3 design, which replaced the dual-vane bidirectional rotary actuator with dual linear actuators and gear train [2]. Although the overall weight increased 20% compared with previous design (680 vs. 560 g), it is capable of generating 190% more torque.

To address control of the PPAFO, we have examined different actuation-timing control strategies, and recognition different gait modes (stairs/ramps/level). Two studies that addressed actuation control were completed.

Hydraulic AFO: During 2015 efforts on the HAFO centered on (1) furthering our system level modeling work to predict weight and efficiency of small hydraulic systems and (2) using these principals to drive the preliminary design of a second generation HAFO that can be worn by children.

Using analytical models for each component of the HAFO we extended our previous work on weight and efficiency analysis from just the actuator and hose to the complete system including battery, electric motor and pump. More recently we extended the model from static operating conditions to a fully dynamic model so that efficiency over an operating cycle can be examined.

In 2015 we started an associated TB6 project which involves applying the HAFO to study walking in children with cerebral palsy, a collaborative project with Gillette Children's Medical Center in St. Paul MN. This means creating an HAFO that can be worn by children ages 8 to 11. Our goal is to cut the HAFO weight by 50%. The key technology for doing this is 3D printed titanium parts with internal fluid passageways and integrated cylinders. The prototype concept is shown in part d of the figure. This furthers the goal of creating lightweight wearable robots powered by hydraulics. Our intent is to use the project as a vehicle for developing design guides for creating hydraulic systems using metal additive manufacturing.

Education, Outreach and Diversity

The mission, vision and strategy of the CCEFP Education Outreach (EO) Program have remained unchanged since inception; however, improvements in programmatic objectives and the approach have certainly evolved. The EO mission is to develop research-inspired fluid power education for pre-college, university and practitioners; integrate research content into courses and curriculum; and increase the public's awareness of fluid power. The EO vision is a general awareness of the importance of fluid power; students of all ages who are motivated to understand fluid power; industry that capitalizes on new knowledge and innovation; and a workforce that reflects the demographic composition of its country. The EO strategy has been to leverage existing networks, programs, and organizations to broadly disseminate, integrate, and collaborate on engineering education and outreach.

As the Center matured, so has our understanding of the industry's workforce needs. As the needs became more evident, a focused approach became more necessary. The CCEFP EO Program, originally designed as a suite of STEM outreach and fluid power activities, disjointed in nature, lacked a strategic set of objectives. Originally, each individual program or activity accomplished objectives specific to the task. In order to effectively impact the fluid power workforce, the EO program, aligned with the CCEFP research program, needed a common set of core objectives by which to formalize a portfolio of programmatic initiatives designed to accomplish very specific goals. This resulted in a series of six crosscutting objectives by which all CCEFP research, education and outreach had a common purpose.

Adhering to those six objectives resulted in a focused effort, improved effective methods of approach, and provided a mechanism by which to assess the CCEFP's impact on its faculty, students, the technology, and the industry.

CCEFP EO objectives, in which all programs must meet three or more, were developed in year 6 of the ERC: motivate all diverse citizens to navigate the STEM pathway in order to expand and promote a talented STEM workforce; promote awareness and excitement of fluid power among technical college, undergraduate and graduate students; disseminate fluid power fundamentals, research, and innovation through evaluated fluid power curricula, projects and programs that highlight fluid power concepts and applications; create a culture that integrates research and education for technical college, undergraduate and graduate students, as well as industry professionals across CCEFP and NFPA partner institutions; increase the number of students well prepared to pursue fluid power research, jobs and careers; strengthen ties between higher education and the fluid power industry.

The strategic approach to programmatic implementation resulted in efforts being focused where greatest impact was to be achieved and highest likelihood of sustainability. Previous engagement in STEM outreach was shifted into K-12 fluid power outreach, more deliberate effort in undergraduate and graduate level education was prioritized, as was networking opportunities between students and industry practitioners. As the CCEFP nears its 10-year anniversary, major EO programs remain a cornerstone of the Center, including the Fluid Power Challenge, Fluid Power REU Program, Fluid Power Scholars, CCEFP Webinar Series, Fluid Power Innovation & Research Conference, and CCEFP Industry Summits. Core mechanical engineering courses at seven institutions have fluid power content embedded into curriculum, a regularly scheduled Fluid Power MOOC is offered through Coursera four times each year, and six professional exhibits on hydraulic and pneumatic technology are permanently on display at the Science Museum of Minnesota. The CCEFP leaves several legacies in the space of collaborative ERC diversity initiatives and programs such as the GEM-ERC Fellows Program and the ERC Exhibition Booth at conferences of national professional societies.

CCEFP Thrusts, Projects and Program Objectives	**Participant Level**	**Promote STEM learning to diverse people**	**Promote awareness of fluid power**	**Fluid power dissemination**	**Culture of research and education integration**	**Increase fluid power workforce**	**Strengthen ties between higher ed and industry**
Thrust A: Public Outreach -- Bringing the message of fluid power to the general public							
A.1 Interactive Fluid Power Exhibits	All						
Thrust B: Outreach – Bringing fluid power education to K12 students with a focus on middle and high school							
B.7 NFPA Fluid Power Challenge Competition	K12						
Thrust C: College Education – Bringing fluid power education to undergraduate and graduate students							
C.1 CCEFP REU Program	BS						
C.4 Fluid Power in Courses, Curriculum and Capstones	BS, MS						
C.4B NFPA Fluid Power Vehicle Challenge	BS						
C.8 CCEFP Student Leadership Council	MS, PhD						
Thrust D: Industry Engagement – Making connections between CCEFP and industry							
D.1 Fluid Power Scholars Program	BS						
D.2 CCEFP Engagement Programs (FPIRC, Summits)	All						
D.5 CCEFP Webinar Series	All						

Current industry membership and involvement, and key technology transfer impacts

At inception, the CCEFP had fifty members. During the first eight years of operation the number of industry members remained nearly constant. New members were added, but attrition was due to two factors, members leaving and members acquiring each other. A major change in the membership structure occurred beginning in Year 8. At that time, the previous membership agreement was terminated. Instead, companies were invited to contribute to the National Fluid Power Association (NFPA) Education and Technology Foundation. To emphasize the change in organization, members are now called supporters. CCEFP now has seventy-one supporters. The current Pascal Society members list is shown in the figure below.

GOLD

- Bimba Manufacturing
- Caterpillar
- Daman Products Company
- Danfoss Power Solutions
- Eaton Corporation
- Enfield Technologies
- Hydra-Power Systems
- Pall Corporation
- Parker Hannifin
- Proportion-Air

SILVER

- Afton Chemical
- Bobcat
- Chevron
- CNH
- Deltrol Fluid Products
- Donaldson Company
- Evonik Oil Additives
- ExxonMobil
- Fluid Power World Magazine
- Gates Corporation
- HYDAC/Schroeder Industries
- Hydraquip
- Linde Hydraulics
- Lubrizol
- Moog
- Netshape Technologies
- Poclain Hydraulics
- Quality Control Corporation
- Simerics
- Trelleborg Sealing Solutions
- Woodward HRT

BRONZE

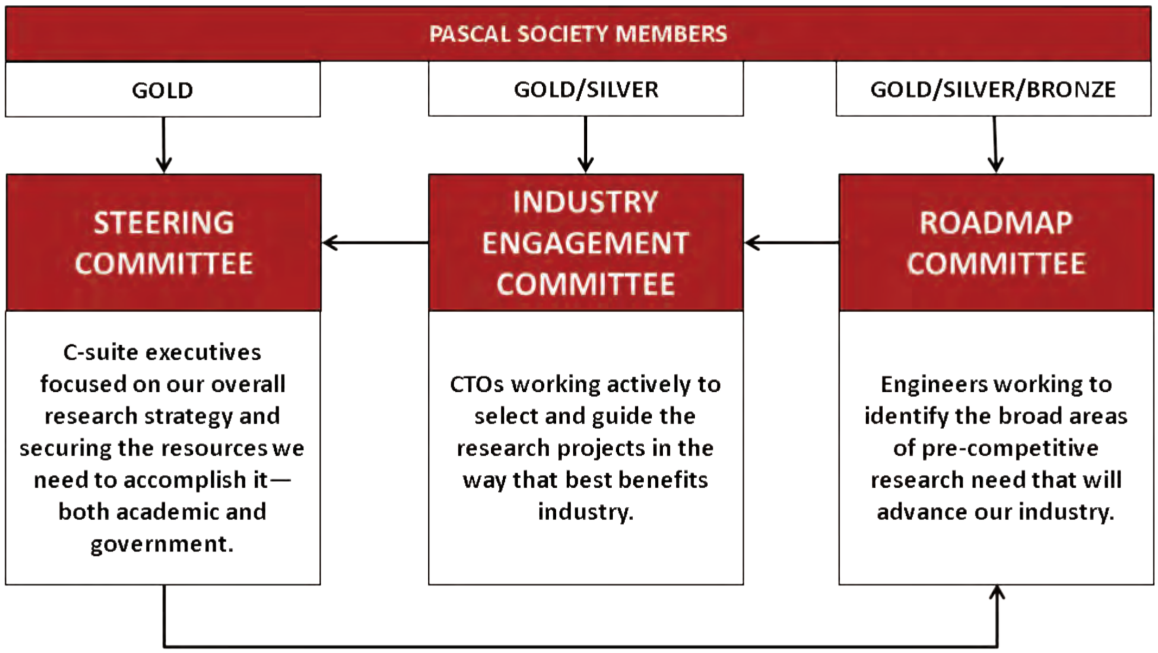
- Bosch Rexroth
- Clippard Instrument Laboratory
- Concentric AB
- Czero
- Delta Computer Systems
- DunAn Microstaq
- Festo Corporation
- FORCE America/Valve Division
- G. W. Lisk Company
- GS Global Resources
- HAWE Hydraulik NA
- HECO Gear
- Hitachi
- HUSCO International
- Idemitsu Kosan
- IMI Precision Engineering
- Industrial Hard Chrome
- Iowa Fluid Power
- JCB
- Kaman Industrial Technologies
- KYB Japan
- Main Manufacturing Products
- Master Pneumatic
- Muncie Power Products
- National Tube Supply
- Nexen
- OEM Controls
- PARTsolutions
- ROSS Controls
- RYCO Hydraulics
- SMC USA
- Stauff Corporation
- Steelhead Composites
- Sumitomo Heavy Industries
- Sun Hydraulics
- The Toro Company
- Walvoil Fluid Power
- White Drive Products
- Womack Machine Supply

The Pascal Society has three levels of membership determined by company size and level (bronze, silver or gold). The membership levels are summarized in the table below.

		Membership Level		
Company size	**Annual global fluid power sales**	**Gold**	**Silver**	**Bronze**
Large	Above $250 million	$100,000	$60,000	$6,000
Medium	Between $50 and $250 million	$50,000	$30,000	$3,000
Small	Below $50 million	$25,000	$15,000	$1,500

Fluid power sales" are measured differently for different kinds of companies. For fluid power component and system manufacturers, it includes all of their sales. For OEMs, it includes the value of fluid power content in their machines, both purchased and manufactured. For suppliers, it includes all of their sales to the fluid power industry.

Depending on the level, Pascal Society members participate on committees that support the CCEFP. Members at all levels; bronze, silver and gold; belong to the Roadmapping Committee. Silver and gold members belong to the Industrial Engagement Committee (IEC), and gold members belong to the CCEFP Steering Committee as shown in the figure, below.



The Roadmapping Committee maintains the Fluid Power Industry Roadmap and the Fluid Power Manufacturing Roadmap. All levels of Pascal Society membership contribute to the roadmaps since it is desirable to have the widest possible representation of the industry. The roadmaps are updated periodically.

The IEC provides the most direct contact between the companies and university researchers. CCEFP research projects are funded for two years. The IEC drafts the call for proposals, evaluates the proposals and makes a recommendation to the Director of which projects to fund. The IEC has monthly teleconferences and participates in a semiannual IEC summit where all researchers present their results and extensive networking and experience sharing is facilitated between industry and academia.

The CCEFP Steering Committee approves the high-level strategy of the Center. The Chair of the Steering Committee is the Center Director. In addition to the industry representatives, two additional representatives are added to the Steering Committee for each five industry members. The University representatives elect one of these members. The Center Director appoints the other. The Steering Committee meets three times annually.

With the transformation from CCEFP membership to Pascal supporter, the intellectual property (IP) policy also changed. In the CCEFP membership model, industry received specific IP rights that included exclusive access and, depending on the membership levels, reduced royalties. Unintended consequences of the IP rights significantly diminished patents and licensing. Since member companies were informed of IP opportunities at the same time as their competitors, none were interested in going forward. With the Pascal Society, no IP rights are granted to industry supporters. This allows universities much more flexibility in making IP decisions. It is expected that this approach will be much more effective.

Since its founding, the CCEFP has increased the number of fluid power educated engineers and researchers at the bachelors, master's and doctoral level by more than a factor of ten, dramatically transforming the level of technical talent in the industry.

The research contributions of CCEFP are having a large commercial impact on the fluid power industry. Our energy saving excavator project has demonstrated more than a 50% energy savings. Some of these ideas have been commercialized in the Caterpillar 336E H hydraulic hybrid excavator, a large commercial success resulting in significant energy savings, increased exports and new jobs.

CCEFP collaboration with Parker Hannifin has resulted in the founding of a new hydraulic power train division in Columbus, Ohio. The new division has employed eighty engineers, most of who are CCEFP graduates, since there are few other sources of well-trained fluid power engineers.

CCEFP has created two new start-up companies, one for a new low-cost, rugged, accurate, non-contact sensor, the other for a much more efficient hydraulic pump. CCEFP is also venturing into wearable robotics and other human-scale applications. These exciting new applications can only be made practical because of the superior power density of fluid power.

1.2 SYSTEMS VISION

The compelling, but achievable future state foreseen by the CCEFP vision statement is “Fluid power is the technology of choice for power generation, transmission, storage, and motion control”. To achieve this vision, the ultimate outcome of the Center’s research must be focused on overcoming the real world challenges facing the fluid power industry. In addition, the benefits of the research must be demonstrated in real world applications to foster their adoption by the fluid power industry. The Center’s test beds provide these real world opportunities and are emblematic of our systems vision. The test beds and the methods used to select them will be detailed later in this section.

The Center’s research agenda is guided by a strategic planning process that is explained in detail in Section 2. The process has identified the following transformational goals necessary to realize our vision:

1. Double fluid power efficiency in current applications and in new transportation applications.
2. Increase fluid power energy storage density by an order of magnitude.
3. Develop new miniature fluid power components and systems including power supplies that are one to two orders of magnitude smaller than anything currently available.
4. Make fluid power ubiquitous - meaning broadly used in many applications and environments. This requires fluid power that is clean, quiet, safe and easy to use.
5. Improve the manufacturing (quality, cost and delivery) of fluid power components and systems so that they become the technology of choice for both existing and new markets.

The Center also identified nine important fluid power technical barriers through our strategic planning process. These attributes define the technical barriers of the Center and are listed in Table 1-1. All of the technical barriers are important to attaining our systems vision; but overcoming three of the barriers will provide transformational changes to the fluid power industry.

Fluid Power Technical Barriers	Transformational
Efficient components & systems	Efficient components & systems
Efficient control	Compact power supplies
Energy management	Compact energy storage
Compact power supplies	
Compact energy storage	
Compact integrated systems	
Safe and easy to use	
Leak-free	
Quiet	

Table 1-1: Fluid Power Technical Barriers

The three transformational technical barriers are efficient components and systems, compact power supplies and compact energy storage. These transformational technical barriers in fluid power provide the largest benefits in mobile applications. As a result, mobile hydraulics has been the dominant research focus for Center since its inception.

The nine technical barriers naturally group into the three thrusts of the Center’s research strategy. They also align with the Center’s four transformational goals. Thrust 1: Efficiency, includes the barriers of efficient components and systems, efficient control and efficient energy management. It is also well-aligned with Center goal 1: Doubling fluid power system efficiency in current applications and in new transportation applications. Thrust 2: Compactness, includes the barriers of compact power supplies, compact energy storage and compact integration. This thrust aligns with goals 2 and 3: Increasing fluid power energy storage density by an order of magnitude and Developing new miniature fluid power components and systems including power supplies that are one to two orders of magnitude smaller than anything currently available Thrust 3: Effectiveness, includes the barriers of safe and easy-to-use, leak-free and quiet. These barriers must be overcome in order to realize goal 4: ubiquitous use if fluid power.

CCEFP's projects are assigned numbers to facilitate communication and tracking of project activities. The first character in the project number is a digit representing the main thrust associated with the project. The efficiency, compactness and effectiveness thrusts are numbered 1, 2 and 3, respectively. This numbering assignment does not mean that a project starting with a 1 is focused solely on efficiency. Most of the projects in the Center combine elements of all three thrusts. Further, every test bed requires contributions from all three thrusts to succeed. Using the hydraulic hybrid passenger vehicle as an example, its systems-level contribution is to energy efficiency, but creating a practical, energy efficient vehicle requires advancements in compactness and effectiveness. Compactness is needed since excessive weight clearly affects fuel economy and space is tight in a passenger vehicle. Creating a compact alternative to the conventional accumulator or replacing the conventional engine and pump with a free-piston engine-pump are two examples of how compactness enables a more efficient vehicle. Effectiveness is also important. A vehicle that is noisy, leaks oil, or has poor drivability is unlikely to be successful in the marketplace.

The current test beds reflect the fact that fluid power scales with size as measured by weight or power and that the competitive advantage of fluid power is greatest in mobile applications but present in many others. CCEFP has chosen six test beds spanning six orders of magnitude of power and weight.

The figure below shows the range of power and weight for fluid power applications. Six test beds have been identified, as listed below and shown in Figure 1-1. The six test beds were carefully selected and representative applications in the following six families.

1. Large Stationary Equipment (500 kW and greater): Wind Power Generator (Test Bed α)
2. Mobile Heavy Equipment (50 kW-500 kW): Excavator (Test Bed 1)
3. On-Highway Vehicles (10 kW-100 kW): Hydraulic Hybrid Passenger Vehicle (Test Bed 3)
4. Mobile Human Scale Equipment (100W-1kW): Patient Transfer Device (Test Bed 4)
5. Human Assist Devices (10W-100W): Ankle-Foot Orthosis (Test Bed 6)
6. Micro Medical Devices (≤10W): Precision Pneumatics for MRI Guided Surgery (Test Bed β)

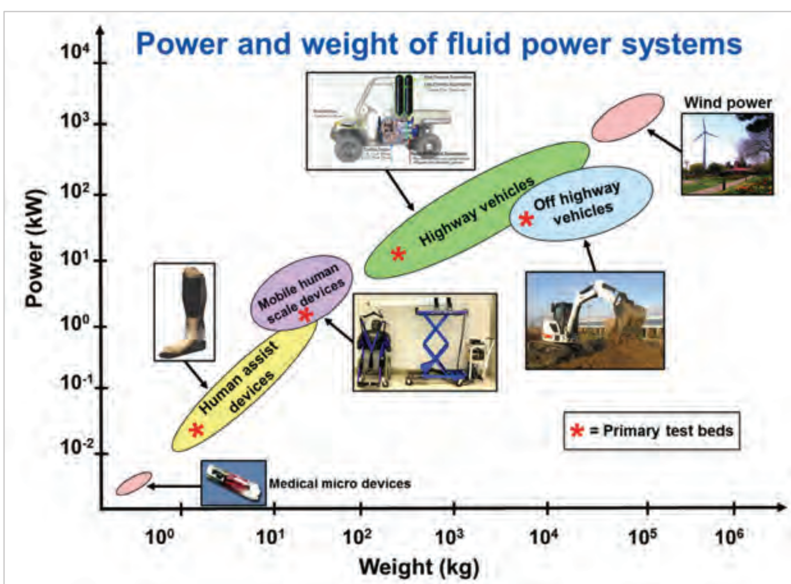


Figure 1-1: Weight and Power Ranges of CCEFP Test Beds

Fluid Power Is Transformational

CCEFP is performing transformational research that will yield significant societal benefits in areas such as the reduction of energy consumption and the creation of new human-scale fluid power devices. Ongoing Center research has demonstrated the potential for substantial energy reduction in current fluid power applications. A December 2012 DOE energy study[2] verifies the importance of fluid power in saving energy. This authoritative survey found that fluid power consumes between 2.1% and 3.0% of our Nation's energy. Fluid power system efficiencies range from less than 8% to as high as 40% (depending upon the application), with an average efficiency of 21%, confirming that new technology has the potential for significant energy savings. The survey found that a 5% improvement in efficiency is easily achievable within the next five years saving $9B to $11B per year in energy costs. A strategic R&D program focusing on new controls, manufacturing and materials could result in a 15% improvement in efficiency over the next fifteen years saving $19B to $25B per year in energy. The scope of the DOE report is restricted to current uses, but many new markets could be created with improved fluid power technology.

An important emerging market for hydraulics is transportation. Hydraulic hybrid technology is commercially available today in large commercial vehicles such as refuse trucks and package delivery vehicles. CCEFP member Parker Hannifin, another CCEFP member, has developed a medium duty hybrid hydromechanical system that is currently being used in UPS and FedEx package delivery vehicles. Parker's RunWise system is commercially available for use in refuse trucks. It combines a hybrid hydrostatic transmission with a two speed mechanical transmission to achieve fuel consumption savings of 35-50%. In addition, brake maintenance on vehicles equipped with RunWise has gone from 4-5 times per year to once every 4-5 years. Lightning Hybrids, a Colorado company, has successfully commercialized a parallel hydraulic hybrid system that is targeted at medium duty delivery vehicles and shuttle buses that provides up to a 35% improvement in fuel economy. They recently received a "Top Venture" award from NREL. In addition, there has also been recent activity from several suppliers to apply hydraulic hybrid transmissions to school buses and city transit buses.

Helping to create new markets that provide value to consumers and commercial entities and help to reduce greenhouse gas emissions is exciting an aggressive program in energy efficient fluid power can invigorate this industry that is an important sector of the economy and increase U.S. competitiveness in the growing world market. In 2008, according to the U.S. Census Bureau, sales of fluid power components exceeded $17.7 billion and employed 68,000 people. Sales of systems using fluid power exceeded $226 billion and employed 683,000 people. The substantial size of this market in terms of dollars and jobs indicates the potential for new and expanded businesses. But more than dollars and jobs are at stake. Reducing energy consumption is directly related to reducing carbon dioxide emissions, the major cause of global warming. Further, new compact fluid power systems will increase our quality of life by enabling human-scale, untethered systems such as the patient transfer device and the orthosis.

Caterpillar's introduction of a hydraulic hybrid excavator that reduces fuel consumption by 50% has proven to be a solid commercial success. Enhancements of this approach and application to other off-road construction and agricultural equipment are sure to follow. On-road vehicle applications of energy saving fluid power technology lag off-road applications but would lead too much greater energy savings. Refuse trucks and delivery vehicles are emerging applications but increasing the energy storage density is a requirement for hydraulic hybrid passenger vehicles to compete with electric hybrids. Natural gas prices have decreased by more than 70% from 2008 to 2015[3] due to fracking. This dramatic price reduction has made the payback period for hybrid vehicles difficult to justify in the short term.

Developing new smaller fluid power components and systems is needed for human and micro scale applications. Two fluid power test beds with associated funding have been added in the last few years. Test Bed α is a wind turbine with a hydrostatic drivetrain and Test bed β is precision pneumatics for MRI

---

[2] Love, L.J., et al, *Estimating the Impact (Energy, Emissions and Economics) of the U.S. Fluid Power Industry*, ORNL/TM-2011/14 (http://info.ornl.gov/sites/publications/Files/Pub28014.pdf).

[3] https://www.eia.gov/dnav/ng/hist/rngwhhdm.htm

guided surgery. This extends the range of power and weight to both larger and smaller sizes. TB β is particularly well suited for demonstrating fluid power ubiquity due to the challenging requirements of a hospital environment.

Over the past several years, the Center has focused more of its research efforts on medical applications which is creating the critical mass needed to generate research funding and industry interest in this area. Of the four primary test beds, only TB3, the orthosis, has medically related since its inception. An associated test bed, TB β, focused on precision pneumatics for MRI guided surgery was established at Vanderbilt, creating a second medically related test bed. Over the past two years, two new medically related test beds were created. The rescue robot test bed was redirected as a patient handler. In addition, as a spin-off of the MRI guided surgery test bed at Vanderbilt, a new associated test bed using precision pneumatics and MRI has been created at Georgia Tech. It will study the potential of real-time MRI imaging and precision pneumatics to be combined with biofeedback for the rehabilitation of stroke victims. This increases the total number of medically related test beds to four. These activities have generated significant industry interest and the Center feels that this increase in focus on fluid power-enabled medical devices is a good strategy for a sustainable CCEFP.

Theory and Science

As demonstrated by the span of size and weight of the Center's test beds, fluid power can be applied over many orders of magnitude of weight and power. However, in these differing size regimes losses that are negligible in one regime may be dominant in another. While many of the basic scientific facts are known, the technological systems solutions employed are not well understood. They depend on optimizing in an environment of multiple, complex interacting factors.

Fluid power and electrical power are the main competing approaches for transmitting power in mobile applications. Fluid power transmission has important competitive advantages over electric power transmission including a higher power to weight ratio for actuation, a higher energy to weight ratio of fuel compared to batteries, and higher forces or torques. Fluid power is also superior in producing or absorbing high power transients, has a higher control bandwidth for the same power and can hold loads without expending energy. Weaknesses of current fluid power systems are component and system inefficiencies, energy storage density, limitations in currently available compact power supplies, and unresolved environmental issues such as leakage and noise. These weaknesses are the fundamental barriers that CCEFP research is addressing.

In defining the CCEFP's systems vision, certain fluid power areas have been intentionally excluded from specific focus. These include stationary manufacturing applications in materials processing and large marine and aerospace applications. The manufacturing applications are out of scope because they are mature applications with limited potential for improvement or increased market share. The large marine and aerospace applications are out of scope because the primary propulsion system does not use fluid power. Although the Center is not demonstrating its research in these areas, the research results can nonetheless lead to important improvements in the excluded areas. In this context, the distinction between what is "important" and what is "transformational" is germane. While CCEFP research will not transform aerospace, marine and stationary applications, it is expected to make important improvements in these areas. Two exceptions to the exclusion of stationary applications are the use of fluid power drivetrains in wind energy, an application in early stages of development where fluid power has the potential to be transformational, and industrial pneumatics where there is large potential for efficiency improvements.

Achieving the CCEFP vision is a strategic challenge. The organization has seven universities and roughly 50 companies spread over a wide geographical area with many different interests and points of view. The strategic thrusts based on efficiency, compactness and effectiveness provide a unifying structure allowing all to understand how their part of the effort contributes to the overall vision of the Center. The three-thrust structure has stood the test of time for providing a clear, concise and accurate guide for achieving our vision.

In order to transformational, not simply incremental, changes to the fluid power industry, more attention must be focused on the transformational technical barriers. These are: efficient components and systems, compact power supplies, and compact energy storage. Of these three, the compact energy storage problem has proven to be the most difficult.

Four different approaches to compact energy storage have been supported by the Center. These are: the open accumulator, the elastomeric accumulator, the flywheel accumulator and the HCCI free-piston engine pump. The first three approaches directly attack the energy storage barrier. The fourth approach provides an alternate approach to the energy storage problem for the hydraulic hybrid vehicle. The open accumulator was found to be inappropriate for the hydraulic hybrid passenger vehicle, but it is very promising for much larger energy storage such as in the electric grid. Follow-on research on the open accumulator has been funded by a $2 million grant from NSF. The concept has been patented and has been licensed to two renewable energy companies. The elastomeric accumulator continues to be a promising alternative for the hydraulic hybrid vehicle and other applications. Recent work has demonstrated that the device can provide compact energy storage for both hydraulic and pneumatic systems. The flywheel accumulator could provide a tenfold increase in energy storage density.

The HCCI free-piston engine-pump solves the energy storage problem by controlling power rather than energy. It epitomizes the system-oriented approach that ERCs strive to create. The primary way that hybridization saves energy in the hybrid passenger vehicles is by running the engine under nearly optimal conditions, that is, heavily loaded at all or nearly all times. Conventional vehicle engines are sized to provide sufficient torque and power for transient operation, such as during acceleration from a stop or during a passing maneuver. This leads to vehicles having engines that have roughly an order of higher power than is required for highway cruising. Hybridization can allow the excess power to be stored for later use, allowing the engine to be turned off when not needed, thus increasing fuel efficiency. Among other advantages, the free-piston engine pump has near instantaneous on-off capability. This benefit coupled with the energy storing accumulator in hydraulic hybrid vehicle means that there is no need to idle. The engine-pump's design is highly modular, so several engines (possibly of different power outputs) could be used to power a vehicle where the total power is the sum of the individual engine powers of those engines that are turned on. Thus, the power level could be modulated to more closely match the current requirement, greatly reducing the vehicle's fuel consumption.

Response to the Site Visit Team SWOT Report

SVT: The new vision statement does not drive research the way that the former vision statement did.

The updated vision statement unambiguously improves on the previous vision statement. It will drive research in a better direction since the addition of “power generation” and “storage” underscores the systems nature of the challenge. Power generation and storage are important in all of the test beds from small to large.

SVT: The CCEFP-NFPA team should incorporate additive manufacturing and medical applications as major new elements of their strategy for pursuing government funding.

The CCEFP is energetically pursuing government funding for additive manufacturing and medical applications.

SVT: CCEFP lacks commitment to the post-graduation inclusiveness of underrepresented individuals.

The CCEFP is fully committed to post-graduation inclusiveness for underrepresented individuals. In Years 9 and 10 diversity supplements were provided to all eligible continuing graduate research assistants in spite of diversity supplements being discontinued by NSF. Oak Ridge National Laboratory has agreed to fund a GEM student in Years 10 and 11. An NSF supplement has provided funding for an additional GEM student.

SVT: There is no tangible plan for academic-scale, proof of concept test beds so that students will learn hardware integration.

CCEFP fully appreciates the value of academic-scale, proof of concept test beds. The challenges are twofold, finding the needed resources and finding the needed expertise. We are in the process of seeking funding for large-scale hardware demonstrations. Industry collaboration is crucial for these efforts because of their superior capability in hardware development. The trust between industry Pascal members who are competitors must be further developed so that pre-competitive research can be more heavily supported by industry.

SVT: Test bed 3 should be re-imagined in a simplified way that avoids the control, integration, and scale issues that have limited the progress of the current test bed, yet maintains a system level of integration that provides a more rigorous and realistic testing environment, and exposes students to a level of complexity similar to what they experience in real industrial applications

Test bed 3 has made slower progress than planned due to continuing unexpected setbacks with hardware. In the future we will apply what we have learned from these difficulties to make a research plan that will make faster progress with more reliable hardware. Students will continue to be actively involved with the project, but extensive industry collaboration on the design and implementation of the plan is needed. The lack of a fully committed automotive partner substantially undermined the project. Future test bed activities would require more extensive funding from a combination of industry and government sources.

SVT: It remains unclear whether Test Bed 4 provides opportunities for advancement of fluid power technology.

Test beds 1 and 3 have a strong and mature industry base, but test beds 4 and 6 do not. The patient mover is exploring the opportunity to exploit the compactness and high force potential of fluid power to expand the fluid power into new markets. What is unappreciated by the SVT is just how difficult the control task is. Both the patient and caregiver must interact with the machine in a way that is safe and natural requiring advanced control approaches.

SVT: Not clear that the sustainability strategy has been broadly discussed among Center participants.

The sustainability strategy has been extensively communicated to CCEFP faculty, students and staff. Several have commented that they are tired of hearing about the "three-legged stool."

SVT: Failure of industry to substantially increase support for precompetitive research after graduation.

The "escalator plan" doubles the financial contribution of Pascal Society members in eight years. An aggressive recruitment strategy aimed at recruiting ten new companies per year, all of whom must pay the highest level of dues under the "elevator plan," will further and substantially increase industry funding for pre-competitive research.

SVT: There was no indication as to whether or not the CCEFP would apply again for an REU site award, as the site award expires at the end of this summer. The SVT urges the CCEFP to apply.

CCEFP has applied and has been awarded a second REU Site Award. The award is funded for $402,840 for three years beginning in 6/1/16.

SVT: Funding for the very successful collaboration with the Fond du Lac Indian Reservation will now be cut off, not a good message to members of the tribe interested in engineering.

We have successfully launched and sustained the gidaa Robotics Program, a school-based offshoot of the gidaa quarterly residential camps, through the Cloquet Middle and High School in Cloquet, MN and South Ridge K12 School in Saginaw, MN. Each school continues to offer robotics curriculum in day and after-school programs and through local support, participates in the national small robotics competition, Robofest, hosted by Lawrence Technological University in Southfield, MI. The CCEFP invested in significant infrastructure to support the Robotics Program in anticipation of receding funds. The Center is pleased to report this robotics initiative has transitioned South Ridge into an engineering and technology school and has enhanced STEM programing at Cloquet Middle and High School. The day and after-school programs continue with support from the school district. The gidaa camps continue with a focus on STEM supported by various NSF grants in the geosciences and are always open to additional STEM partners.

SVT: The partnership with the local science museum has always been a highlight of the ERC, but phasing down of NSF funded has led to the curtailment of these efforts.

The fluid power floor exhibits at the Science Museum of Minnesota will continue to be a permanent feature in the Experimental Lab at the museum.

SVT: Spin-off companies are important to market for new technologies, but there seems to be little enthusiasm for this new dimension to the innovation spectrum in the US economy.

Since the site visit we are pleased to report that the two spin-offs cited by the SVT are making excellent progress. One is the recipient of a NSF PFI: AIR award and other's proposal is pending.

SVT: The CCEFP-NFPA Work Force strategic plan should place increased emphasis on methods and incentives for recruiting minority students.

The CCEFP and NFPA believe diversity within engineering and the fluid power industry is critical. The joint workforce strategy will embed diversity, as a priority, throughout its mission and vision. The programs initiated through the CCEFP are considered candidates to incorporate into the new workforce program. The full NFPA and CCEFP Workforce and Education Program Portfolio will be vetted in Y10, approved by the NFPA Board and CCEFP Steering Committee and implemented in Y11 and beyond.

SVT: Support will be needed for the ILO and administrative functions of CCEFP so these core skills are not lost to the center during the transition period. The ILO and the E&O director are supported part time by the NFPA, which is a plus but care should be taken to monitor the remainder of their support. Another concern is that universities may eliminate their support when NSF's support ceases.

Beginning in year 11, the ILO and E&O director salaries will be fully funded by NFPA. The University of Minnesota will provide $250,000 per year to support other administrative costs in Years 11 and 12.

SVT: ERCs are to report to the Dean of Engineering, not a department head, to broaden their cross-disciplinary scope.

The CCEFP director has always reported to the Dean of the College of Science and Engineering and will continue to do so into the future.

.

This page is intentionally left blank

2. INTELLECTUAL MERIT AND RESEARCH IMPACT

2.1 INTELLECTUAL MERIT

Unlike many ERCs, the CCEFP focuses on technologies that have been broadly used, primarily in commercial applications, for the better part of a century. The existing industry base has focused on incremental improvements rather than breakthroughs for many years. Pre-competitive and collaborative research in fluid power was virtually non-existent ten years ago. The Center has changed that paradigm and there is now a vibrant and active group of academic researchers performing research in fluid power.

The research at CCEFP is demonstrated on four core test beds spanning four orders of magnitude of power and weight. These test beds and the classes of equipment they represent are:

- Hydraulic excavator (mobile heavy equipment, 50 kW-500 kW),
- Hydraulic hybrid passenger vehicle (on-highway vehicles, 10 kW-100 kW),
- Patient transfer device, formerly rescue robot. (mobile human scale equipment, 100W-1kW), and
- Ankle/foot orthosis (human assist devices, 10W-100W).

Research on these for core test beds has been continously conducted over the the ten year NSF life CCEFRP. But the research areas of the Center have matured as our researchers have gained knowledge and developed our relationships with our industry partners. The history of test bed evolution is shown in Figure 1.1. Early in the Center's existence, it was recognized that the two industrial test beds held little interest for our industry members, so it was decided to drop them. Currently, all of the core test beds are mobile applications where the inherent advantages of fluid power are most evident. Two newer test beds at the extremes of the power scale, the wind turbine and the MRI surgical device were added in year five. These are transformational test beds in emerging application areas on the frontiers of fluid power. A key feature of fluid power is its high power output in a small package, thus providing very high power density. Conversely, fluid power systems have low energy density. Stationary fluid power applications do not put a premium on compactness or power density, but both industrial and mobile applications value efficiency.

The test beds integrate research aimed at overcoming nine technical barriers of fluid power:

1. *Efficient components*
2. Efficient systems
3. Control and energy management
4. *Compact power supplies*
5. *Compact energy storage*
6. Compact integrated systems
7. Safe and easy to use
8. Leak-free
9. Quiet

The three barriers that are italicized above; efficient components, compact power supplies and compact energy storage; are transformational. They have been given priority focus in the Center's research. This focus was underscored as through our strategic planning process. CCEFP identified the following important goals:

1. Doubling fluid power efficiency in current applications and in new transportation applications
2. Increasing fluid power energy storage density by an order of magnitude
3. Developing new fluid power supplies that are one to two orders of magnitude smaller than anything currently available

The Center has made significant progress against these goals. For goal 1, a fuel consumption reduction of more than 40% was demonstrated in independent testing on Test Bed 1, the hydraulic excavator. For goal 2, the novel elastomeric accumulator increases energy density by 3-4 times and new designs could approach the goal of an order of magnitude increase. For goal 3, Center researchers created the world's smallest free-piston engine and an innovative Stirling cycle engine that because of its size and energy output is extremely well suited for use in human-scale applications such as Test Bed 6, the ankle-foot orthosis. This will be discussed in more depth in section 2.2.

The CCEFP fills a void in fluid power research that existed for decades. Until the Center was established, the U.S. had no major fluid power research center (compared with thirty centers in Europe and five centers in Asia). Fluid power researchers numbered in the single digits and little, if any, inter-university research collaboration was taking place. This resulted in the industry's image being that it used "tractor technology" that had low efficiency, leaks, noise and other deficiencies. As a direct result of the CCEFP's influence, today there are dozens of fluid power researchers in the US. Fluid power researchers, who were previously disconnected, are now linked through the CCEFP. The industry-focused strategic research directions the Center has established has become the gold standard for fluid power research around the world. Fluid power researchers around the world have adopted the focus of CCEFP's three thrusts, efficiency, compactness and effectiveness, as key aspects of their research. CCEFP has enjoyed strong industry support since its inception, averaging fifty industry members over its first ten years. As a result of the Center's sustainability focus over the past several years, the number of industry supporters is currently more than seventy. The CCEFP has helped create a new paradigm for the fluid power industry that includes pre-competitive research benefitting the industry as a whole and working with the unique skills and tools that academia can provide to accelerate the commercialization of promising technologies.

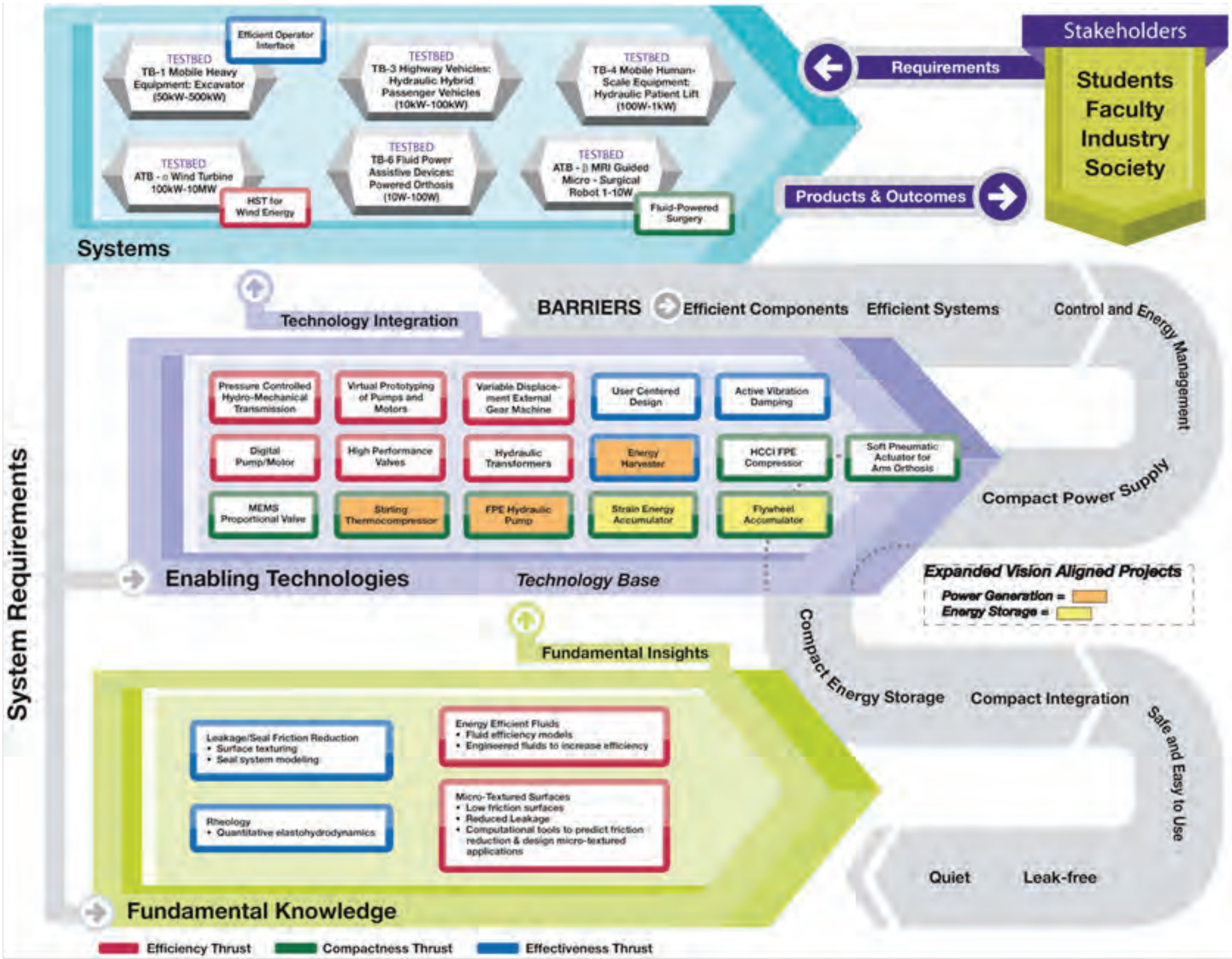


Figure 2.1: CCEFP FY10 Three Plane Chart (2016)

2.2 RESEARCH IMPACTS

As would be expected from a successful engineering research center, the CCEFP's three-plane strategic plan has matured over the life of the Center. Discoveries made on the fundamental knowledge plane move to the enabling technologies plane and are then implmented in a complete system in one or more of the test beds. Figure 2.1 shows the CCEFP's current three-plane chart.

Test Bed 6, the human-scale ankle-foot orthosis, provides a number of example of how test bed system requirements flowed down to generate research and technology projects. One of the limiting factors for the orthosis is that no power supply that was sufficiently small and lightweight to allow untethered operation was commericially available. This need led to the development of two compact power supplies. The research projects started on the fundamental knowledge plane. The first power supply on which fundamental research was done was the free-piston engine compressor (FPEC). The homogeneous charge compression ignition (HCCI) engine in the FPEC is two order of magnitude lower in output than other HCCI engines. The project resulted in the creation and testing of the world's smallest free-piston engine, but it ultimately proved to be a poor solution for the orthosis because of noise and heat generation. It may still be possible to use the knowledge gained from this project in another applications. The second power supply to be developed for Test Bed 6 was a Stirling thermocompressor. The sound power output from a Stirling engine is very low, the device is compact and the thermal challenges faced by the FPEC were manageable with the Stirling thermocompressor. It appears to be an excellent fit that will allow the orthosis to be an untethered device.

One of the transformational technical barriers identified in the Center's strategic planning is compact energy storage. Early in the Center's existence, a project was funded to create a novel open air accumulator for Test Bed 3, the hydraulic hybrid passenger car. As a result of the project's research it was determined that this type of accumulator could not be effectively scaled down to provide the energy storage needs of Test Bed 6 while meeting the size and weight requirements. However, it was determined that the open air accumulator could more be scaled up to utility-scale energy storage systems. The patents for the technology is currently licensed by two companies. The researchers also received a $2M NSF grant to continue research on the concept. A second project focused on compact energy storage for Test Bed 3 started as a fundamental research project on the use of elastomers for hydraulic and pneumatic energy storage. Conventional hydraulic accumulators are gas over liquid devices in which the hydraulic fluid is pumped into a thick walled elastomeric bladder compressing nitrogen in the accumulator shell. Shells are typically made from steel, resulting in a very heavy device, or wound composites, which are much lighter, but more expensive. In the elastomeric accumulator, the energy is stored as strain. This increases the energy density of the accumulator by three to four times. Improved designs could achieve the goal of an order of magnitude increase. Test Bed 3 was not ready to test the elastomeric accumulator, but the researchers created a pneumatic version of the strain energy accumulator that was demonstrated on Test Bed 6, the ankle-foot orthosis. The pneumatic strain energy accumulator is able to store a portion of this exhaust gas of the actuator and then reuse it to assist its powered return motion. In testing on the orthosis, the use of the pneumatic strain energy accumulator resulted in an energy savings of over 25% compared to operating the pneumatic actuation of the orthosis in the conventional manner. The result is a significant increase (33%) in untethered run time for the orthosis.

Test Bed 6 also provides an excellent example of successful inter-disciplinary research involving most of the CCEFP universities. Prof. Elizabeth Hsiao-Wecksler in Mechanical Systems Engineering at the University of Illinois at Urbana-Champaign (UIUC) is the principal investigator. Since the orthosis is worn by and provides assistance to a human, Dr. Geza Kogler in Applied Physiology at the Georgia Institute of Technology is a co-PI. Another faculty member on the research team is Prof. Girish Kirshnan, Industrial & Enterprise Systems Engineering at the UIUC. Professor Eric Barth of Vanderbilt provided elastomeric accumulator expertise. Assistance in human factors design involved several industrial engineering professors at NCAT and key components were fabricated at MSOE under the guidance of Vito Gervasi. The device has undergone clinical testing during which the research team collaborated with researchers at the Rehabilitation Institute of Chicago. The testing explored the orthosis' function compared to a range of other assistive devices (e.g., tibial stimulators and commercially-available passive AFOs) in a post-stroke subject population.

2.3 INTELLECTUAL PROPERTY CREATED

CCEFP participates in many technology transfer efforts. In addition to the various interactions previously described, CCEFP faculty and staff are encouraged to consult with industry to transfer research knowledge and move Center discoveries toward commercialization. Many of the lead researchers are active consultants. Faculty members have also taken leave to be on location at the partner organizations. In addition, several graduate students have worked on internships with our member companies.

Since its inception, the CCEFP has produced 56 disclosures, 40 patent applications filed, seven patents awarded, five licenses issued, three spin-off companies and another three potential start-ups. Although the fluid power industry has been historically slow to adopt new technologies we see increased global competition as well as CCEFP research discoveries beginning to change this attitude. The trend of adopting, indeed requiring, new technologies is only expected to accelerate going forward and is a major reason given by industry for supporting Center sustainability. Table 2.1 summarizes the CCEFP invention disclosures and current status since the Center started in 2006**.**

Table 2.1: ERC Intellectual Property

IP File number at the Home University	Home University	IP Title	Provisional Application Date (PP)	Patent Application Date	Patent Number (FP)	Existing or possible licensing opportunities
Z07054	Minnesota	Open Accumulator Compact Energy Storage for Regenerative Fluid Power Applications	10/10/2006	6/30/2009	12/445,176	Licensed to SustainX Inc and LightSail Energy Inc
Z07129	Minnesota	Hydro-mechanical Hybrid Drive Train	4/10/2007	4/10/2008	PCT/US2008/004618	
Z08013	Minnesota	Hydraulic Actuation of a Spool Using an Actuated Pump	8/20/2007	4/9/2009	12/444,910	Passively marketed. No licensing negotiations
2008P00304	MSOE	Method for reducing torque ripple in hydraulic motors	12/31/2008	7/1/2010 7/8/2010	US 12/347,608 WO 2010/076241 A1	
65083	Purdue University	Axial Sliding Bearing with Structural Sliding Surface	4/1/2008	11/16/2010 (US), 10/29/2010 (KR), 4/1/2009 (JP), 4/1/2009 (EP)	None issued yet	Licensed to a CCEFP member
	UIUC	Micro- and Nano-Texturing for Low-Friction Fluid Power Systems		8/10/2009	Pending	Nitta-Moore
Lattice Family	MSOE	Lattice Structures	3/13/2013	3/13/2014	PCT/US2014/026472 WO 2014/160389 A1	Available
Z09145	Minnesota	Rotary On/Off Valve for Virtually Variable 4 Quadrant Pump/Motor Applications	None	None	None	
VU09108	Vanderbilt University	High Energy Density Elastomeric Accumulator	4/6/2009	3/31/2010	PCT/US10/29361	Discussions underway with CCEFP member
VU09107	Vanderbilt University	High Inertance Liquid Piston	4/6/2009	4/5/2010	8,297,237	
TF09137	UIUC	Ankle-Foot-Orthoses Device	10/5/2009	10/5/2010	Pending	
65550	Purdue University	Bi-directional Check Valve	1/24/2011	1/24/2012 (US)	None issued yet	Available
65293	Purdue University	Piston with Waved Surface for Positive Displacement Pumps and Motors	4/1/2009	11/23/2011 (US), 9/28/2011 (EP), no date listed (KR)	None issued yet	Licensed to a CCEFP member

5344	Georgia Tech	Multiple Disclosures for Acoustic Management	not yet filed	not yet filed	NA	Archive/Waived Title
5345	Georgia Tech	Multiple Disclosures for Acoustic Management	not yet filed	not yet filed	NA	Archive/Waived Title
5346	Georgia Tech	Multiple Disclosures for Acoustic Management	not yet filed	not yet filed	NA	Archive/Waived Title
5347	Georgia Tech	Multiple Disclosures for Acoustic Management	not yet filed	not yet filed	NA	Archive/Waived Title
5348	Georgia Tech	Multiple Disclosures for Acoustic Management	not yet filed	not yet filed	NA	Archive/Waived Title
5350	Georgia Tech	Multiple Disclosures for Acoustic Management	not yet filed	not yet filed	NA	Archive/Waived Title
5408	Georgia Tech	Multiple Disclosures for Acoustic Management	not yet filed	not yet filed	NA	Archive/Waived Title
5480	Georgia Tech	Piezo-Array Embedded Polymeric Seals for Effective Micro-Control of Sealing	1/28/2011	61/437,179	NA	Archive/Waived Title
VU1172	Vanderbilt University	Elastic Hydraulic Accumulator /Reservoir System	N/A	1/31/2011	US 13/017,118 AND PCT PCT/US11/23120	
VU1195	Vanderbilt University	Multiple Accumulator Systems and Methods of Use Thereof	2/3/2011	1/30/2012	US 13/360,929 AND PCT/US12/23073	
65810	Purdue University	Hydraulic Hybrid Architecture for Systems having Rotary and Linear Actuators	3/16/2011	Utility Patent being drafted	None issued yet	Available
5567	Georgia Tech	Multiple Disclosures for Acoustic Management	not yet filed	not yet filed	N/A	Archive/Waived Title
5568	Georgia Tech	Multiple Disclosures for Acoustic Management	not yet filed	not yet filed	N/A	Archive/Waived Title
5569	Georgia Tech	Multiple Disclosures for Acoustic Management	not yet filed	not yet filed	N/A	Archive/Waived Title
20110146	Minnesota	Integrated Portable Pneumatically Powered Ankle-foot Orthosis	3/14/2011	3/14/2012		
	UIUC	Ankle-Foot-Orthoses Device	3/14/2011	3/13/2012	Pending	
MSOE Muscle (I0D 1)	MSOE	Fluid Power Actuator (MSOE Muscle)	4/1/2012	TBD	N/A	
VU12052	Vanderbilt University	Continuous Perimeter Clamp	N/A	N/A	N/A	
20120199	Minnesota	Mini HCCI Compressor	6/18/2012	Not yet filed		
20120205	Minnesota	Method of Control of FPE	4/2/2012	Not yet filed		
20140116	Minnesota	Powered Exoskeleton Using Tiny Hydraulics		Not yet filed		
GTRC ID 6517	Georgia Tech	Control of Voluntary and Involuntary Nerve Impulses for Hemiparesis Rehabilitation and FMRI Study	10/21/2013	61/893,491	N/A	Archive/Waived Title
	Vanderbilt University	Motive Apparatus for use in Magnetically-Sensitive Environments	11/16/2011	11/16/2012		
VU12048	Vanderbilt University	Distributed Piston Elastomeric Accumulator		Not yet filed		
VU12045	Vanderbilt University	Precision Pneumatic Robot for MRI Guided Surgery		Not yet filed		
VU13090	Vanderbilt University	Intrinsically Fail-Safe Linear Pneumatic Actuator		Not yet filed		
VU13142	Vanderbilt University	Collapsible Miniature Heat Exchanger for Reciprocating Piston Engines		Not yet filed		
Walking Engine	MSOE	Actuation System for a Joint	3/13/2013	3/13/2014	14/209,849 US 2014/0260950 A1	Available

	MSOE	High-efficiency Compressor	Not yet filed	Not yet filed		
6125	Georgia Tech	A Modelica Library for Hydraulic Components and Systems	N/A	N/A	N/A	Archive/Waived Title
5182	Georgia Tech	A Flow Control Circuit with Dynamic Compensations	2/28/2012	61/604,214	N/A	Archive/Waived Title
5652	Georgia Tech	MRI Compatible Force Sensor	4/26/2011	61/479,214	N/A	Archive/Waived Title
4574-PR-08	Georgia Tech	Hydraulic Rod Seal with Saw Tooth Sealing Surface Pattern	11/26/2008	61/118,080	N/A	Archive/Waived Title
4574-PR-10	Georgia Tech	Hydraulic Rod Seal with Saw Tooth Sealing Surface Pattern	11/24/2009	61/263,894	N/A	Archive/Waived Title

This page is intentionally left blank

3. UNIVERSITY EDUCATION, PRE-COLLEGE OUTREACH AND INDUSTRY ENGAGEMENT PROGRAM

The Center's mission, vision, strategy, and objectives are the basis for each of its education and outreach projects. The projects are organized around four thrust areas: public outreach, pre-college outreach, college education, and industry engagement. The Education and Outreach Program's value chain demonstrates how each core objective and initiative accomplishes the Center's end goal to change the way fluid power is researched, applied, and taught by way of developing intellectual capital that can create, innovate and lead.

The mission of the Education and Outreach (EO) Program of the NSF Center for Compact and Efficient Fluid Power (CCEFP) is to develop research inspired, industry practice directed fluid power education for pre-college, university and practitioner students; to integrate research findings into education; to broaden the general public's awareness of fluid power; and through active recruiting and retention, to increase the diversity of students and practitioners in fluid power research and industry.

The vision of the Education and Outreach (EO) Program is a general public that is aware of the importance of fluid power and the impact to their lives; students of all ages who are motivated to understand fluid power, who can create new knowledge, and innovate; industry that capitalizes on new knowledge to lead the world in fluid power innovation; and participants in all aspects of fluid power who reflect the gender, racial and ethnic composition of this country.

The strategy of the Education and Outreach (EO) Program is to develop and deliver high quality projects that wherever possible capitalize on existing, broadly distributed education and outreach networks to maximize program impact; to develop projects that can be replicated and/or adapted by other educators and program leaders for new audiences; and to leverage and coordinate the accomplishments of individual projects to facilitate the progress and successes of others.

The objectives of the Education and Outreach Program are to:

1. Motivate all diverse citizens to navigate the STEM pathway in order to expand and promote a talented STEM workforce.
2. Promote awareness and excitement of fluid power among technical college, undergraduate and graduate students.
3. Disseminate fluid power fundamentals, research, and innovation through evaluated fluid power curricula, projects and programs that highlight fluid power concepts and applications.
4. Create a culture that integrates research and education for technical college, undergraduate and graduate students, as well as industry professionals across CCEFP and NFPA partner institutions
5. Increase the number of students well prepared to pursue fluid power research, jobs and careers.
6. Strengthen ties between higher education and the fluid power industry.

CCEFP Y10 Thrusts, Projects and Program Objectives	Participant Level	Promote STEM learning to diverse people	Promote awareness of fluid power	Fluid power dissemination	Culture of research and education integration	Increase fluid power workforce	Strengthen ties between higher ed and industry
Thrust A: Public Outreach -- Bringing the message of fluid power to the general public							
A.1 Interactive Fluid Power Exhibits	All	■	■		■		■
Thrust B: Outreach – Bringing fluid power education to K12 students with a focus on middle and high school							
B.7 NFPA Fluid Power Challenge Competition	K12	■	■			■	■
Thrust C: College Education – Bringing fluid power education to undergraduate and graduate students							
C.1 CCEFP REU Program	BS	■	■	■	■	■	
C.4 Fluid Power in Courses, Curriculum and Capstones	BS, MS	■	■	■	■	■	■

C.4B Parker Hannifin Chainless Challenge	BS						
C.8 CCEFP Student Leadership Council	MS, PhD						
Affiliated Project: Excavator Cab Design Competition	BS						
Thrust D: Industry Engagement – Making connections between CCEFP and industry							
D.1 Fluid Power Scholars Program	BS						
D.2 CCEFP Engagement Programs	All						
D.5 CCEFP Webinar Series	All						

	REU	RET + Non-RET	Pre-College	Public
Lead: University of Minnesota	☑	★	☑	☑
Georgia Institute of Technology	☑	■	■	☑
Milwaukee School of Engineering	☑	☑	☑	☑
University of Illinois, Urbana-Champaign	☑		★, ☒	☑
North Carolina A&T State University	☑	■	★, ☒	☑
Purdue University	☑	■	■	☑
Vanderbilt University	☑	★, ☒	★, ☒	☑

Education Activities Table

☑ All Years | ★ Years 1-3 | ☒ Years 4 – 6 | ■ Years 7 – 10

Diversity: The CCEFP is striving to change the face of fluid power by providing opportunities for a diverse population to become involved in fluid power--women, underrepresented minorities, those with disabilities and recent war veterans. The CCEFP is committed to recruiting, engaging and retaining these diverse audiences in its programs: university faculty, undergraduate and graduate students; pre-college students and teachers; and students of all ages through its outreach activities.

Engineering Research, Assessment, and Program Impact The CCEFP's approach to program evaluation and assessment is novel and has evolved over time. The Center has contracted with an external intellectual partner to utilize traditional evaluation methods and data to systematically and strategically clarify program objectives, quantify results, and chart a course towards post-ERC sustainability. This method has resulted in a comprehensive assessment protocol of all CCEFP research, education and outreach programs measured across six crosscutting objectives. CCEFP is able to determine, through this high level approach, how it is able to impact an entire spectrum of research, teaching and learning, as opposed to individual impacts of disconnected programs and activities.

Administration of the Education and Outreach Program: The EO Program is lead and coordinated by Education Program Director James Van De Ven and Education and Administrative Director Alyssa Burger. The Directors report to CCEFP Director Kim Stelson. Additionally, Principal Investigators of specific projects contribute to program direction and implementation. Responsibility for fluid power education and outreach rests with every CCEFP participant. CCEFP research and test bed projects are considered a method of education and workforce development. The EO activities of individual research projects are reflected in the project update reports.

Professional Partnership of the Education and Outreach Program: The National Fluid Power Association's (NFPA) Education and Technology Foundation has created the Pascal Society to combine the contributions of many individuals into a single effort, the Pascal Society seeks to develop the resources, tools, and people to meet the technology and workforce needs of the U.S. fluid power industry. A major goal is the support of pre-competitive research projects through the CCEFP. These projects are important because they connect advanced-degree students to our industry, create more infrastructure in our leading universities, and increase the ability of those universities to teach fluid power to their undergraduates. The Society has been structured to facilitate the engagement of its industry members in setting a research strategy, selecting the projects most likely to benefit our industry, and reviewing the progress of the students working on them. It is one of the best ways to introduce talented engineers to the technology and to bring them into the fluid power industry.

Highlights resulting from the Center's Education and Outreach program include:

- **Industry Student Engagement** - A deliberate focus of the EO program is to foster industry and student engagement through events, activities, and webinars. The Center creates networking opportunities through the Fluid Power Innovation & Research Conference (FPIRC), Industry University Engagement Summits and the regularly offered CCEFP Webinar Series. In all cases, both stakeholders attend, presenting relevant report-outs on achievements, in conjunction with social functions to foster collaboration. (Project D.2)

- **Courses, Curriculum and Capstones** - The CCEFP is leading the effort to develop new, and to modify existing courses with fluid power content based on CCEFP research. Center faculty continue to enhance curriculum in their home universities, which ultimately creates a cadre of highly skilled students who will become future fluid power industry professionals and future engineering faculty. One teacher reaches many students and by integrating fluid power into existing curriculum, including mini-books and new curriculum modules, the CCEFP is responsible for exposing thousands of students to this technology over the course of its 10 years. The University of Minnesota recently offered the first Massive-Open-Online-Course (MOOC) in Fluid Power, a significant achievement in undergraduate and practitioner-level curriculum. In addition, the Science Museum of Minnesota, CCEFP, and industry sponsors are jointly funding fluid power capstone projects. Advanced graduate courses with content based on CCEFP research provide a means for knowledge transfer of research results. (Project C.4)

- **CCEFP Receives NSF REU Site Award** - The Center received the competitive NSF Research Experiences for Undergraduates (REU) Site Award for Years 8 – 10. CCEFP has applied for a second REU Site Award, post-graduation, Years 11 – 13. To date, the chances of success are high, given reviewer feedback. The goals of NSF REU programs are to kindle the interest of diverse participants in attending graduate school. Additionally, CCEFP's goal also includes increasing the number of undergraduate students knowledgeable in fluid power. To date, more than 185 REU students have participated in the CCEFP program -- more than in many REU site programs. The CCEFP completed a longitudinal study of our past participants in early 2014. At the time of the report, 57% of all former CCEFP undergraduate researchers enter graduate school, and 25% of those are PhD candidates. Extremely positive statistics! Since 2008, the CCEFP REU Program has recruited, on average, over 35% women, and over 35% racially or ethnically underrepresented students into the program on a yearly basis. The CCEFP's recruiting strategy includes identifying institutions, programs, and people with whom to develop relationships that, in turn, open pathways to CCEFP summer programs and beyond for underrepresented students. (Project C.1)

- **REU Fluid Power Boot Camp** – Due to being geographically distant and home to a technology not taught nor generally understood, the CCEFP incorporated a 2-day Fluid Power Boot Camp for participants of the REU Program. Since 2008, undergraduates have participated in the event that provides a quick hands-on overview of the CCEFP, fluid power technology, terminology, hydraulic and pneumatic applications. Students also conducted fluid power lab circuits, simulations, and trouble-shooting. Originally offered at the University of Minnesota, the REU Fluid Power Boot Camp is offered at the outset of the program at Purdue University and the Maha Fluid Power Research Laboratory. (Project C.1)

- **CCEFP-GEM Partnership** - A formal partnership with the National GEM Consortium and a proposed program structure, designed and piloted by CCEFP, has been recommendation for adoption within the NSF ERC system, to increase the ability of ERCs to recruit and retain underrepresented students in graduate engineering programs. The GEM-ERC Fellows Program overcomes barriers to ERC student recruitment of underrepresented students in engineering. This rich collaboration offers nothing but benefits to the GEM Fellow, the ERC, the Industry member, and the GEM Consortium. The CCEFP was instrumental in initiating a new fellowship program at GEM – the University Fellows Program.

- **Science Museum of Minnesota** - The six fluid power exhibits at the Science Museum of Minnesota (SMM) are on permanent display in the Experimental Gallery. The SMM welcomes nearly 1,000,000 visitors yearly, to result in thousands of people of all ages' exposed to hands-on hydraulic and pneumatic exhibits. Additionally, as a way of vetting new ideas for fluid power exhibits, the SMM advises fluid power capstone projects at the University of Minnesota. (Project A.1)

- **Student Leadership Council** - The Student Leadership Council (SLC) serves a vital role in meeting the Center's goal of providing fluid power education and awareness for pre-college, university, and practitioner students. The SLC Travel Grant Program provides funds for students to travel to another project or industry location, making collaboration more feasible. The SLC Travel Grant Program has been highly successful, providing over 27 travel grants to CCEFP graduate students. This program has proven to be very popular among students and faculty. (Project C.8).

- **CCEFP Webinar Series** – The Center's popular webinar series continues to evolve to better align with the needs of all Center stakeholders. The webinars include Center research updates, guest industry presentations, and research initiatives not funded by, but are aligned with CCEFP work. Following a change in webinar technology, the CCEFP has conducted a survey of participants and results are positive. The Webinar Series will be a legacy of the CCEFP. (Project D.5).

- **Fluid Power Challenge** - The Fluid Power Challenge, a strategic program through the National Fluid Power Association (NFPA), is a hands-on engineering design competition for eighth grade students, utilizing hydraulics and pneumatics. Since adoption and implementation of the program, CCEFP has offered 11 events since 2009 at the University of Minnesota, Georgia Institute of Technology and Purdue University. Overall, over 2,000 middle school students have participated, including 35 teachers, and have been exposed to fluid power technology and applications. In the future, the NFPA is exploring the idea of partnering with the national 4-H program, which have extension partnerships with land-grant institutions in all United States. (Project B.7).

- **Engineering Education Research** - Quality Evaluation Designs (QED) is the CCEFP's intellectual partner in engineering education research. The overall goal of the QED research is to collect data that have the potential to promote sustainability of education and outreach programming beyond NSF years. QED's objectives: help provide overall focus and structure to CCEFP's EO program; and implement a simple uniform metric for evaluating all EO activities that completely revealed the successes and challenges related to its core mission. (Thrust E).

- **Fluid Power Scholars** - The Fluid Power Scholars Program is a sponsorship program of interns to attend a short-course on fluid power at the Milwaukee School of Engineering (MSOE). To date, 57 high-performing undergraduate engineering students completed a fluid power boot camp followed by a full-time summer internships at companies who are corporate supporters of the CCEFP through the NFPA's Education and Technology Foundation's Pascal Society. Since 2010, 75% of Scholars have been hired into the fluid power industry. In the future, the NFPA will assume the sponsorship of the program, while CCEFP staff continue to coordinate the effort. (Project D.1)

3.1 UNIVERSITY EDUCATION PROGRAM

The University Education Program addresses the following objectives: 1) Infuse new fluid-power research and innovative, evaluated, fluid power curricula and programs into informal, K-12, and college level course offerings; 2) Create a culture that integrates research and education for undergraduate and graduate students across all partner institutions; 3) Increase the number of students well-prepared to pursue fluid power research, jobs and careers and 4) Strengthen ties between higher education and the fluid power industry.

The goal of the CCEFP university education program is to train graduate and undergraduate students in fluid power with the expectation that they will become future intellectual capital in the fluid power industry and in university-based fluid power research and teaching. Three methods are used to attain these goals: 1) Attract undergraduate and graduate students and engage them in cutting edge fluid power research, 2) Infuse fluid power into traditional engineering curriculum so that every undergraduate student gains exposure, and 3) Provide advanced students with the opportunity to study cutting edge curricular material based on the latest CCEFP research.

Examples from CCEFP education projects illustrate progress towards the goals:

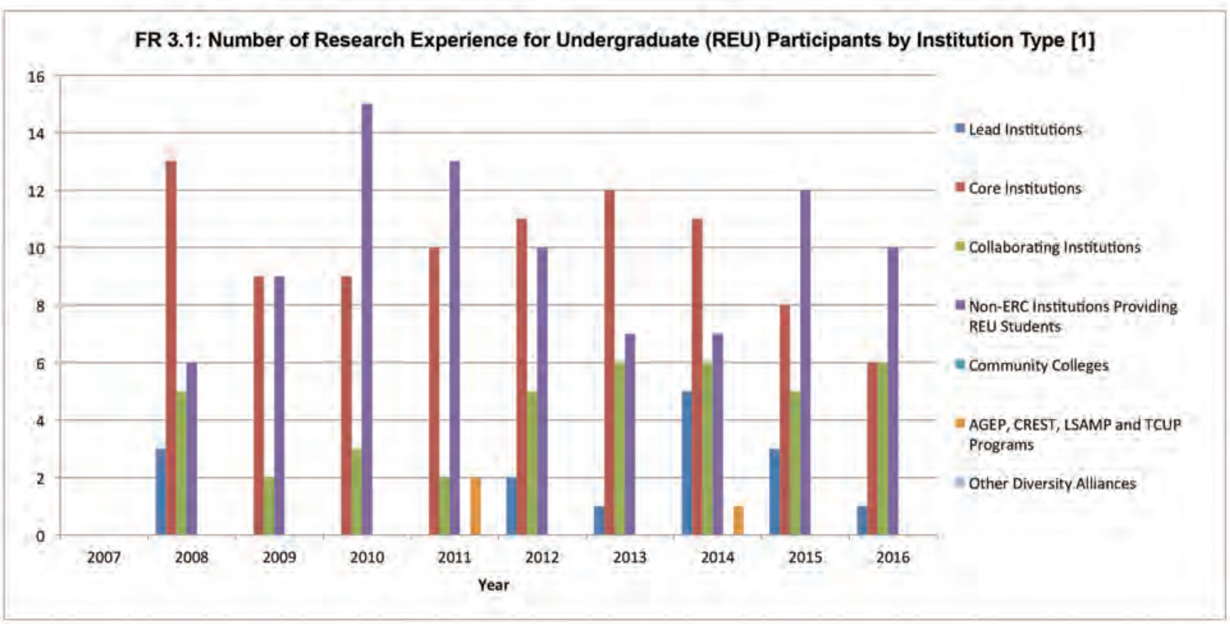
Engineering Education Research: The CCEFP has taken an innovative and novel approach at studying the impact of the Education and Outreach program portfolio. CCEFP's intellectual partner in engineering education research is Quality Evaluation Designs (QED). QED's task is to provide overall strategic focus and structure to the EO program and to implement a uniform metric for evaluating all EO activities that was simple to complete and yet revealing of EO successes and challenges related to its core mission. QED invested in a comprehensive study to reveal six crosscutting objectives. These objectives were operationalized in a survey utilized by each and every EO program slated for sustainability. The results of the survey reveal that ratings are uniformly high and positive. This method would prove to be a concept worth populating through each NSF Engineering Research Center to collectively assess the national impact of all ERC EO programs. A two-page description is provided at the end of Section 3. In addition to the crosscutting approach to program evaluation and assessment of impact, QED also performed a Fluid Power Pathways Study and a Workforce Demand Study. The results of this research helps to identify intersections of influence to career trajectory and determines the needs of industry.

REU Program: The Center determined that committing significant funding to its REU program would kindle participants' interests in attending graduate school and would yield undergraduate students with research experience who were knowledgeable in fluid power. In addition to an impressive program infrastructure, the CCEFP has been the recipient of an NSF REU Site Award for three years, a $390,000 grant. More than 185 REU students have participated in the program--more than many traditional REU site programs. A cohort of at least two REUs is based at each CCEFP partner institution. Often, REU advisors are able to secure additional sources of funding resulting in more participation and greater leverage. The local faculty and graduate student mentors are responsible for creating a welcoming environment for CCEFP REUs. To remain connected across the CCEFP community and in the REU Program, all participants attend a Fluid Power Boot Camp at the outset of the experience. Once students are integrated into their host institution, the REUs remain connected through a weekly blog and bi-weekly professional development webinars. REUs are encouraged to remain connected to the CCEFP through other affiliated research and workforce development programs. Several REUs have been travel grant recipients to attend the CCEFP's Fluid Power Innovation & Research Conference (FPIRC) to present a poster on their work and network with industry practitioners. Others participate in the Fluid Power Scholars Program, a scholarship for incoming interns of corporate partners. Over 75% of students participating in the Fluid Power Scholars program are hired into the host company. Others participate in local campus activities related to fluid power – capstone design course projects, one-on-one research, or undergraduate engineering competitions in fluid power.

Based on two longitudinal studies, the CCEFP determined over 57% of its REU participants attend graduate school and 25% of those pursue PhDs in their preferred area of expertise.

The CCEFP desires for the REU Program to continue after the Center's Year 10. The CCEFP has applied for another REU Site Award to support the REU program in years 11 and beyond. At the date of this writing, the likelihood of success is good, given the proposal review feedback. Without additional supplemental funding, the chances of sustainability are slim, given the significant financial investment needed to support the program in full.

According to the assessment and analysis conducted by external research team, Quality Evaluation Designs, a high proportion of respondents showed a high level of interest in working in fluid power.



[1] REU students include NSF REU Site Award Students and ERC's Own REU Students.

Fluid Power Scholars Program: The Fluid Power Scholars program is a sponsorship of an industry intern to fluid power training program at the outset of the internship experience. This program is identified as a cornerstone of the future collaborative CCEFP and NFPA workforce development initiatives. The Fluid Power Scholars program compliments the REU program. The program was launched in 2010, and continues through 2016. The program can continue in the future with CCEFP coordination and NFPA Support.

Fifty-seven Fluid Power Scholars have been named since the program inception; it reached its maximum capacity in 2015. Goals for 2016 are to fill the program and increase the number of participating companies. Maxing out the course enrollment has been an outcome of the partnership with the NFPA

Foundation's Pascal Society as a recruitment tool for corporate participation. All scholars/interns participate in an intensive fluid power orientation followed by an exceptional summer internship experience within a fluid power company. To date, 75% of Fluid Power Scholars are working in the fluid power field, a majority of the interns remaining full time employees with their host company. The CCEFP's Fluid Power Scholars Program is an outstanding example of an effective industry/university partnership spawned by NSF's ERC program. At every stage and at every level, CCEFP corporate supporters worked enthusiastically to create environments where scholars/interns could effectively apply what they had learned about fluid power in the classroom to hands-on, real-world applications. Success stories from the undergraduate Fluid Power Scholars program are reaching industry decision makers who are now expressing interest to support interns at the graduate level. The Center understands that interns are the least likely candidates for a company to provide sponsored training; however, they may be the likeliest candidates for full-time employment in the corporate host and the fluid power industry.

This growing cadre of undergraduate REU and Scholar students with skills in fluid power is precisely the pool that fluid power manufacturers were looking for when they committed to supporting the CCEFP ten years ago.

Diverse Graduate Recruitment CCEFP has transitioned, to the ERC family, CCEFP's innovative approach to recruitment of underrepresented students in engineering through the National GEM Consortium. The innovative membership model between Engineering Research Centers and the National GEM Consortium--a well established and highly regarded program aimed at increasing the participation of underrepresented groups--and the mutual corporate members of each organization. A formal partnership with the National GEM Consortium and a proposed program structure, designed and piloted by CCEFP, is recommended to be adopted and implemented within the NSF ERC system, to increase the ability of ERCs to recruit and retain underrepresented students in graduate engineering programs. The GEM-ERC Fellows Program overcomes barriers to ERC student recruitment of underrepresented students in engineering. The GEM-ERC Fellows Program is differentiated from the traditional GEM Fellow in that the internship experience and the research work is integrated and aligned. To date, the CCEFP investigated this program over the course of three years. Late in the Center's existence, the first pilot was initiated. The CCEFP was able to successfully recruit and retain one PhD student at Georgia Institute of Technology. The CCEFP returns this program to the NSF to consider broad adoption and implementation with a significant return on investment. The budget allocation for this activity is minimal and leveraged by the contributions of the industry partner, the academic institution and the ERC. A one-page detailed description of this program can be found in Section 5.

Fluid Power in Engineering Courses, Curriculum and Capstones: The Fluid Power OpenCourseWare site exists to digitally publish and disseminate high-quality, college-level teaching materials in fluid power. The materials can be used in fluid power elective courses, but more importantly they can be inserted into core engineering courses taken by all students. Lecture notes from three courses developed by CCEFP faculty have been posted along with two mini-books. An additional mini-book is in draft form and others are in the planning stages. The SLC contributed to problem sets in the first CCEFP mini-book, Fluid Power System Dynamics. To date, over 30 courses and seven freestanding modules with CCEFP content were taught or developed by CCEFP faculty. This demonstrates the growing commitment to university fluid power education across the Center.

In the future, CCEFP will be responsible for the coordination and implementation of the NFPA Curriculum Grants program. This will provide two $25,000 grants to faculty awardees in order to accomplish one of three goals. 1) To complete the suite of fluid power curriculum modules to be inserted into core engineering courses; 2) To design a low-cost universal fluid power laboratory trainer; 3) To propose novel fluid power teaching and learning methods which have the ability to be easily replicable. Two education products will be an outcome of the program. Those products will then be broadly disseminated across the country. The goal is to motivate faculty in the utilization of fluid power teaching methods in existing core courses and expose even more undergraduate and graduate students to fluid power.

Recently, University of Minnesota faculty successfully offered a Massive Online Open Course (MOOC) titled “Fundamentals of Fluid Power.” Coursera competitively selected the course. This course introduces students to the fundamental principles of fluid power systems, circuits, and components. The course was delivered through short, focused video presentations, which include lectures, laboratory demonstrations, large system demonstrations, and interviews with industry experts. The target audience for the course includes entry-level engineers, senior-level undergraduate students, and entry-level graduate students. The six-week course was fist offered Fall 2014, again Fall 2015 and will be offered on a self-directed on-going basis up to four times per year.

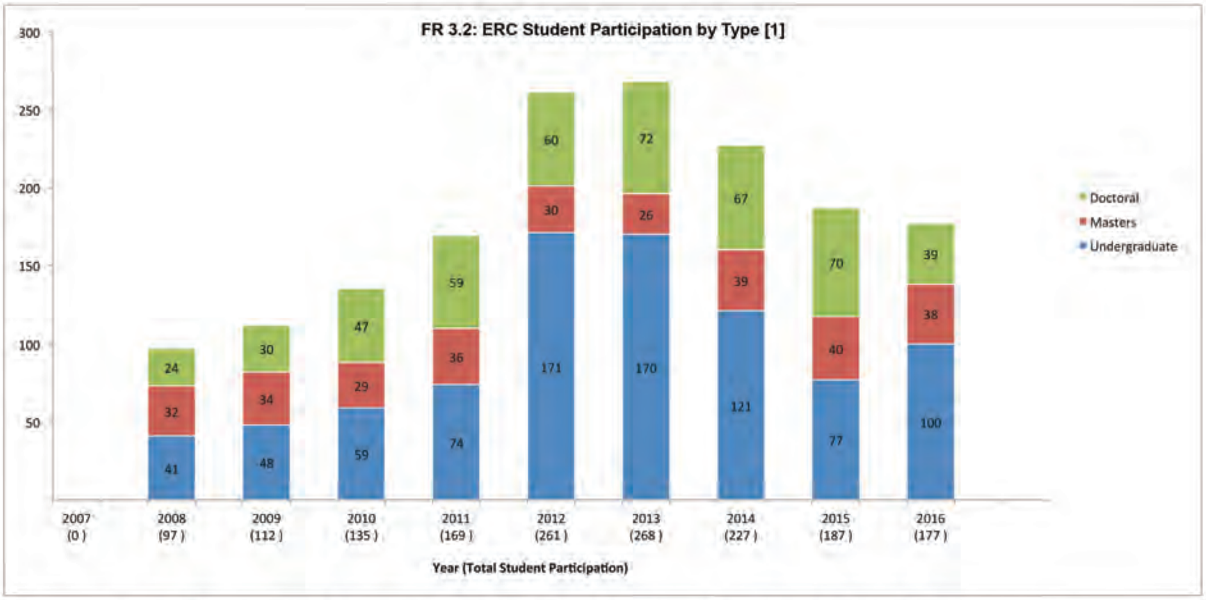
Fluid Power Vehicle Challenge
The CCEFP has identified an opportunity to expand fluid power in capstone design courses across the country. Utilizing the existing senior-design course infrastructure, partnering with fluid power companies to sponsor and actively engage with students in capstone projects with fluid power content is a natural fit. CCEFP, in partnership with NFPA, adopted the Parker Hannifin Chainless Challenge—an undergraduate engineering design competition to create and build the most efficient and effective human-assisted green energy vehicle. Each year, teams of 5-6 senior engineering students from 10 U.S. universities compete in a head-to-head event at the conclusion of the school year. A number of those students are recruited to the fluid power industry. Participating schools include Cleveland State University, Cal Poly San Luis Obispo, University of Central Arkansas, Illinois Institute of Technology, University of Cincinnati, Purdue University, University of Illinois, Urbana-Champaign, University of Akron, Murray State University and Ohio State University. This program will be re-branded to the be the NFPA Fluid Power Vehicle Challenge, sponsored by NFPA, administered by CCEFP staff, and will serve as the cornerstone of the strategic university-level education program. The NFPA Board of Directors is incredibly supportive of the investment in this hands-on undergraduate engineering initiative.

Student Leadership Council: The Student Leadership Council is an independent board of the CCEFP. The Education and Outreach program sponsors the activities of the SLC. The SLC’s responsibilities include serving as a liaison to the CCEFP headquarters, administration of the CCEFP Webinar Series, and support the SLC Travel Grant Program. As the Center matures, the SLC will evolve into a student governance board that maintains much of the same functions as the SLC, however, will be more focused in nature, with a smaller representation of leaders.

Outstanding CCEFP Graduates: The following recent CCEFP graduates exemplify students who are making an impact in fluid power and related fields:

CCEFP Student Course of Study, Graduation, Institution	Current Employment and Contributions to the Field	An Outstanding Achievement
Naseem A. Daher Purdue University PhD, December 2014	**American University of Beirut** *Assistant Professor of Engineering and Architecture* Teach undergraduate and graduate level courses in control systems and mechatronics. Research interests include advanced control theory and application, automotive active safety systems, efficient hydraulic actuation technologies, and robotics.	*Ingersoll-Rand Fellowship* School of Mechanical Engineering Purdue University 2013-2014
Rohit Hippalgaonkar Purdue University PhD, May 2014	**Ford Motor Company** *Analytical Drivetrain/Transmission Research Engineer*	*Finalist, 3MT Competition* Purdue University 3MT (‘3-Minute Thesis’)

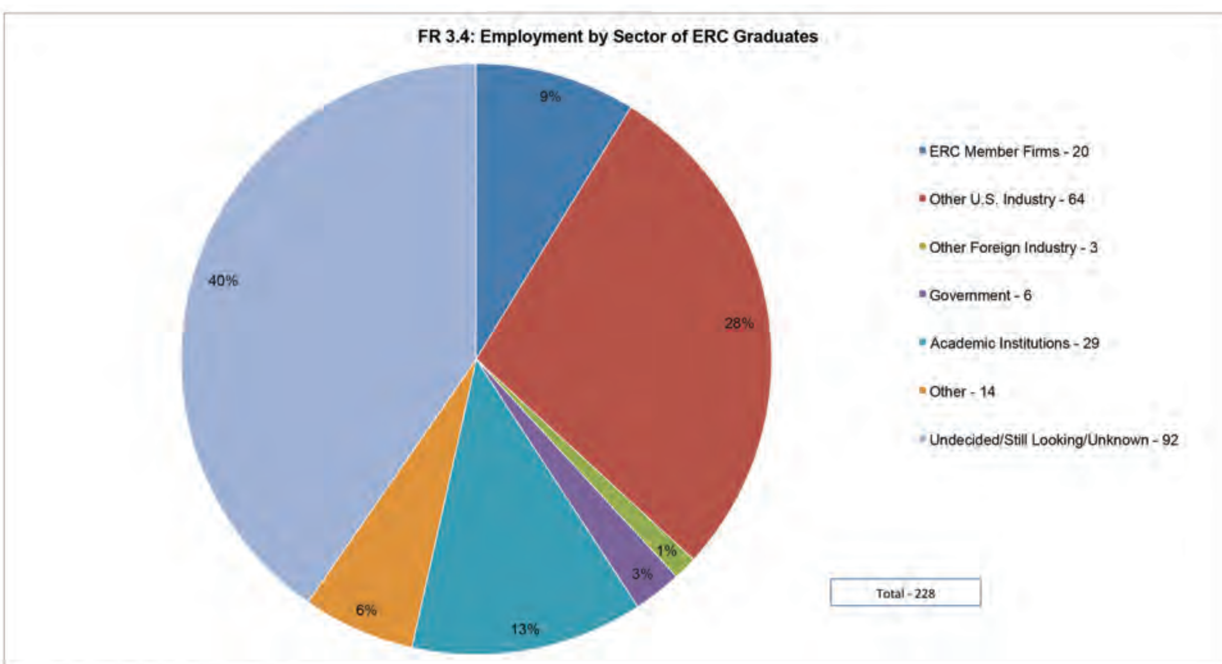
	Responsible for developing high-fidelity models, methodologies and processes to investigate drivetrain component and system characteristics, improve designs and to develop innovative controls for next-generation drivetrain systems, including 10-speed transmission and hybrid drivetrain systems with advanced electro-hydraulic technologies.	Competition. One of 12 finalists out of a university-wide competition, April 2014
Mark Hofacker Vanderbilt University PhD, December 2013	**Schlumberger** *Mechanical Engineer* Responsible for designing a new tool that will stimulate deep well production and will function properly in a high pressure, high temperature, and acidic environment.	
Ashwin Ramesh University of Illinois, Urbana-Champaign MS, August 2012	**Lam Research Corporation** *Process Engineer* Lam Research is an equipment manufacture in semiconductor industry. Responsible to design and develop the product.	Played a significant role in increasing the market share of the electroplating product from around 78% to over 90%
Andrew Schenk Purdue University Ph.D., December 2014	**The Mathworks** *Application Support Engineer* Assist users of Matlab, Simulink, and other toolboxes worldwide on a wide range of technical issues. Continually exposed to new scientific and engineering disciplines and how they utilize computational resources to accelerate the pace of engineering and science. Work with development teams on focused projects either improving existing Matlab functionality or creating new features entirely.	*Laura Winkelman Davidson Fellowship* *Best Paper Award* 2011 International Japan Fluid Power Symposium best paper award *Backe Medal and Best Paper Award* 2012 FPNI Fluid Power PhD Symposium
Lei Tian University of Minnesota Ph.D, January 2013	**Polaris Industries** *Powertrain Development Engineer* Leading a powertrain calibration project for a new off-road all terrain vehicle project. Responsible to setup the engine controller unit and calibrate its parameters, to achieve the best compromise among performance, reliability, drivability and emissions.	Performed mathematical modeling, delivered a running prototype and initial testing data of a novel free-piston engine compressor.



[1] The sum of Undergraduate, Masters and Doctoral students may exceed the Total number of students because students may be classified with multiple personnel types

FR 3.3: Degrees Granted to ERC Students by Type of Degree

Degree Type	Number Of Degrees
Undergraduate	135
Master's	121
Doctoral	69
Total Degrees	**325**



[1] Includes Undergraduate, Masters & Doctoral Graduates

Priorities for the Future

The college education program continues to focus on several priorities: 1) to infuse fluid power into the core curriculum 2) to create a culture where research *is* education 3) to excite a significant number of students about fluid power and 4) to bridge the relationship between fluid power education and the industry. We expect the partnership with NFPA will result in greater impact than even what has been achieved thus far. We expect curriculum development and dissemination will remain a priority, and in particular, that universities outside the CCEFP will use and find value in the materials. We expect the Fluid Power MOOC to generate continued interest in fluid power training. By leveraging resources through NFPA and NSF, the REU program, the Fluid Power Scholars program, the Fluid Power Vehicle Challenge, and the expectation of each research project to include at least one non-graduate research student, significant numbers of undergraduate and graduate students will gain fluid power experience during the summer and the academic year.

We are making significant impacts within the fluid power industry and education community. The CCEFP completed a longitudinal study of our past participants in early 2014. At the time of the report, 57% of all former CCEFP undergraduate researchers enter graduate school, and 25% of those are PhD candidates, and 45% of all students formerly engaged in research utilize fluid power in their career in some way.

The college education program will be forward-thinking in terms of sustainability and will emphasize programs and projects that lead to significant workforce and professional development of our undergraduate and graduate students. The education and outreach sustainability plan calls for a dedicated and deliberate effort to foster the integration of research and education such that research becomes the truly effective educational path that it is possible for it to be, a systemic approach to workforce development, and the promotion of new intellectual capital to create and innovate. In the sustainability plan, the education and outreach program transitions into a workforce development program, where the Center leverages efforts of the National Fluid Power Association, a cooperative entity in education, and utilizes the investment of our existing programs as a starting or continuation point for many of the college level initiatives.

The research faculty of the CCEFP will continue to integrate research findings into undergraduate and graduate curriculum. A long-range goal is to incorporate fluid power curriculum into the ABET objectives of a handful of CCEFP institutions. There is so much to be gained from collaboration and cooperation within the fluid power industry.

CCEFP EO Sustainability Plan

CCEFP and NFPA will work together to leverage organizational strengths to achieve the greatest gains in workforce development in the fluid power industry. NFPA will assume the oversight and leadership of all fluid power workforce development programs (as part of its bigger strategic plan) and will adopt, incorporate, and utilize many of the initiatives launched by CCEFP. Rather than work independently on workforce development goals, the two organizations would be collaborative in the approach. In Year 11, and beyond, NFPA will be sponsoring the salary of the CCEFP Education and Administrative Director. The NFPA Board of Directors will be the final authority on fluid power education goals and objectives. An NFPA University Education Committee will provide support and regular oversight to the university-level programs and initiatives. By leveraging each organization's strengths, the workforce development program has the potential of being a game changer in creating intellectual capital in the fluid power industry.

The strategy of the Workforce Development Program is to leverage the strengths, collaboration and existing programs of the CCEFP and NFPA to further develop and deliver high quality educational and training tools that capitalize on existing, broadly distributed workforce networks to maximize program impact; to develop training opportunities and methods that can be replicated, adapted and disseminated; and to leverage and coordinate the accomplishments and investment of the established education and outreach initiatives of the existing CCEFP and NFPA programs.

The following is a snapshot of the entire workforce development spectrum lead by NFPA. CCEFP will provide leadership in the areas of university-level education and industry-academia engagement programs. The program portfolio continues to meet the CCEFP's six crosscutting objectives.

Growing the Fluid Power Workforce	**Participant Level**	**Promote STEM learning to diverse people**	**Promote awareness of fluid power**	**Fluid power dissemination**	**Culture of research and education integration**	**Increase fluid power workforce**	**Strengthen ties between higher ed and industry**
NFPA Fluid Power Challenge and Online Community	K12	■	■				
NFPA Student Career Connections	K12	■	■			■	■
IFPS Fluid Power Boy/Girl Scout Merit Badge	K12	■	■				
NFPA Fluid Power Careers e-Portal	Tech		■			■	■
NFPA NSF Fluid Power ATE Center (*proposed*)	Tech	■	■			■	■
NFPA Laboratory Grants Program	Tech	■	■			■	
IFPS Fluid Power Certifications	Tech		■			■	■
CCEFP REU Program	BS	■	■	■	■	■	■
NFPA Curriculum Grants Program	BS, MS		■	■	■	■	■
NFPA Fluid Power Vehicle Challenge	BS		■			■	■
CCEFP Fluid Power Scholars Program	BS		■			■	■
CCEFP Pre-Competitive Research Program	MS, PhD		■	■	■	■	■
CCEFP Student Leadership Council	MS, PhD		■		■	■	■
CCEFP Webinar Series	All		■	■	■		■
CCEFP Fluid Power Innovation & Research Conference	All		■	■	■		■
CCEFP Industry University Engagement Summits	All			■	■		■

3.2 PUBLIC AND PRE-COLLEGE OUTREACH PROGRAMS

The Outreach Program addresses the three objectives: 1) motivate diverse citizens to travel the STEM pathway in order to expand and promote a talented STEM workforce, 2) promote awareness of fluid power and its applications through positive, authentic experiences in informal, K-12, undergraduate, graduate, and industrial contexts and 3) infuse new fluid power research and innovative, evaluated, fluid power curricula and programs into informal, K-12, and college level course offerings.

A core objective of the CCEFP pre-college outreach program is to expose young students to fluid power with the added objective of increasing the number of students pursuing STEM fields in college. The Center is of the opinion that increasing interest in STEM fields among young students is an important first step to increase the number of students later pursuing engineering studies, some of them in fluid power.

Progress in the CCEFP pre-college program is illustrated by the following examples, drawn from our project portfolio:

Fluid Power Challenge
The NFPA Fluid Power Challenge encourages students to learn about fluid power technology and gain hands-on experience while building a fluid power mechanism with real world applicability. The program is designed to introduce the students, and their teachers, to the world of engineering and fluid power careers. Over 350 8th grade students participated in four outreach events hosted by CCEFP institutions (U of Minnesota, Milwaukee School of Engineering, Purdue University, and Georgia Institute of Technology) in Y10. Cumulatively, the CCEFP has hosted 9 events, resulting in over 2,000 middle school students engaged in hands-on fluid power technology since initiation. The Milwaukee School of Engineering has traditionally hosted this event, before the CCEFP adopted it as its primary outreach program. In the future, CCEFP will no longer host Fluid Power Challenge events, but will serve as mentors to events held in geographically neighboring areas.

Research into the impact of the Fluid Power Challenge program, conducted by Quality Evaluation Designs, results in significant shifts during pre- and post-event experiences with regards to students' familiarity with fluid power and fluid power careers. Whereas 55% of students' reported no or minimal familiarity on the pre-survey, only 7.4% reported so on the post-survey. Similarly, 64.2% reported being very familiar with fluid power, compared to 9% on the pre-survey. Overall, the program was rated quite highly and was highly valued by nearly all participants.

Research Experiences for Teachers Program: In the final reporting year, no RET teacher participants conducted research in the CCEFP. Rather, engagement with teachers through the Fluid Power Challenge program was better aligned with the focused outreach efforts of the CCEFP, NFPA (our sustainability partner), and the industry at large. A majority of teachers recruited to participate in the Fluid Power Challenge program are Project Lead The Way teachers. Overall, the CCEFP has sponsored 44 RET projects to date, and many teachers have been repeat participants. In 2014, the RETs from NCAT were community college faculty members. All CCEFP institutions have been host to RET teachers. The CCEFP was the first ERC to have RET-designed curriculum published to the NSF website, TeachEngineering.com, a repository of STEM curriculum. Three fluid-power teaching modules are available for download from www.ccefp.org.

Museum Public Outreach The Science Museum of Minnesota (SMM) is home to six fluid power exhibits at the on permanent display in the Experimental Gallery. The SMM welcomes nearly 1,000,000 visitors yearly, resulting in thousands of people of all ages' exposed to hands-on hydraulic and pneumatic exhibits. Additionally, as a way of vetting new ideas for fluid power exhibits, the SMM advises fluid power capstone projects at the University of Minnesota. The fluid power exhibits will remain a permanent feature of the SMM. Exhibits include 1) hydraulic hybrid car 2) axial piston pump 3) hydraulics lab and circuits 4) variable force pump 5) double-weight pendulum and 6) pneumatic ball run.

State Fair Public Outreach For what is anticipated to be the last time, the CCEFP exhibited at the University of Minnesota building at the Minnesota State Fair in August 2015. Previous exhibits in the early years of the Center, 2007 – 2012. Hundreds of fair goers, especially those who are Gopher alumni, visit the U of MN building at the Great Minnesota Get Together. The CCEFP had two hands-on excavator demonstrators in which visitors of all ages got to try their hand at being an Excavator Operator.

Priorities for the Future

With the CCEFP entering its post-NSF phase, planning and implementation of EO sustainability is underway. In the proposed sustainability plan, the focus shifts from a comprehensive education and outreach program, to a workforce development program, geared towards creating an experienced and knowledgeable fluid power workforce.

In the future, pre-college initiatives will be lead by NFPA. The CCEFP will serve as a supporter role rather than a lead role in pre-college outreach. The NFPA has the necessary communication infrastructure, resources, and industry support not to mention and more robust program portfolio currently underway.

Growing the Fluid Power Workforce	Participant Level	Promote STEM learning to diverse people	Promote awareness of fluid power	Fluid power dissemination	Culture of research and education integration	Increase fluid power workforce	Strengthen ties between higher ed and industry
NFPA Fluid Power Challenge and Online Community	K12						
NFPA Student Career Connections	K12						
IFPS Fluid Power Boy/Girl Scout Merit Badge	K12						

3.3 INDUSTRY ENGAGEMENT PROGRAM

Industry engagement is an essential component of the CCEFP mission. With the launch of the NFPA Foundation's Pascal Society, over seventy fluid power manufacturers, distributors or organizations are supportive of fluid power technology, innovation, education and training. The CCEFP is one recipient, of many, of the financial and intangible support of the industry leaders and practitioners. The industry regularly recites that education outcomes (i.e. intellectual capital) of the Center are as important, if not more, than research outcomes.

The CCEFP, NFPA and its corporate supporters share in several common goals: 1) to create a culture that integrates research and education for undergraduate and graduate students across all partner institutions; 2) to increase the number of students well-prepared to pursue fluid power research, jobs and careers and 3) to strengthen ties between higher education and the fluid power industry.

Highlights from CCEFP projects illustrate progress towards these goals:

Industry and Academic Engagement: The CCEFP provides opportunities for its students to network with industry representatives through a variety of channels. There are multiple benefits to this effort: students will better understand the fluid power industry's needs and its markets; interested students will find internships and job opportunities upon graduating; companies will be able to meet, interact, and discuss potential employment opportunities with students. Channels utilized in this project include company tours, poster sessions, resume exchanges, and additional opportunities that extend the Center's outreach to more students and companies. This program leverages the existing events and activities of the CCEFP to engage students in the fluid power industry, often offering them opportunities to stay in the industry so they can impact fluid power research and application.

In total, the CCEFP invested its bridge between industry and students in the following ways.

- Fluid Power Innovation and Research Conference (FPIRC)
    - FPIRC has replaced the CCEFP Annual Meeting.
    - FPIRC is to become the premier fluid power technical conference in the United States.
    - FPIRC is often held in conjunction, or co-located, with other ASME technical meetings.

- Industry Engagement Committee / Industry Engagement Summits
    - The NFPA Pascal Society's Industry University Engagement Summits are held twice a year at partner universities. Students present research updates to the industry audience and the attendees give immediate feedback on the research progress.
    - Social dinners and receptions lend themselves to networking among peers, colleagues, and friends.

- CCEFP Webinar Series
    - Popular on-line research seminar series on CCEFP progress, and affiliated research, presented by students and special topics by industry guests.

- Fluid Power Capstone Courses
    - Promote industry support of undergraduate capstone projects
    - Parker Hannifin Chainless Challenge
    - Additive Manufactured Excavator Cab Design Teams

- Fluid Power Scholars Program
    - Highly successful sponsorship program of incoming corporate interns

An ongoing portfolio of accomplishments:

- FPIRC, formerly CCEFP Annual Meeting: The CCEFP hosted its first annual FPIRC event at Vanderbilt University, October 2014 and it's second, a year later, in downtown Chicago, October 2015. The vision of FPIRC is to become the premier fluid power technical conference in the United States. Presenters and attendees include leading academic researchers, sponsored students and experts from the field. Upcoming FPIRC events include Minneapolis, MN in October 2016. Both events are co-located with other academic conferences for increased visibility within the research community. The program agenda includes poster sessions, resume-exchange for industry and students, company and laboratory tours, social activities, etc.

    - Speed Meetings: Held at each CCEFP FPIRC (formerly Annual Meetings) in 2011, 2012, 2013, 2014 and 2015. A one-on-one session between Center students and representatives of corporate supporters.
    - Research Poster Sessions: Held at each CCEFP FPIRC (formerly Annual Meetings) since inception. These events allow students to enhance their presentation and professional skills as they describe their research to industry members, while industry members can stay informed of research being done in the Center. A cash award competition is included.
    - Commercialization Pitch Competition:

- Industry University Engagement Summits (formerly IAB Summits): Added to the Center's agenda in 2012, the CCEFP hosts Industry Engagement Committee (IEC) Summits at one of Center's partner institutions two times each year. The Summits exist to provide a more intimate knowledge transfer between CCEFP research and industry supporters. This is an excellent opportunity for industry to engage with students on a one-to-one level. The atmosphere gives the student a chance to demonstrate their research and area of expertise. Socializing is a significant component of the meetings.

- The Student Leadership Council (SLC) hosts a research webinar once per month. Students and faculty from CCEFP institutions participate, along with industry supporters. These webinars are intended to keep all stakeholders informed about students engaged in the research program, project progress, give and receive suggestions, and generally promote inter-university collaboration as well as cooperation between academia and industry. These webinars are well attended, with an average of 73 participants per week. All are welcome and invited to tune in.

- Student Retreats: Each year a student retreat is held for all CCEFP students. These have been held at member institutions, as well as in conjunction with the National Fluid Power Association's (NFPA) 2009 and 2011 Industry and Economic Outlook Conference. Retreats provide students with the opportunity to expand their networking connections as they present their research to company representatives, some of whom are not members of the CCEFP but work in fluid power. It is to be determined if the student retreats are sustainable in the phase-down cycle of the CCEFP.
    - 2013: Caterpillar, Inc., Joliet, IL
    - 2012: Sauer-Danfoss, Ames, IA

- The Fluid Power Scholars Program was launched in 2010. It is a sponsorship program for incoming interns to attend a fluid power immersion short-course at MSOE at the outset of the internship experience. To date, 57 Fluid Power Scholars have been supported through the program. Over 75% of Scholars transition to full-time employees after the internship.

- The CCEFP supports the Parker Chainless Challenge Competition for undergraduate engineering students interested in fluid power. Several institutions use this competition as a basis for fluid power capstone projects.

- The CCEFP supports the NFPA Fluid Power Challenge Competition for 8th grade students, an engineering design competition using fluid power. Competition judges include representatives from local industries who invited students to ask them questions about their careers. CCEFP has hosted the Challenge at the University of Minnesota in 2009, 2012, 2013, 2014, and 2015 (at UMN, GT and PU). Over 2,000 8th grade students and their teachers engaged through this program and dozens of corporate sponsors participating.

- NSF and GEM: NSF adopts CCEFP's innovative approach to recruitment of underrepresented students in engineering through the National GEM Consortium. A formal partnership with the National GEM Consortium and a proposed program structure, designed and piloted by CCEFP, is expected to be adopted and implemented within the NSF ERC system, to increase the ability of ERCs to recruit and retain underrepresented students in graduate engineering programs. The GEM-ERC Fellows Program overcomes barriers to ERC student recruitment of underrepresented students in engineering.

Priorities for the Future
The CCEFP will continue to develop networking opportunities for students and industry. The Center will expand the content of the CCEFP Webinar Series framing it as a key element of knowledge transfer to increase the participation of the academic and industry audiences. In the spirit of sustainability, the industry engagement program will be highly influential in garnering the support of our current and future industry members.

The CCEFP sustainability plan calls for a workforce development program with the objectives to increase the intellectual capital entering the fluid power industry and to provide professional development opportunities to experts in the industry. To this end, the CCEFP will partner with the National Fluid Power Association (NFPA). In the future, the CCEFP expects to expand undergraduate and graduate education, as well as industry development.

Together, the CCEFP and NFPA will continue to:

- Hold retreats and summits at company facilities and new partner universities to provide academia the chance to interact with practicing engineers and will facilitate opportunities for knowledge transfer.
- FPIRC research poster sessions and commercialization competition will continue with industry representatives as judges. The future FPIRC technical program will be industry presenters and panelists.
- Resume exchange, Industry Kiosks and Corporate Sponsorship will continue at future FPIRC events. Students will have a chance to meet with industry supporters one-on-one and visit corporate kiosks and/or booths, which are of particular interest.
- Recently initiated NFPA University Education Committee will continue to provide oversight to the mutual workforce development strategic plan.
- The Student Leadership Council will continue, serving as the student voice to the CCEFP.

Growing the Fluid Power Workforce	Participant Level	Promote STEM learning to diverse people	Promote awareness of fluid power	Fluid power dissemination	Culture of research and education integration	Increase fluid power workforce	Strengthen ties between higher ed and industry
CCEFP REU Program	BS	■	■	■	■	■	■
NFPA Curriculum Grants Program	BS, MS		■	■	■	■	■
NFPA Fluid Power Vehicle Challenge	BS		■			■	■
CCEFP Fluid Power Scholars Program	BS		■			■	■
CCEFP Pre-Competitive Research Program	MS, PhD		■	■	■	■	■
CCEFP Student Leadership Council	MS, PhD		■		■	■	■
CCEFP Webinar Series	All		■	■	■		■
CCEFP Fluid Power Innovation & Research Conference	All		■	■	■		■
CCEFP Industry University Engagement Summits	All			■	■		■

Quality Evaluation Designs
Education Research, Evaluation, Policy

Crosscutting Evaluation Design:

Center for Compact & Efficient Fluid Power (CCEFP), Education & Outreach (EO)

OVERVIEW
The crosscutting evaluation of CCEFP EO programs was designed to:

- Help provide overall focus and structure to CCEFP's EO program
- Implement a uniform metric for evaluating all EO activities that was simple to complete and yet revealing of EO successes and challenges related to its core mission

PROCESS
The crosscutting assessment began in Year 7. After meetings with CCEFP leadership, QED formulated core objectives that reflected the EO mission. These were revised by EO staff and then shared with the NSF program officer, who made some substantive revisions. The core objectives were then operationalized so they could be deployed as survey items. In Year 8, a new objective was added and operationalized to encompass sustainability efforts as ERC graduation neared. Beginning Year 9, the EO survey was deployed to participants of all EO programs, projects, courses, and activities. QED analyzed the survey at the end of fall term and will analyze new results at the end of spring term.

SURVEY
The EO survey includes eight items that operationalize the six, crosscutting objectives. A ninth item asks respondents to rate the overall value of the activity they are assessing. The tenth item asks respondents to rate their current desire to work in the fluid power industry. All items are rated on a five-point scale: 1 (not at all), 2 (minimally), 3 (moderately), 4 (extensively), and 5 (to a great extent). Piloting revealed a ceiling effect at the top end, so the "great extent" option was provided and many respondents have utilized it.

In addition to identifying the specific program, project, course, or activity being evaluated, respondents are asked to provide their race/ethnicity, gender, and level in school or if they are in industry. An open-ended item asks for suggestions of other fluid power activities. Participants have also used this item to elaborate on the experience they are evaluating. Respondents are asked if they wish further information about fluid power activities or opportunities, and are prompted to provide their email addresses for this purpose. The survey is deployed exclusively online (data are accessible only to QED) and takes 3-4 minutes to complete. An example of the survey can be accessed at: https://www.surveymonkey.com/s/ERCsurveyEXAMPLE.

The survey is considered valid by EO staff and faculty, and responses seem to reliably assess participants' experiences. The survey can be analyzed from the perspective of EO overall, through the filter of any of the demographic variables, and/or program-by-program. Variation in ratings across programs can be expected, with different EO activities emphasizing different objectives. The instrument does appear sensitive enough to identify strengths and weaknesses at the individual program level (if at least about 8 participants respond).

From Cross-Cutting Objectives to Survey Ratings

CCEFP Education & Outreach Cross-Cutting Objectives	How Objectives Are Operationalized as Survey Items
Motivate all citizens to navigate the STEM pathway in order to expand and promote a talented STEM workforce.	This program/curriculum made me more interested in studying science, engineering, math, and/or technology.
Promote excitement about fluid power among technical college, undergraduate and graduate students.	This program/curriculum made me more excited about fluid power.
Disseminate fluid power fundamentals, innovations, and research, through evaluated fluid power curricula, projects, and programs.	a) This program/curriculum increased my understanding of fluid power *fundamentals. b)* This program/curriculum increased my understanding of fluid power *innovations. c)* I feel that because of this program/curriculum I have a better understanding of fluid power research.
Create a culture that integrates research and education for technical college, undergraduate and graduate students, as well as industry professionals across CCEFP and NFPA partner institutions	I believe that this program/curriculum linked fluid power research to my classes, labs, or work experience.
Increase the number of students prepared to pursue fluid power research, jobs, and careers.	This activity/program better prepared me to work in the fluid power industry.
Strengthen ties between higher education and the fluid power industry.	I feel that this program/curriculum helped connect my academic experience to the fluid power industry.

CCEFP SURVEY TO ASSESS ALL E&O PROGRAM IMPACT

Item	**Please answer the items below with the response that best fits your opinion.**	1. Not At All	2. Minimally	3. Minimally to Moderately	4. Moderately to Extensively	5. A Great Extent	0. Does not apply
1.	This program/curriculum made me more interested in studying science, engineering, math, and/or technology. (1)	1	2	3	4	5	0
2.	This program/curriculum increased my understanding of fluid power. (2)	1	2	3	4	5	0
3.	This program/curriculum increased my interest in fluid power. (2)	1	2	3	4	5	0
4.	This program/curriculum taught me new concepts in and/or applications of fluid power. (3)	1	2	3	4	5	0
5.	I feel that because of this program/curriculum I have a better understanding of fluid power research. (3)	1	2	3	4	5	0
6.	I will be able to apply what I learned in this program/curriculum to my work and/or classes. (4)	1	2	3	4	5	0
7.	This program/curriculum increased my interest in working in the fluid power industry (5)	1	2	3	4	5	0
8.	This activity/program better prepared me to work in the fluid power industry. (5)	1	2	3	4	5	0
9.	I rate the overall value of this activity/program as:	1	2	3	4	5	0

4. INDUSTRIAL/PRACTITIONER IMPACT AND TECHNOLOGY TRANSFER

In year 10 the CCEFP management's primary focus was implementation of its unique sustainability strategy. The key uniqueness of our strategy compared to other ERCs is that from an industry perspective the CCEFP no longer utilizes an industry membership agreement organizational format but rather an industry gifting structure called the Pascal Society. Prior to its implementation, all changes were discussed and approved with NSF ERC program administration. The successful implementation realized to date was highly dependent upon an even closer collaboration with the National Fluid Power Association (NFPA), an industry consortium alliance that represents much of the fluid power industry. While the NFPA has always been active in the CCEFP, over the past several years they became committed to the Center achieving sustainability. In year nine of our NSF grant, our two organizations reached a formal agreement to collaborate more closely in the areas of industry engagement, fund raising, workforce development and sharing of administrative costs through synergistic leveraging of each organization's strengths. Greater detail of the growing partnership with NFPA will be described further in subsequent paragraphs as well as in section 6 on long-term Center sustainability.

4.1 VISION AND STRATEGY

Industry Engagement

The industrial collaboration vision for the CCEFP remains unchanged: to achieve regular and seamless transfer of research findings, technologies, IP and students between the Center and its industry members. The key avenues for achieving this vision continue to be meaningful engagement through robust communication, frequent interaction and strong personal relationships. It is even more critical that the CCEFP embrace these efforts as it refines and improves the new sustainability strategy it rolled out last year. However, because the CCEFP enjoys such broad industry representation, it can be challenging to achieve the necessary level of engagement to ensure each industry supporter's continued, long-term commitment. To improve this engagement, we have initiated efforts to improve and build upon our already well-established industry communications network while leveraging the numerous media outlets of the NFPA. A mutually developed Industry Engagement Strategy with the NFPA was created and is in various stages of deployment. Table 4.1 shows a summary of engagement activities that are either currently underway or planned for future implementation.

Method	Frequency	Content	Audience
NFPA Meetings and Conferences	~3x per year	Meeting with industry leaders on the Steering Committee. Review and approve strategic initiatives.	Industry CEOs, academic thought leaders
CONEXPO/IFPE Conference	1x per 3 years	Demonstrate to show attendees the impact of the CCEFP and its value to the fluid power industry.	Industry wide
FPIRC Conference	1x per year	Updates on all research projects. Numerous networking opportunities. Plans to include industry research presentations going forward.	All CCEFP industry boards, faculty and students. Open to all interested industry participants.
IEC Summits	2x per year	Research Updates on ~1/2 of CCEFP sponsored projects, refresh Research Roadmaps	Industry Technologists
Research Webinars	Biweekly	Updates on research and topics of interest	Industry members, faculty and students

Table 4.1: CCEFP/NFPA Engagement Strategy

NFPA regularly posts articles and information about the CCEFP on its website and communicates these postings to its 330 industry members through various means. This ensures that the Center is always front and center on the minds of its industry supporters. Some examples lifted from the NFPA website are shown below.

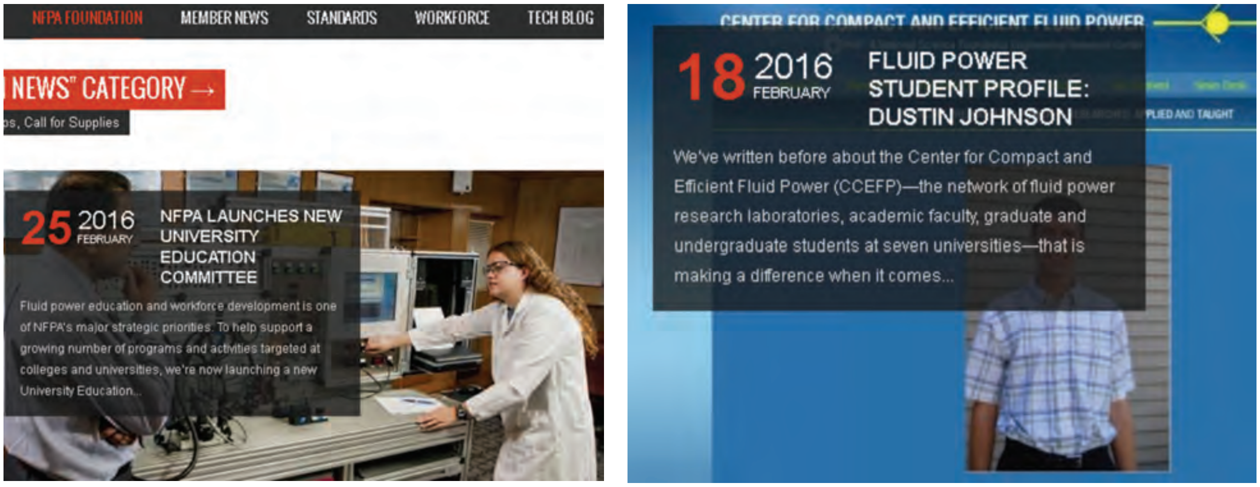


Figure 4.2: NFPA Website Highlights of CCEFP

Furthermore, the CCEFP maintains its own website (Figure 4.3) for posting important information for communicating to its stakeholders. Together this combined approach ensures that industry is fully aware of and engaged with the Center.

Figure 4.3: CCEFP Website

The Center has created an excellent communication tool to facilitate technology transfer that is both simple and effective. These are non-confidential single page (front and back) project summary sheets for each research project funded by the Center (Figure 4.4). Included in each summary is an overview of the research project, the unmet need in the marketplace, expected benefits, achievements to date and where the project is headed. Photos of the PI and their student(s) working on the project are shown to provide the recipient with a sense of familiarity. The project's Technology Readiness Level (TRL) is also indicated so that members can quickly determine which projects are nearing the end of the CCEFP research pipeline and which ones are in their infancy. These summaries have proven to be excellent tools for communicating to potential new members the value of the various research projects underway in the Center and are beneficial in recruiting both new members and associated research projects.

The project summary sheets are available in professional printed form on a heavy gauge, glossy paper printed on two sides creating a single leaf document. These hard copies are regularly used by the ILO and the perspective University Technology Transfer Office to market the technology to its members and other firms. In addition, these sheets are easily available for download in pdf format from the CCEFP website. An improvement incorporated in the past year is to have the PIs provide an updated summary sheet in their annual report submission. This ensures that the project summaries remain up to date. In return the PIs or their respective Technology Transfer Officer are welcome to use the materials for their own marketing purposes.

CCEFP Industry leaders also recognize that even if their organization does not directly participate in commercialization of research findings they can take great pride in the community support aspects of the Center. The annual “By the Numbers” summary of key CCEFP metrics such as students engaged, degrees awarded, papers published, etc., is an extremely popular means of capturing the non-commercialization benefits of the Center and is always well received by industry leaders. Industry surveys have indicated that perhaps the most important output of the CCEFP is its students and resulting future workforce talent pool. To facilitate student exposure to industry the popular student-led biweekly research webinar updates will continue. These research presentations are recorded and stored on the “CCEFP Members Only” section of the Center website so that members can view at their leisure if they have conflicts during the scheduled broadcast. We estimate over 100 industry participants attend these biweekly events. Another popular means for student and industry engagement is the Center Fluid Power Scholars industry internship program where interns are provide a 3-day training course on fluid power at a member university before their internship begins. Our plan to leverage the NFPA communication network to highlight student profiles to industry was successfully rolled out last year. This year our plans are to further expand and improve this activity. These activities highlight the impact that our CCEFP students have on our industry members and long-term sustainability. They truly are one of our greatest assets.

Figure 4.4: Research Project Summary Sheet

To ensure maximum industry participation the CCEFP has committed to an event cadence document that is publically posted and to which the Center adheres (Figure 4.5). This allows for interested parties to save these dates early in the year to avoid potential conflicts. Regular communication opportunities such as this, along with much better event planning and promotion, resulted in significant growth for our recent FPIRC conferences. Attendance has doubled over the last two years.

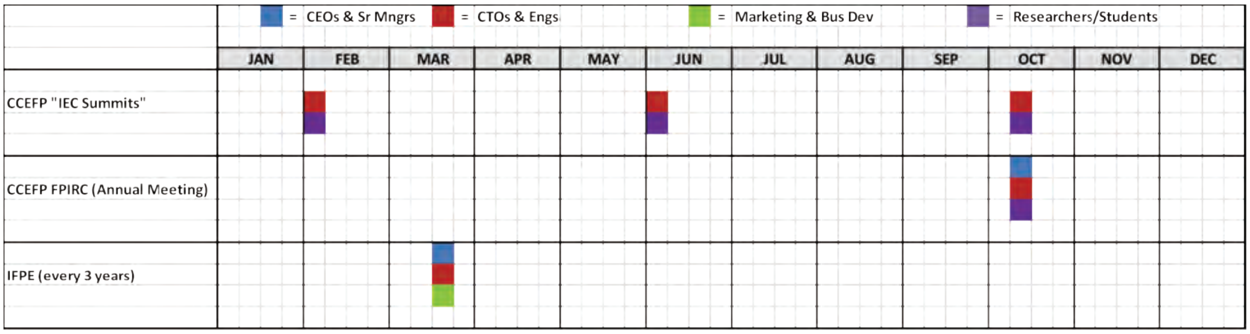


Figure 4.5: CCEFP Event Cadence Document

Members have differing reasons for affiliating with the CCEFP. Besides the pre-competitive research benefits, some members are interested in advancing the state of the fluid power industry. Others are motivated to improve the society we live in. Industry member feedback indicates that the most important reason is to gain access to fluid power knowledgeable students. We need to engage people in our industry member's organizations at the level that matches their interests.

Our new sustainability strategy calls for replacing our existing industry membership dues structure with an annual "gift" from the Pascal Society which is housed within the existing 501(c)(3) NFPA Foundation. This gift combines individual company donations into a single award, administered by the CCEFP, to support pre-competitive research, workforce development and Center administration. In recognition of their support industry representatives will be invited to serve on three governing committees. These committees are:

- CCEFP Steering Committee (SC) – Comprised of C-suite executives focused on the Center's overall research and sustainability strategies and securing the resources we need to accomplish it—both academic and government.
- CCEFP Industry Engagement Committee (IEC) – Industry CTOs working actively to help select and guide the CCEFP research projects in the way that best reflects the needs of industry.
- NFPA Roadmap Committees – Industry experienced engineers working to identify the broad areas of pre-competitive research, both design and manufacturing related, needed to advance the fluid power industry.

NFPA plays a pivotal role in connecting the Center with CEOs of industry members by hosting Steering Committee meetings at its conferences 2-3 times per year. This greatly benefits the Center by raising visibility and helping to gain greater support from key industry supporters as we focus on long-term sustainability. The IEC continues to hold monthly teleconferences to discuss and address key Center activities. They meet face to face twice per year, onsite at a participating university and at the Fluid Power Innovation and Research Conference (FPIRC). The NFPA Roadmap Committees have met for two separate 2-day conferences to create the initial roadmaps and now meet every other year to refresh them to reflect market changes.

The interaction of these committees is shown pictorially in Figure 4.6

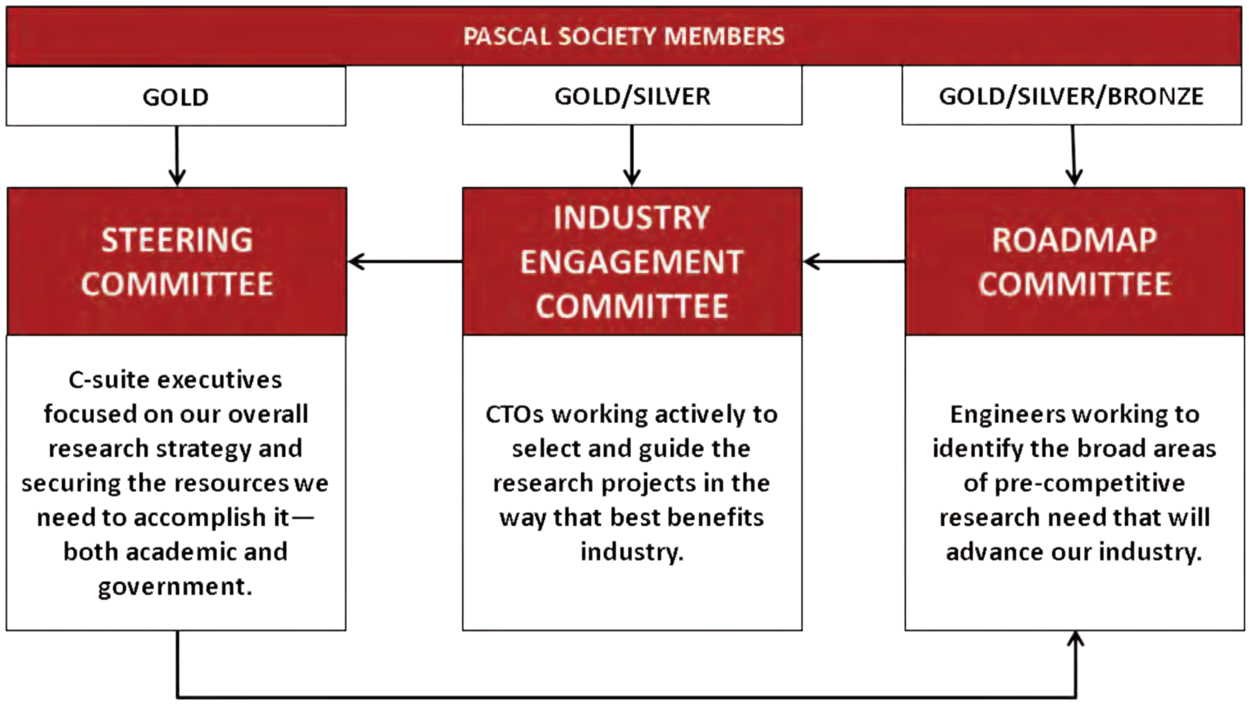


Figure 4.6: CCEFP Industry Committees

The boards to which an individual company can nominate representatives is determined by the organization's sales and support level as shown in Table 4.7.

		Membership and Annual Giving Levels		
Company size	**Annual global fluid power sales**	**Gold**	**Silver**	**Bronze**
Large	Above $250 million	$100,000 or more	At least $60,000	At least $6,000
Medium	Between $50 and $250 million	$50,000 or more	At least $30,000	At least $3,000
Small	Below $50 million	$25,000 or more	At least $15,000	At least $1,500

Table 4.7: CCEFP Giving Levels for Industry Supporters

"Fluid power sales" have different meanings for different kinds of companies:

- For fluid power component/system manufacturers and distributors, it includes all of their sales.
- For OEMs, it includes the value of fluid power content in their machines, both purchased and manufactured.
- For suppliers, it includes all of their sales to the fluid power industry.

These are charitable contributions, fully tax-deductible under the NFPA Foundation's 501(c)(3) status as a charitable organization.

The NFPA has assumed the role of fund raising for the CCEFP with support from key CCEFP member staff. In exchange for this support, the Center has ceased to invoice its members. Each year this gifting contract is reviewed with another year of funding agreed upon and guaranteed for the year after the current two-year contract. This allows sufficient notice for planning purposes. We continue to invite all companies to become supporters of the CCEFP with a goal of widening the base of industry supporters to include significantly greater industry participation. NFPA will lead this effort and call heavily upon its 350+ members. Non-NFPA companies will be invited to participate as well.

Our secondary goals are to promote an atmosphere that will promote and foster commercialization of Center research discoveries. This will be a challenge but achievable. Interactive discussions with our members has resulted in a refined value proposition that more accurately captures the essence of what our industry members get from active participation and support of the Center. Besides the benefits described above we have learned that providing industry direct access to CCEFP technology experts is very desirable. This type of interaction often leads to affiliated research projects. This has been factored into our sustainability planning efforts. These efforts are further detailed in Section 5.

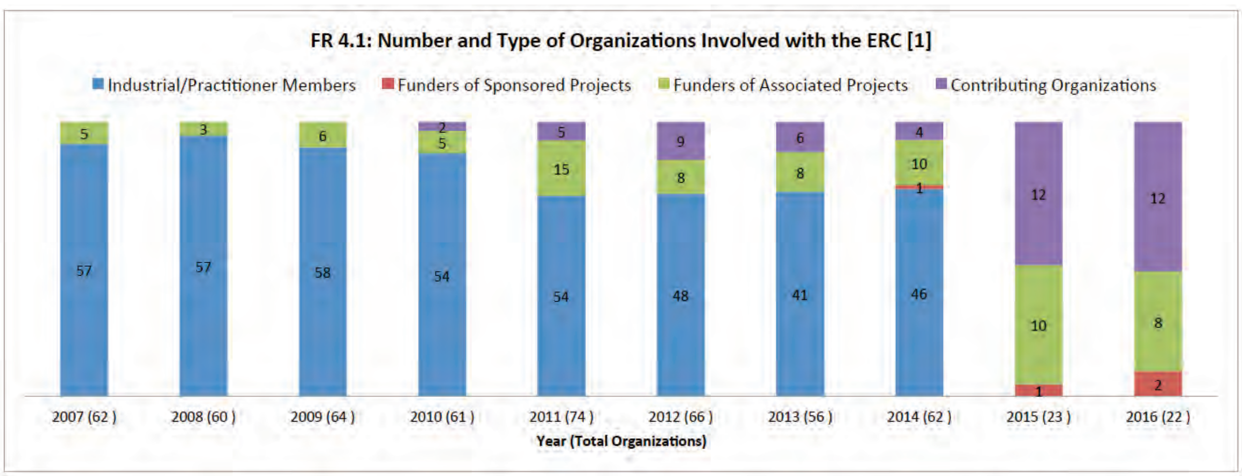
4.2 INDUSTRY SPONSORSHIP

As previously described the CCEFP sustainability strategy call for migrating its industry supporters from a formal membership agreement to a gifting society. Our primary objective last year was to transition all of our industry members to the new Pascal Society model. We are happy to report this was accomplished successfully. This year our goal was to grow our industry supporter base. We have been successful in this effort as well growing from 46 to 71 industry supporters. Our focus is now switching to having our supporter base raise their support levels. Our current industry supporters are shown in Table 4.8. We also intend to strategically reach out to less represented areas of supporters including pneumatics providers, medical, filtration and wind power.

GOLD		
• Bimba Manufacturing	• Eaton Corporation	• Parker Hannifin
• Caterpillar	• Enfield Technologies	• Proportion-Air
• Daman Products Company	• Hydra-Power Systems	
• Danfoss Power Solutions	• Pall Corporation	
SILVER		
• Afton Chemical	• ExxonMobil	• Moog
• Bobcat	• Fluid Power World Magazine	• Netshape Technologies
• Chevron	• Gates Corporation	• Poclain Hydraulics
• CNH	• HYDAC/Schroeder Industries	• Quality Control Corporation
• Deltrol Fluid Products	• Hydraquip	• Simerics
• Donaldson Company	• Linde Hydraulics	• Trelleborg Sealing Solutions
• Evonik Oil Additives	• Lubrizol	• Woodward HRT
BRONZE		
• Bosch Rexroth	• HUSCO International	• OEM Controls
• Clippard Instrument Laboratory	• Idemitsu Kosan	• PARTsolutions
• Concentric AB	• IMI Precision Engineering	• ROSS Controls
• Czero	• Industrial Hard Chrome	• RYCO Hydraulics
• Delta Computer Systems	• Iowa Fluid Power	• SMC USA
• DunAn Microstaq	• JCB	• Stauff Corporation
• Festo Corporation	• Kaman Industrial Technologies	• Steelhead Composites
• FORCE America/Valve Division	• KYB Japan	• Sumitomo Heavy Industries
• G. W. Lisk Company	• Main Manufacturing Products	• Sun Hydraulics
• GS Global Resources	• Master Pneumatic	• The Toro Company
• HAWE Hydraulik NA	• Muncie Power Products	• Walvoil Fluid Power
• HECO Gear	• National Tube Supply	• White Drive Products
• Hitachi	• Nexen	• Womack Machine Supply

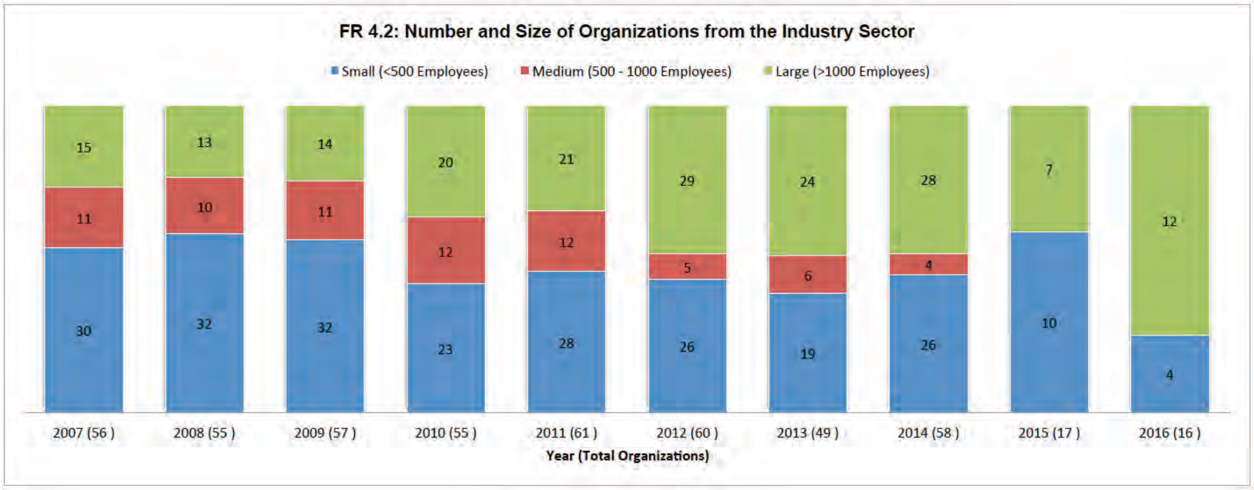
Table 4.8: CCEFP Industry Supporters

The number and type of organization involved in the CCEFP is shown in FR 4.1 below. The results can be deceiving without further interpretation. The dramatic drop in industrial members from 2014 to 2015 corresponds to the implementation of the previously described Pascal Society. All 46 industry members are now represented as one funder of sponsored projects. In fact, industry supporters have grown from 46 to 71 since the change. Another important detail shown is the rise in contributing organizations. This is the result of industry supporters being more engaged in the Center. With increased engagement come additional contributions typically in the form of products donations.



[1] Innovation Partners were not reported by the ERC class of 2003

The number and size of organizations from the industry sector supporting the CCEFP is shown in FR4.2 below. The increase in large company involvement in the past year is attributed to sustainability activities such as the DOE off-highway vehicles, NIST fluid power manufacturing roadmap and NSF 3D printed excavator that are generating keen interest in these organizations.



The Numbers of Members by Technology Sector is shown in the table below. The components & systems group is the largest group, the majority of which are members of the NFPA. OEMs are typically large companies such as Caterpillar and John Deere. Their membership has been stable over the life of the Center. Fluids companies are becoming increasingly active in Center activities as indicated by the fact that their numbers have doubled over the life of the Center.

Number of Members by Technology Sector										
Technology Sector	**Yr 1**	**Yr 2**	**Yr 3**	**Yr 4**	**Yr 5**	**Yr 6**	**Yr 7**	**Yr 8**	**Yr 9**	**Yr 10**
Analysis & New Technologies	0	1	0	0	2	2	2	2	3	3
Components & Systems	42	39	40	36	34	32	27	27	38	42
OEMs	5	6	6	6	5	5	4	6	6	7
Suppliers & Fluids	6	7	8	8	9	8	7	10	12	14
Total	**53**	**53**	**54**	**50**	**50**	**47**	**40**	**45**	**59**	**66**

Membership Agreement

In year nine, the CCEFP transitioned from a Membership Agreement (MA) to a giving society. A Grant Agreement (GA) between the Center and NFPA and associated CCEFP Operating Procedures (COPs) now cover how industry interacts with the Center. The major elements covered include: support level (Gold, Silver and Bronze); escalating gift amounts based on membership level and company sales; industry governance committees and how these committees interact with Center leadership. The most significant difference between the two approaches is that industry supporters do not receive any tangible benefits, including preferred access to Center generated IP, in exchange for their support. We are pleased to report that industry has enthusiastically embraced this change. Their primary reasons for supporting the CCEFP are: meaningful input into the Center research strategy, ability to recommend research projects, pre-competitive research in fluid power, an anti-trust compliant venue whereby industry can meet to exchange ideas and access to highly qualified future employees.

Industrial Engagement Committee *(formerly Industrial Advisory Board)*

With the introduction of the Pascal Society, the Industrial Advisory Board (IAB) was replaced by an Industry Engagement Committee (IEC). Participation on the IEC is governed by the Grant Agreement and CCEFP Operating Procedures (COPs). The Grant Agreement and COPs are available online at www.ccefp.org/industry/become-a-member. The IEC is composed of one representative from each member company at the Sustaining or Principal Membership level. The CCEFP pursues active communication with all its members but this is especially true with IEC supporters. All of the previous IAB functions have carried over to the IEC. There are monthly IEC conference calls where topics of particular interest are discussed. This meeting is run by the IEC chair who establishes the meeting agenda in concert with the ILO. Agenda topics include issues of interest to the IEC. These meetings can cover a wide range of topics from future research project areas of interest to sustainability planning. Twice per calendar year, the on-site IEC meetings occur at a member university on a rotating schedule. These meetings typically last a day and a half. The first day is dedicated to technical presentations by the researchers and includes a tour of the university laboratory facilities. Two informal dinners during the evenings provide an excellent venue to get to know one another better. All local and attending PIs and students are invited to attend. The second day of the meeting is a half-day event that includes a feedback session on the technical presentations and special topics discussions. These meetings provide an excellent opportunity for our members to network not only among themselves but with the research teams. It is common to invite potential industry supporters to these site meetings. It allows a perspective industry supporter an opportunity to experience firsthand the value of the CCEFP before deciding to pledge their support. These site meetings have proven to be very popular to attendees. In year 11 the CCEFP is planning its first such IEC meeting at Iowa State University. This is significant as this represents the first such meeting at a university that was not part of the original ERC. The CCEFP plans to continue adding universities that have strategic significance in terms of capability or location near key industry supporters.

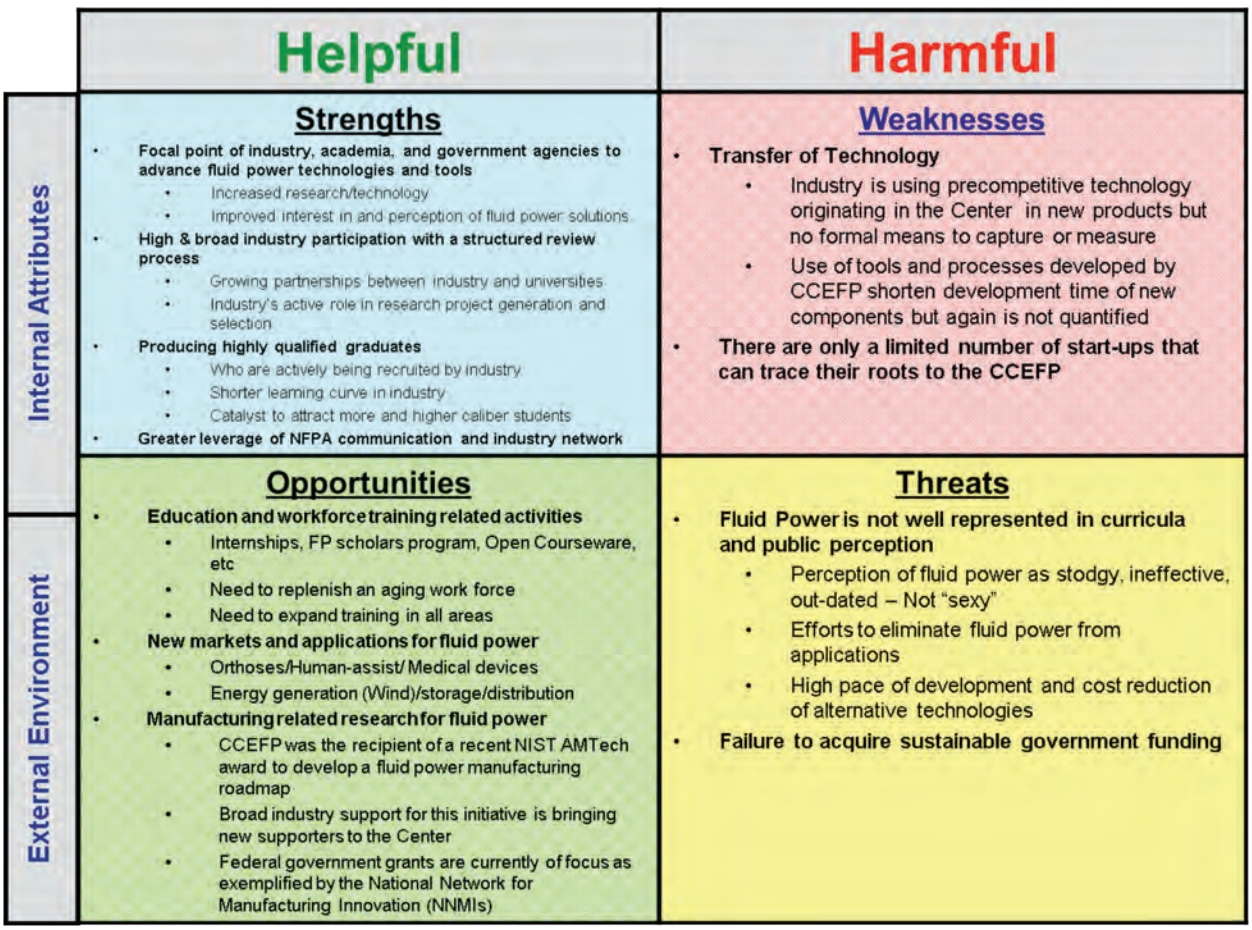


Figure 4.9: CCEFP Industrial Engagement Committee SWOT

The IEC continues to work within the IAB organizational framework developed with the help of its members during the first year of the Center. Within this framework, roles and responsibilities for key leadership positions (Chairman, Vice Chairman, subcommittee chairs, etc.) are clearly defined and major IAB goals/objectives are identified on an ongoing basis. Continuity of leadership is assured by a transition policy under which the existing Chairman's role is assumed by the Vice Chairman, whose vacancy is subsequently filled through a nominating and voting procedure involving all IEC members.

The SWOT shown in Figure 4.9 previously developed by the Center's Industrial Advisory Board and now assumed by the Industry Engagement Committee continues to be a valuable communication vehicle to provide industry feedback to the CCEFP. Throughout the Center's history an area once deemed as a "weakness" by industry has grown over time to an area of "strength". This transformation occurred again this past year with the IEC providing significant input into the new CCEFP sustainability strategy. This is indicative of an organization that listens to its customers. New areas for improvement will take the place of previous ones as they are addressed and the cycle for improvement continues.

4.3 TECHNOLOGY TRANSFER AND NEW BUSINESS DEVELOPMENT

CCEFP participates in many technology transfer efforts. In addition to the various interactions previously described, CCEFP faculty and staff are encouraged to consult with industry to transfer research knowledge. Many of the lead researchers are active consultants. Faculty members have taken leaves to be on location at the partner organizations and several graduate students have worked on internships with our member companies.

Since its inception, the CCEFP has produced 56 disclosures, 40 patent applications filed, seven patents awarded, five licenses issued, three spin-off companies and another three potential start-ups. Although the fluid power industry has been historically slow to adopt new technologies, we see increased global competition, as well as, CCEFP research discoveries beginning to change this mindset. This trend is only expected to accelerate going forward and is a major reason given by industry for supporting Center sustainability. Table 2.1 in the section 2 of this report summarizes the CCEFP invention disclosures and current status since the Center started in 2006.

Technology Impact

Some of the more impactful CCEFP technologies are mapped in the Impact vs. Maturity chart below (Figure 4.10). The numbers in the markers are the project numbers. A status review for each project appears in Volume II of this report. The projects identified are:

- 1E.4: Piston-by-Piston Control of Pumps and Motors using Mechanical Methods
- 2F: MEMS Proportional Pneumatic Valve
- 2B.3: Free Piston Engine Hydraulic Pump
- 2G: Fluid Powered Surgery and Rehabilitation via Compact, Integrated Systems
- 2C1: Compact Energy Storage using Open Accumulator
- 1A.2: Multi Actuator Hydraulic Hybrid Machine Systems
- 2C2: Advanced Strain Energy Accumulator
- 2B1: Free Piston Engine Compressor
- 3E.1: Pressure Ripple Energy Harvester
- Test Bed 6: Fluid Power Ankle-Foot Orthosis
- Test Bed 1: High Efficiency Excavator
- 3B.1: Passive Noise Control in Fluid Power

- 1J.1: Hydraulic Transmissions for Wind Energy
- 1A.1: Technology Transfer Process for Energy Management Systems
- 1F.1: Variable Displacement Gear Machine
- 2C.3: Flywheel Accumulator for Compact Energy Storage
- 1E.6: High Performance Valve Actuation Systems
- 1G.1: Energy Efficient Fluids
- 1J.2: A Novel Pressure-controlled Hydro-Mechanical Transmission
- 2F.1: Soft Pneumatic Actuator for Arm Orthosis
- 2G: Fluid Powered Surgery and Rehabilitation via Compact, Integrated Systems

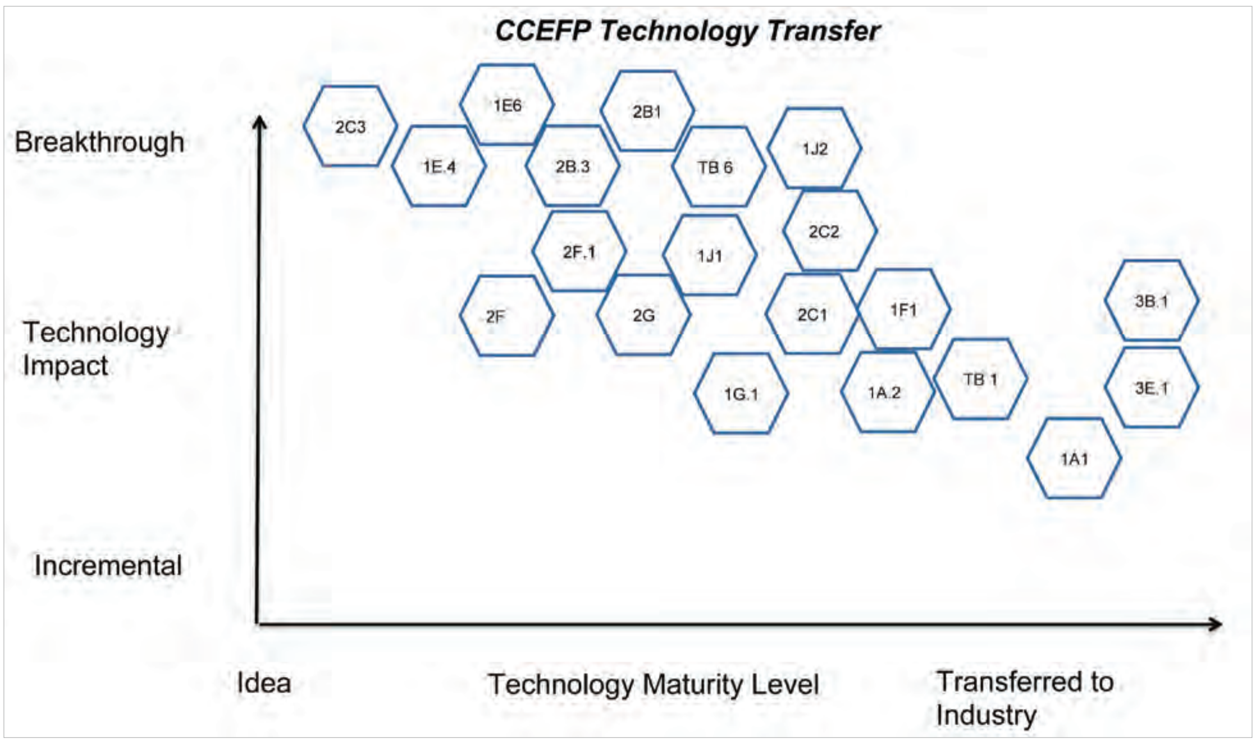


Figure 4.10: Center Technology Transfer Chart

		Industrial Application		
Adopting Company	**Technology**	**When (Date)**	**Use in Company**	**Impact**
Lightsail Energy, Inc.	A localized compressed air approach for storing excess energy from off-shore wind turbines.	July 12, 2012	Capturing heat energy and regenerating useful energy from it	Dramatically alleviate power supply and demand imbalances during daily use.

ERC Technology Transfer Table

4.4 INNOVATION

The fluid power industry is very capital intensive with long product life cycles. This is not conducive to new business start-up activities. In addition, our industry members are the some of the most dominate in their market. Therefore, our most promising intellectual property is typically reserved by our members. We believe that the technologies that we bring forward will help our members grow their business. However, it is not sufficient that we just accept this current paradigm. To further improve our innovation track record and bring Center innovations to market faster we must encourage and foster start-up firms. The CCEFP is ripe with bright young minds eager to see their research commercialized. However, most are simply not familiar with how to do so. To overcome this obstacle the CCEFP has put an added emphasis on fostering entrepreneurialism. In the past year an Industry Relations Committee (IRC) was formed to help drive this activity as well as promote industry led commercialization. Presentations on key elements of the IRC process were made on Center-wide webcasts and at key center meetings such as the FPIRC. The CCEFP also sponsored a team of graduate engineering and MBA students through a New Product Design and Business Development (NPDBD) course to investigate the new world of "human scaled" hydraulics. The market investigation and subsequent development of an associated robust business plan is a key requirement of this course. The CCEFP Sustainability Director and the ILO continually monitor potential grants that either PIs or industry can leverage to assist with commercialization activities. This has resulted in several PFI:AIR submittals and subsequent awards. The CCEFP is committed to fostering an environment whereby anyone affiliated with the organization who is interested in commercializing Center discoveries will feel supported.

Name of Firm	Contact Information at Firm	Date Established	Name of Principle & Relationship to ERC	Funding Status	Technology	Market Impact or Societal Benefit (Value Added)
Smart Hydraulic Solutions, LLC	Monika Ivantysynova, President. 3505 Cypress Lane, Lafayette IN 47905 765-418-2291	May 8, 2008	Prof. Monika Ivantysynova (PI) Josh Zimmerman (Grad Student)	Not currently funded.	R&D for hydraulic energy saving solutions	Reduction in energy consumption in hydraulic systems.
Innotronics, LLC	Mike Gust, President 6213 St. Croix Tr. N.#212, Stillwater, MN 55082	Nov. 13, 2014	Mike Gust (ILO) Prof. Rajesh Rajamani (Researcher)	NSF PFI:AIR-TT Award Sponsorship from Member Firm	Sensors	Productivity & Efficiency gains through automation & controls.
Flow Links	James Van De Ven vandeven@umn.edu 612-625-2499	Pending	Prof. James Van de Ven (PI) Shawn Wilhelm (Grad Student)	Pending	Pump	Improved efficiency and a wider range of possible applications

Spin-Out Firms Table

5. INFRASTUCTURE

The CCEFP lead and partner universities are fully committed to the mission of the Center. This commitment can be seen in tangible investments in headquarters space, research facilities and equipment and communication networks. Intangible commitments can also be seen in the collaborative university research culture and interaction with industry.

The CCEFP universities are shown on the map below. They are University of Minnesota (lead), Milwaukee School of Engineering, Purdue University, University of Illinois Urbana-Champaign, Vanderbilt University, Georgia Institute of Technology and North Carolina A&T State University. These universities have remained constant throughout the NSF funded period of the Center. As the Center graduates, participation will be opened to any US university. In year 11 two new partner universities, Marquette University and University of California Merced, were added.

Figure 5.1: CCEFP Universities

The structure of the leadership team has remained stable throughout the NSF life of the Center. The team includes the Director, two Co-Deputy Directors, the ILO, the Sustainability Director, the Contracts and Finance Director and the Education and Administrative Director.

Figure 5.2: Current CCEFP Leadership Team

After graduation the size of the leadership team must be decreased for budgetary reasons. The positions of Sustainability Director and Communications Director have been eliminated. Many key functions such as communications, event planning and industry fund raising will be transferred to our partner, the National Fluid Power Association. The organization chart for the future CCEFP leadership team is shown below.

Figure 5.3: Future CCEFP Leadership Team

With the transition to the new structure other changes will be made. As was described in section 4 three new industry led committees have been formed. These are the CCEFP Steering Committee, the Industry Engagement Committee and the Industry Road-mapping Committee. The Steering Committee is chaired by the CCEFP Director and is made up of Gold level industry supporters and appointed members from academia and government. The Industry Engagement Committee replaces the Industrial Advisory Board but continues with the same responsibilities. The Road-mapping Committee is led by NFPA and is tasked with identifying the key research needs of the fluid power industry. The Scientific Advisory Board will continue. Its primary responsibility is to conduct a review of CCEFP research during the Fluid Power Research and Innovation Conference, formally called the CCEFP Annual Meeting.

A key element of sustainability is world-class experimental facilities. The CCEFP currently has three such facilities, the Fluid Power Institute at MSOE, the Maha Lab at Purdue and the Manufacturing Lab at Georgia Tech. Two emerging world class labs are being established, the Thomas E. Murphy Powertrain Lab at the University of Minnesota and the LASiR Lab at Vanderbilt University. (see: Infrastructure highlights in Appendix III)

The diverse team and the multi-disciplinary configuration of the CCEFP are shown in the graphs and tables that follow in this section. Major cultural shifts include a systems orientation towards research, multi-disciplinary collaboration, cross institutional collaboration, increased diversity and a closer partnership with industry.

The leadership and accomplishments of the Center are validated by the many awards received by its faculty and students, and by best paper and poster awards a conferences. A list of CCEFP awards is given below.

Faculty Achievement Awards

- Scott Bair, Georgia Tech--STLE International Award (the Society's highest technical honor), 2009; Regents' Researcher, 2010.

- Wayne Book, Georgia Tech--HUSCO/Ramirez Distinguished Chair in Fluid Power and Motion Control, 2001; Professor Emeritus, 2011; Robert E. Koski Medal, 2013.

- Will Durfee, University of Minnesota--President's Award for Outstanding Service, University of Minnesota, 2011.

- Paul Imbertson, University of Minnesota--Outstanding Professor, University of Minnesota, 2011.

- Monika Ivantysynova, Purdue University--Joseph Bramah Medal, 2009; Honorary Doctorate, Doctor Honoris Causa, Slovak Technical University, 2010; Backe Medal, 2012; Purdue Innovator Hall of Fame, 2013; SAE Fellow, 2014; Robert E. Koski Medal, 2015.

- John Lumkes, Purdue University--Charles B. Murphy Outstanding Undergraduate Teaching Award, 2011; Purdue Global Engineering Impact Award, College of Engineering, Purdue University, 2012.

- Paul Michael, MSOE--Karl O. Werwath Engineering Research Award, 2011.

- Chris Paredis, Georgia Tech--Royal Academy of Engineering Distinguished Visiting Fellowship, 2009.

- David Saintillan, UIUC-- Pi Tau Sigma Gold Medal for outstanding achievement in mechanical engineering. 2011.

- Richard Salant, Georgia Tech--ASME Mayo D. Hersey Award, 2009.

- Kim Stelson, University of Minnesota--College of Science and Engineering Distinguished Professor, University of Minnesota, 2015.

- Zongxuan Sun, University of Minnesota-- SAE Ralph R. Teetor Educational Award, 2011; George W. Taylor Career Development Award, College of Science and Engineering, University of Minnesota, 2012; CAREER Award, NSF, 2012; Charles E. Bowers Faculty Teaching Award, University of Minnesota, 2015.

- Robert Webster, Vanderbilt University--IEEE Volz award for greatest US Robotics PhD thesis impact, 2011.

Student Achievement Awards

- Heather Humphreys, Georgia Tech--won NSF and NSDEG fellowships in 2008.

- Ken Marek, Georgia Tech--Best Student Presentation Award, Noise Technical Committee 158th Meeting of the Acoustical Society of America, San Antonio, TX, 26-30 October, 2009.

- Nick Earnhart, Georgia Tech--ARCS Scholar (Achievement Rewards for College Scientists), 2011.

- Nick Earnhart, Georgia Tech—Leo Beranek Student Medal for Excellence in the Study of Noise Control, Institute of Noise Control Engineering, 2012.

Best Poster Awards

- Toennies, J. L. and R. J. Webster III, "Best Poster Award" at DMD 2009” ASME Design of Medical Devices Conference, 2009.

- Ken Marek and Nick Earnhart - placed first overall in the Spring Royster poster competition held by the Georgia Tech Acoustical Society of America (ASA) student chapter. Also First place poster competition award North Carolina regional Acoustical Society of America Meeting, Spring 2010.

Best Paper Awards

J. A. Riofrio and E. J. Barth. “Experimental Assessment of a Free Elastic-Piston Engine Compressor with Separated Combustion Chamber,” Bath/ASME Symposium on Fluid Power and Motion Control (FPMC 2008), pp. 233-244, Bath, U K., September 10-12, 2008, Winner of the Best Paper Award for the entire Symposium.

Zimmerman, J. and Ivantysynova, M., Effect of Installed Hydraulic Corner Power on the Energy Consumption and Performance of Multi-Actuator Displacement Controlled Mobile Machines. Bath ASME Symposium on Fluid Power and Motion Control (FPMC2009), [DSCC2009-2781]. 2009.

Schenk, A. and Ivantysynova, M. An Investigation of the Impact of Elastohydrodynamic Deformation on Power Loss in the Slipper Swashplate Interface. 8th JFPS International Symposium on Fluid Power, , Okinawa, Japan. 2011.

Pelosi, M. and Ivantysynova, M. Surface Deformation Enables High Pressure Operation of Axial Piston Pumps. ASME/Bath Symposium on Fluid Power and Motion Control, Arlington, VI, USA. - Best paper award 2011.

Schenk, A. and Ivantysynova, M.. “The influence of swashplate elastohydrodynamic deformation”. Proc. of the 7th FPNI PhD Symposium, Jun. 27-30, 2012. Reggio Emilia, Italy, pp 611 - 632 - Best paper award. 2011.

Sprengel, M. and Ivantysynova, M.. Hardware-in-the-Loop Testing of a Novel Blended Hydraulic Hybrid Transmission. Proceedings of the 8th FPNI PhD Symposium. Lappeenranta, Finland. - Best Paper Award (Backe Medal) 2014.

Busquets, E. and Ivantysynova, M. The World's First Displacement Controlled Excavator Prototype with Pump Switching - A Study of the Architecture and Control. Proceedings of the 9th JFPS International Symposium on Fluid Power. Matsue, Japan. pp. 324-331. Best Paper Award. 2014.

Tian, Lei, David B. Kittelson and William Durfee, "High Quality Paper Award" Small Engine Technology Conference, Penang, Malaysia, 2009.

Baker, J. and Ivantysynova, M., "Investigation of Power Losses in the Lubricating Gap Between the Cylinder Block and Valve Plate of Axial Piston Machines". Proceedings of the 5th FPNI PhD Symposium, Cracow, Poland, pp. 302 - 319 (2008). Best paper award.

Riofrio, J.A. and Barth, E.J., "Experimental Assessment of a Free Elastic-Piston Engine Compressor with Separated Combustion Chamber". Bath/ASME Symposium on Fluid Power and Motion Control, Bath, United Kingdom, pp. 233-244 (2008). Winner of the BEST PAPER AWARD for the entire Symposium.

Figure FR 5.1 shows the distribution of final year research project investigators by educational discipline. The research focus of CCEFP is centered in mechanical engineering and most of the participants are mechanical engineers. Industrial engineering researchers conduct human-machine interface research and the chemists conduct energy efficient fluid research. Figure FR 5.2 shows faculty participation by rank and Figure FR 5.3 shows staff participation by type. The distribution of faculty by rank has been fairly constant with faculty participation increasing over time. The distribution of staff by type has also remained fairly constant by time with the number increasing and decreasing as the CCEFP funding has ramped up and down.

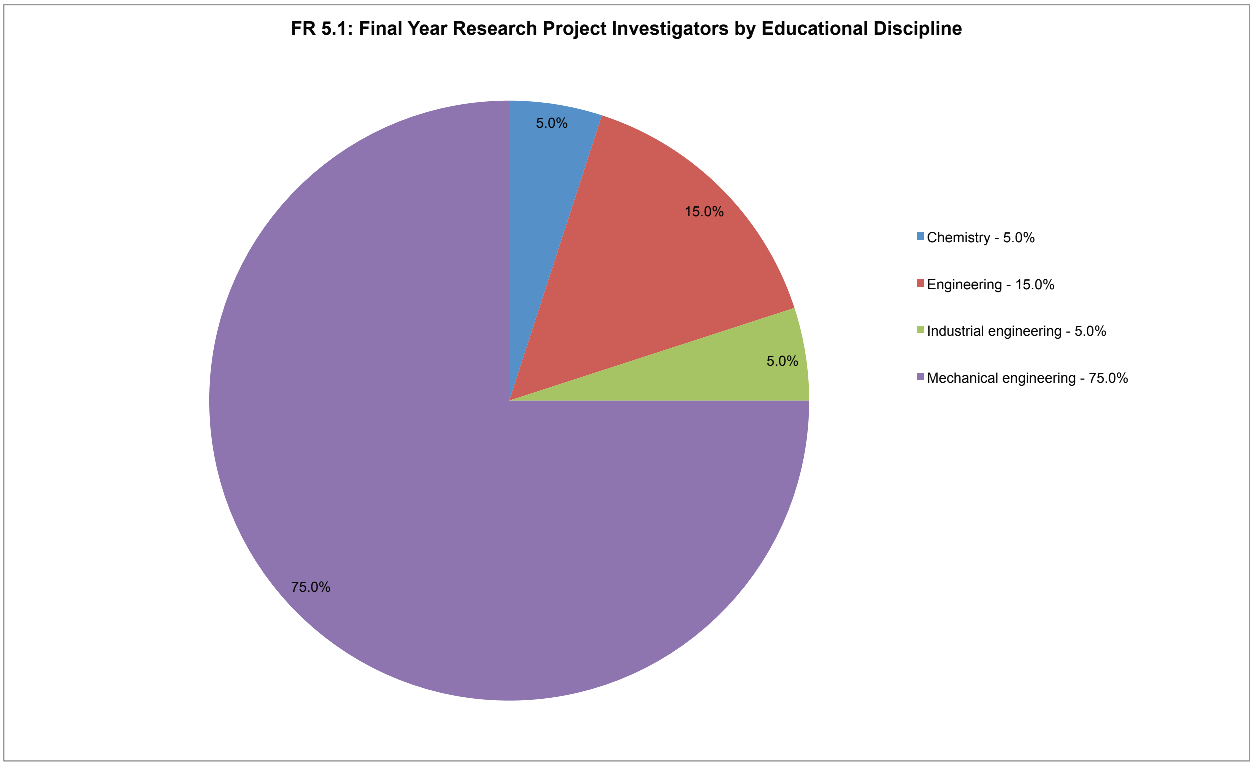
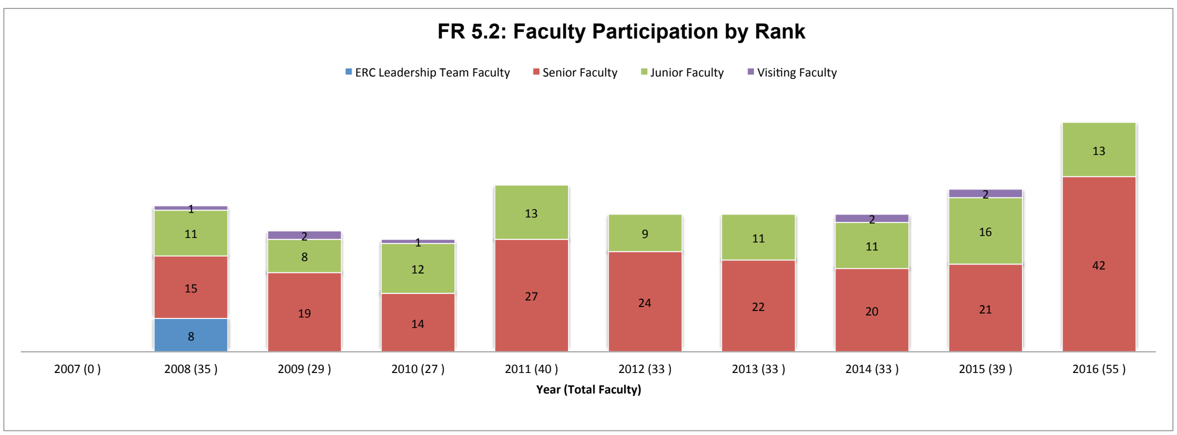


Figure FR 5.1: Final Year Research Project Investigators by Educational Discipline



[1] Faculty personnel types from both research and curriculum are included.

[2] Leadership Directors, Thrust Leaders, and Education Program Leaders are counted as faculty for years in which the ERC reported demographics by group. During these years, the data collection system did not provide a way for ERCs to indicate that personnel fulfilled multiple roles such as leadership and faculty.

Figure FR 5.2: Faculty Participation by Rank

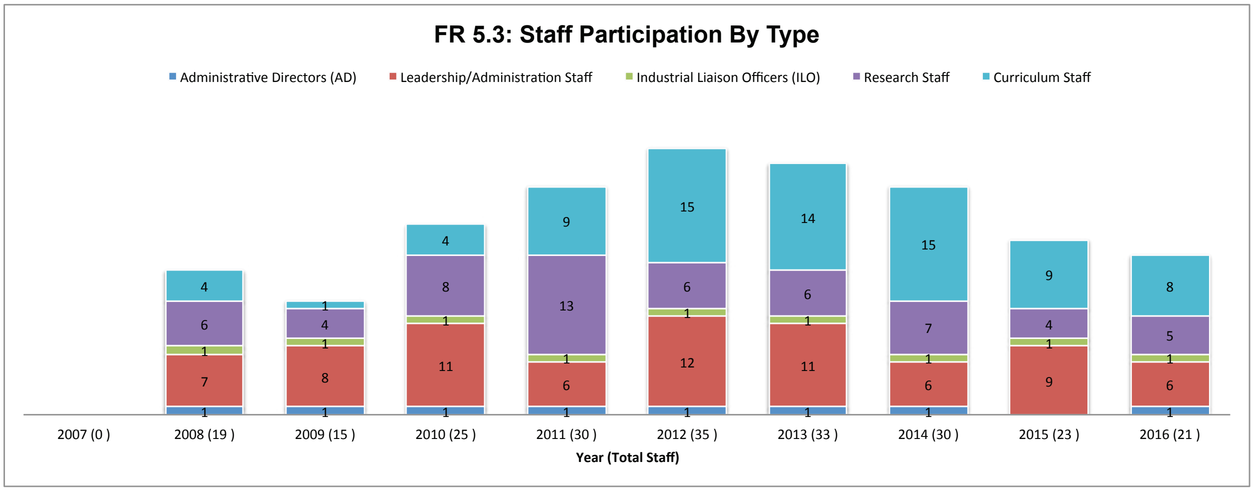


Figure FR 5.3: Staff Participation by Type

DIVERSITY EFFORT AND IMPACT

The CCEFP diversity strategy is broad in scope encompassing research, education and workforce development. The strategy, projects, and programs of the Center portfolio emphasize efforts to increase diversity throughout the Center, in the fluid power industry, and among students of all ages engaged in STEM-related initiatives. NSF ERCs are among the most visible and influential organizations within universities, creating an outsize influence on university culture. The Center Director reports directly to the Dean of the College of Science and Engineering at the University of Minnesota. In the formal review meetings held semiannually with the Dean, diversity is a frequent focus.

CCEFP's mission under the Diversity Strategic is to change the face of the industry by providing opportunities for a diverse population to become involved in fluid power. The CCEFP will use its research, education and outreach program to recruit and retain underrepresented students in engineering--women, racial and ethnic minorities, those with disabilities and recent war veterans--to increase the diversity of practitioners in the fluid power industry and related fields.

The vision of the Diversity Strategic Plan is of diverse citizens motivated to traverse the STEM pathway; a general public that is aware of the importance of fluid power and its impact on their lives; students of all ages and demographics who are motivated to understand fluid power and who can create new knowledge and innovate; a fluid power industry and related fields that reflects the gender, racial and ethnic composition of this country.

The strategy of the Diversity Strategic Plan is to provide opportunities for a diverse population to become involved in fluid power through active recruitment, engagement, and retention of pre-college students, teachers, undergraduate, graduate, and university faculty through the ambitious research and workforce development initiatives of the CCEFP. The strategy includes capitalizing on existing and successful institutional programs and infrastructure. The strategy starts with identifying key colleges and universities, including ABET-accredited programs and minority-serving institutions with engineering or related academic paths. The next step is to locate programs or people within the organizations, whose focus is directly related to providing student services, including support, to underserved populations. A third step aims at identifying and making connections with individuals within specific programs or teaching specialties who have demonstrated interests in mechanical engineering and fluid power research and applications. Additionally, some efforts are conducted through offices and programs at each of its seven universities while others are realized through the work of the Center's affiliated organizations, including student organizations (such as AISES, SACNAS, NSBE, etc.) and other NSF-sponsored programs (such as LSAMP programs and partners). Still other efforts are designed, launched, and coordinated by the

CCEFP staff. A novel relationship among the National GEM Consortium, a reputable organization committed to the advancement of underrepresented students earning advanced degrees, the CCEFP and the corporate members of the fluid power industry. This partnership includes leveraging supplemental funding provided by NSF and a synergistic relationship between the research and the corporate internship opportunity provided to the student fellow. The Center's diversity strategy continues to focus on building a network of recruiting partners across the country.

Program highlights and activities are described below.

- **A CCEFP Legacy** NSF supports an innovative membership model between Engineering Research Centers and the National GEM Consortium--a well established and highly regarded program aimed at increasing the participation of underrepresented groups--and the mutual corporate members of each organization. CCEFP's innovative approach to recruitment of underrepresented students in engineering through the National GEM Consortium. A formal partnership with the National GEM Consortium and a proposed program structure, designed and piloted by CCEFP, is expected to be adopted and implemented within the NSF ERC system, to increase the ability of ERCs to recruit and retain underrepresented students in graduate engineering programs. The GEM-ERC Fellows Program overcomes barriers to ERC student recruitment of underrepresented students in engineering. The GEM-ERC Fellows Program is differentiated from the traditional GEM Fellow in that the internship experience and the research work is integrated and aligned. The GEM-ERC Fellows Program value statement is included at the end of this section.

- **A CCEFP Legacy** A recruitment mechanism in collaboration with other ERCs to recruit and fund underrepresented students in undergraduate and graduate research. The CCEFP no longer coordinates the joint ERC exhibitor booths at SACNAS and AISES National Conferences, but does participate by contributing some support to the cost of the booths as well as providing materials to students on REU programs. The ERC exhibitor booth is a legacy of the CCEFP.

- **A CCEFP Legacy** CCEFP's Research Experiences for Undergraduates (REU): This program has traditionally been very successful in recruiting diverse participants, in race, ethnicity, and/or gender. The CCEFP REU Program has recruited, on average, over 35% women, and over 35% racially or ethnically underrepresented students into the program on a yearly basis. The CCEFP's recruiting strategy includes identifying institutions, programs and people with whom to develop relationships that, in turn, open pathways to CCEFP summer programs and beyond for underrepresented students. The Center was successful in being awarded its 2013-2015 REU Site Award.

- The CCEFP's Research Diversity Supplements are on hold in the phase-down years of the Center. It is expected that with additional sources of funding, the workforce development initiatives can be ramped up to previously sustainable levels.

Final report tables 5.4 – 5.12 demonstrate the Center's personnel statistics cumulatively since 2007. Data includes representation of women, racial and ethnic minorities, persons with disabilities, as well as citizenship of the CCEFP participants. Much of the data, in particular, those underrepresented in engineering are shown in contrast to national engineering averages across the United States and other ERCs. Line by line, the CCEFP showcases an impressive history.

The vast majority of participants are US Citizens or Permanent Residents. Not unlike the norm, CCEFP does have a significant representation graduate students and faculty who are foreign citizens. The CCEFP values diversity of all unique perspectives.

Women – Collectively, CCEFP has demonstrated consistency in its representation of women in the ERC. Traditionally, women in the CCEFP are near or above national averages in all categories. It is notable that CCEFP's percentages of female graduate students are 22%, 18% of all undergraduates, and 36% of REUs are women. CCEFP has historically had a strong representation of women at the faculty and leadership levels. Traditionally, mechanical engineering has one of the lowest percentages of women across all engineering disciplines.

Racial Minorities – Historically, the CCEFP has exceeded national averages in nearly all categories of racial minorities. Highlights include the percentage of doctoral, undergraduate and REU students.

Hispanic/Latinos, Persons with Disabilities – Numbers of Hispanic/Latinos and persons with disabilities remain small, but have grown within CCEFP at the graduate and undergraduate/REU level.

As a basis for comparison, specifically in mechanical engineering, the American Society for Engineering Education [ASEE] "Engineering By the Numbers" reports that 11.4% of women earn a bachelor degree in mechanical engineering, and of all undergraduate engineering degrees, 4.7% are African American students and 6.5% are Hispanic/Latino students. Similarly, of those students who pursue a Master's degree in mechanical engineering, 14.7% are women, 4.8% are African American and 5.4% are Hispanic in all engineering fields. As shown in the final report tables, the CCEFP's data indicates that we compare favorably with these national engineering percentages.

Partners for Diversity

There is appreciation throughout the Center of the importance of individual efforts as well as partnerships in fulfilling an overarching goal of the CCEFP: increasing the diversity of students and practitioners in STEM-related study and in fluid power research and the industry it serves. The Center recognizes that the research and educational opportunities led and funded by the Center provide key pathways for reaching this goal.

The Center's diversity strategy continues to focus on building a network of recruiting partners from across the country. The Center identifies institutions, identifies programs, and subsequently forms social networking relationships with individuals likely to promote CCEFP opportunities to their diverse and underrepresented students. The e-relationships built upon this strategy tend to generate positive outcomes for student recruitment and relationship retention. In the recent reporting year, the Center expanded its networking database by a third to over 1000 unique contacts.

The outreach efforts of the CCEFP report a significant representation of diverse populations in programs across the Center. The REU, the former Research Diversity Supplements and GEM-ERC Fellows programs have served as effective and influential tools in recruiting underrepresented students for research within the CCEFP, as well as in developing a strong and diverse network of contacts within schools outside of the Center. As subsequent charts indicate, these efforts have been yielding positive outcomes.

PROPOSED: GEM-ERC Fellow

OBJECTIVE

To promote the dissemination of a pilot GEM-ERC fellowship program, which utilizes the professional infrastructure of The National GEM Consortium, to increase the number of underrepresented domestic graduate in ERC research programs.

The Center for Compact and Efficient Fluid Power (CCEFP) has collaborated with The National GEM Consortium (GEM) to devise a novel interface between National Science Foundation's (NSF) Engineering Research Centers (ERC), GEM and the companies of the manufacturing, biotechnology, energy and electronics industries, to recruit and retain underrepresented students pursuing graduate study in science, technology, engineering, and applied mathematics (STEM). The proposed interface is a **GEM-ERC FELLOW**, sponsored by the collaborating organizations of the NSF ERC, GEM and a corporate member of the ERC. The GEM-ERC Fellow would conduct traditional ERC research, engage in an industry internship and would be supported in full through a variety of sponsorship through the ERC, GEM, and the GEM Member University.

The proposed GEM-ERC Fellow leverages the existing and established infrastructures of the NSF Engineering Research Centers, the corporate members of the NSF ERCs and The National GEM Consortium to employ a comprehensive fellowship program for masters and doctoral students pursuing engineering within an ERC. The GEM-ERC Fellow 1) would participate in traditional research and engagement activities of the ERC/GEM Member University, 2) would be an intern with a ERC corporate member (also an affiliate of GEM, by proxy), and 3) would be a graduate student matriculating through the GEM Consortium's professional development programming.

The proposed GEM-ERC Fellow interface directly answers NSF's goal to expand efforts to increase the participation of underrepresented groups at the most challenging level for ERCs -- the graduate level. Using the established GEM Fellowship model, the CCEFP and GEM have negotiated an innovative and advantageous way in which ERCs can recruit an underrepresented graduate student into the ERC research program. A student, the GEM-ERC Fellow, will conduct ERC research aligned with the goals of the ERC, the faculty advisor, and the interests of the corporate member. The corporate member, in turn, provides the GEM-ERC Fellow a hands-on internship. Unique to this new model, the ERC, alongside the corporate member, serves as the GEM Co-Employer to fully support the GEM-ERC Fellow as s/he matriculates through the graduate program and the ERC.

ANNUAL BUDGET

The proposed GEM-ERC Fellow is a program that could be duplicated and replicated across all NSF Engineering Research Centers for a relatively low one-time investment. A $51,000 yearly commitment from an ERC would support two underrepresented graduate students each year. $22,500 fellowship stipend per student, $6,000 GEM Membership ($5,000) and Overhead Fee ($1,000) (yearly).

The initial investment to sponsor a GEM-ERC Fellow would allow NSF ERCs, as a programmatic body, to recruit and retain a significant number of underrepresented graduate students each year. It is recommended that all NSF ERCs participate in this program, supporting at a minimum of two GEM-ERC Fellows each year.

CALL TO ACTION

- It is recommended a promotional effort be initiated through NSF and the ERC family.
- It is encouraged that NSF adopt this program as a core diversity strategy that is offered by most, if not all, NSF ERCs, as a means to comprehensively recruit and retain underrepresented students in engineering.

PROGRAM ARCHITECTS

Alyssa A. Burger, Program Director
Center for Compact and Efficient Fluid Power
alyssa@umn.edu

Marcus A. Huggans Ph.D., Senior Director, External Relations
The National GEM Consortium
mhuggans@gemfellowship.org

AAB 4/3/2015

Figure 5.4: The GEM-ERC Fellows Program value statement

Engineering Research Center for Compact and Efficient Fluid Power at the University of Minnesota – Twin Cities 2007 - 2016

FR 5.4: Women in the ERC

Personnel Type	Metric	Total 2007	Total 2008	Total 2009	Total 2010	Total 2011	Total 2012	Total 2013	Total 2014	Total 2015	Total 2016
Leadership Team [2]	Total Leadership Team	0	10	10	10	11	10	9	11	9	9
	Number of Women	0	4	4	4	4	3	3	3	2	2
	Percentage of Women	0.0%	40.0%	40.0%	40.0%	36.4%	30.0%	33.3%	27.3%	0	0
	National Engineering Averages Percent of Women	Not Available	Not Available	Not Available	Not Available	Not Available	Not Available	Not Available	Not Available	0	0
Faculty [3]	Total Faculty	0	35	29	27	40	33	33	32	37	55
	Number of Women	0	8	4	3	5	5	4	3	4	5
	Percentage of Women	0.0%	22.9%	13.8%	11.1%	12.5%	15.2%	12.1%	9.4%	0	0
	National Engineering Averages Percent of Women[5]	11.8%	12.3%	12.7%	13.2%	13.8%	14.1%	14.5%	15.2%	0	0
Doctoral Students	Total Doctoral Students	0	24	30	47	59	52	57	54	57	39
	Number of Women	0	2	4	7	6	7	8	7	11	10
	Percentage of Women	0.0%	8.3%	13.3%	14.9%	10.2%	13.5%	14.0%	13.0%	0	0
	National Engineering Averages Percent of Women	22.5%	22.6%	22.9%	22.8%	22.9%	23.4%	23.6%	23.8%	0	0
Master's Students	Total Master's Students	0	32	34	29	36	29	24	35	35	38
	Number of Women	0	3	6	5	5	4	3	5	6	7
	Percentage of Women	0.0%	9.4%	17.6%	17.2%	13.9%	13.8%	12.5%	14.3%	0	0
	National Engineering Averages Percent of Women	22.0%	22.0%	21.6%	21.8%	22.2%	23.0%	24.0%	24.6%	0	0
Undergraduate Students	Total Undergraduate Students	0	41	48	52	63	123	137	112	50	100
	Number of Women	0	6	25	17	24	35	32	33	11	14
	Percentage of Women	0.0%	14.6%	52.1%	32.7%	38.1%	28.5%	23.4%	29.5%	0	0
	National Engineering Averages Percent of Women	17.3%	17.7%	18.0%	18.3%	18.5%	19.0%	19.6%	20.3%	0	0
REU Students	Total REU Students	0	27	20	26	26	19	26	23	25	22
	Number of Women	0	2	8	10	9	7	7	7	6	8
	Percentage of Women	0.0%	7.4%	40.0%	38.5%	34.6%	36.8%	26.9%	30.4%	0	0
	National Engineering Averages Percent of Women	17.3%	17.7%	18.0%	18.3%	18.5%	19.0%	19.6%	20.3%	0	0

[1] Data are for all personnel regardless of citizenship.

[2] Leadership Team includes Directors, Thrust Leaders, Education Program Leaders, Industrial Liason Officer, Administrative Director, and Research Thrust Management and Strategic Planning.

[3] Faculty includes personnel types from both research and curriculum. Leadership Directors, Thrust Leaders, and Education Program Leaders are counted as faculty for years in which the ERC reported demographics by group. During these years, the data collection system did not provide a way for ERCs to indicate that personnel fulfilled multiple roles such as leadership and faculty.

[4] Personnel may be reported under multiple categories, for example as an undergraduate student and a REU student.

[5] National Engineering Averages for faculty are for U.S. citizens only.

FR 5.5: Underrepresented Racial Minorities in the ERC

Personnel Type	Metric	Total 2007	Total 2008	Total 2009	Total 2010	Total 2011	Total 2012	Total 2013	Total 2014	Total 2015	Total 2016
Leadership Team [2]	Total U.S. Citizens	0	10	10	10	11	10	9	11	9	9
	Number of URM	0	1	1	1	1	1	1	1	1	1
	Percentage of URM	0.0%	10.0%	10.0%	10.0%	9.1%	10.0%	11.1%	9.1%	0	0
	National Engineering Averages Percent of URM	Not Available	Not Available	Not Available	Not Available	Not Available	Not Available	Not Available	Not Available	0	0
Faculty [3]	Total U.S. Citizens	0	32	26	23	36	29	29	27	29	32
	Number of URM	0	3	2	1	5	4	4	0	3	2
	Percentage of URM	0.0%	9.4%	7.7%	4.3%	13.9%	13.8%	13.8%	0.0%	0	0
	National Engineering Averages Percent of URM	2.7%	2.8%	2.8%	2.8%	3.0%	3.1%	2.9%	2.5%	0	0
Doctoral Students	Total U.S. Citizens	0	17	19	35	34	27	30	24	26	15
	Number of URM	0	1	1	4	4	5	6	3	3	3
	Percentage of URM	0.0%	5.9%	5.3%	11.4%	11.8%	18.5%	20.0%	12.5%	0	0
	National Engineering Averages Percent of URM	4.9%	4.9%	5.0%	4.8%	4.7%	4.7%	4.7%	4.8%	0	0
Master's Students	Total U.S. Citizens	0	30	30	24	27	22	18	27	19	18
	Number of URM	0	7	3	2	2	1	1	0	0	0
	Percentage of URM	0.0%	23.3%	10.0%	8.3%	7.4%	4.5%	5.6%	0.0%	0	0
	National Engineering Averages Percent of URM	5.4%	5.7%	5.9%	5.9%	5.8%	6.0%	5.8%	6.2%	0	0
Undergraduate Students	Total U.S. Citizens	0	41	47	48	59	100	99	85	41	23
	Number of URM	0	8	28	28	33	60	47	40	5	0
	Percentage of URM	0.0%	19.5%	59.6%	58.3%	55.9%	60.0%	47.5%	47.1%	0	0
	National Engineering Averages Percent of URM	6.6%	6.6%	6.5%	6.6%	6.4%	6.4%	6.0%	5.9%	0	0
REU Students	Total U.S. Citizens	0	26	16	24	25	16	20	17	22	3
	Number of URM	0	6	3	5	7	5	6	5	5	0
	Percentage of URM	0.0%	23.1%	18.8%	20.8%	28.0%	31.3%	30.0%	29.4%	0	0
	National Engineering Averages Percent of URM	6.6%	6.6%	6.5%	6.6%	6.4%	6.4%	6.0%	5.9%	0	0

[1] Data is for U.S. Citizens and Permanent Residents Only.

[2] Leadership Team includes Directors, Thrust Leaders, Education Program Leaders, Industrial Liason Officer, Administrative Director, and Research Thrust Management and Strategic Planning.

[3] Faculty includes personnel types from both research and curriculum. Leadership Directors, Thrust Leaders, and Education Program Leaders are counted as faculty for years in which the ERC reported demographics by group. During these years, the data collection system did not provide a way for ERCs to indicate that personnel fulfilled multiple roles such as leadership and faculty.

[4] Personnel may be reported under multiple categories, for example as an undergraduate student and a REU student.

FR 5.6: Hispanics/Latinos in the ERC

Personnel Type	Metric	Total 2007	Total 2008	Total 2009	Total 2010	Total 2011	Total 2012	Total 2013	Total 2014	Total 2015	Total 2016
Leadership Team [2]	Total U.S. Citizens	0	10	10	10	11	10	9	11	9	9
	Number of Hispanics/Latinos	0	0	0	0	0	0	0	0	0	0
	Percentage of Hispanics/Latinos	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0	0
	National Engineering Averages Percent of Hispanics/Latinos	Not Available	Not Available	Not Available	Not Available	Not Available	Not Available	Not Available	Not Available	0	0
Faculty [3]	Total U.S. Citizens	0	32	26	23	36	29	29	27	29	32
	Number of Hispanics/Latinos	0	0	0	0	2	1	1	0	2	1
	Percentage of Hispanics/Latinos	0.0%	0.0%	0.0%	0.0%	5.6%	3.4%	3.4%	0.0%	0	0
	National Engineering Averages Percent of Hispanics/Latinos	3.4%	3.5%	3.5%	3.6%	3.7%	3.8%	3.6%	3.7%	0	0
Doctoral Students	Total U.S. Citizens	0	17	19	35	34	27	30	24	26	15
	Number of Hispanics/Latinos	0	1	0	0	1	0	0	1	1	0
	Percentage of Hispanics/Latinos	0.0%	5.9%	0.0%	0.0%	2.9%	0.0%	0.0%	4.2%	0	0
	National Engineering Averages Percent of Hispanics/Latinos	4.8%	4.7%	5.2%	5.3%	5.5%	6.2%	6.3%	6.8%	0	0
Master's Students	Total U.S. Citizens	0	30	30	24	27	22	18	27	19	18
	Number of Hispanics/Latinos	0	0	1	1	0	0	0	0	0	1
	Percentage of Hispanics/Latinos	0.0%	0.0%	3.3%	4.2%	0.0%	0.0%	0.0%	0.0%	0	0
	National Engineering Averages Percent of Hispanics/Latinos	6.7%	7.2%	7.2%	7.9%	8.6%	8.9%	9.6%	9.5%	0	0
Undergraduate Students	Total U.S. Citizens	0	41	47	48	59	100	99	85	41	23
	Number of Hispanics/Latinos	0	2	5	2	3	3	5	4	4	2
	Percentage of Hispanics/Latinos	0.0%	4.9%	10.6%	4.2%	5.1%	3.0%	5.1%	4.7%	0	0
	National Engineering Averages Percent of Hispanics/Latinos	10.0%	10.6%	10.9%	11.1%	11.6%	12.1%	12.3%	13.0%	0	0
REU Students	Total U.S. Citizens	0	26	16	24	25	16	20	17	22	3
	Number of Hispanics/Latinos	0	4	0	4	0	1	2	2	2	0
	Percentage of Hispanics/Latinos	0.0%	15.4%	0.0%	16.7%	0.0%	6.3%	10.0%	11.8%	0	0
	National Engineering Averages Percent of Hispanics/Latinos	10.0%	10.6%	10.9%	11.1%	11.6%	12.1%	12.3%	13.0%	0	0

[1] Data is for U.S. Citizens and Permanent Residents Only.

[2] Leadership Team includes Directors, Thrust Leaders, Education Program Leaders, Industrial Liason Officer, Administrative Director, and Research Thrust Management and Strategic Planning.

[3] Faculty includes personnel types from both research and curriculum. Leadership Directors, Thrust Leaders, and Education Program Leaders are counted as faculty for years in which the ERC reported demographics by group. During these years, the data collection system did not provide a way for ERCs to indicate that personnel fulfilled multiple roles such as leadership and faculty.

[4] Personnel may be reported under multiple categories, for example as an undergraduate student and a REU student.

FR 5.7: Persons with Disabilities in the ERC

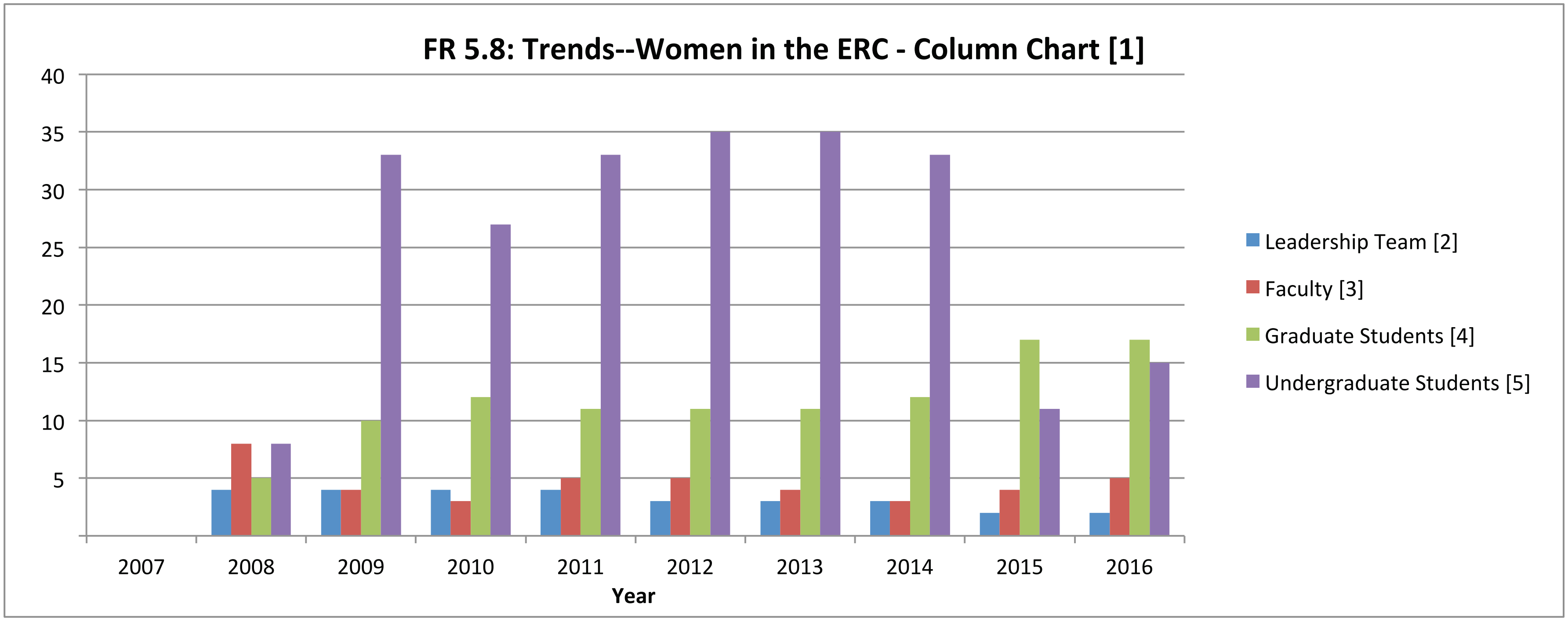
Personnel Type	Metric	Total 2007	Total 2008	Total 2009	Total 2010	Total 2011	Total 2012	Total 2013	Total 2014	Total 2015	Total 2016
Leadership Team [2]	Total Leadership Team	0	10	10	10	11	10	9	11	9	9
	Number of Disabled	0	1	1	0	0	0	0	0	0	0
	Percentage of Disabled	0.0%	10.0%	10.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0	0
	National Engineering Averages Percent of Disabled	Not Available	Not Available	Not Available	Not Available	Not Available	Not Available	Not Available	Not Available	0	0
Faculty [3]	Total Faculty	0	35	29	27	40	33	33	32	37	55
	Number of Disabled	0	0	0	0	0	0	0	0	0	0
	Percentage of Disabled	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0	0
	National Engineering Averages Percent of Disabled	Not Available	7.4%	Not Available	8.5%	Not Available	Not Available	8.3%	Not Available	0	0
Doctoral Students	Total Doctoral Students	0	24	30	47	59	52	57	54	57	39
	Number of Disabled	0	0	0	1	2	1	1	1	1	0
	Percentage of Disabled	0.0%	0.0%	0.0%	2.1%	3.4%	1.9%	1.8%	1.9%	0	0
	National Engineering Averages Percent of Disabled	Not Available	7.1%	Not Available	Not Available	Not Available	4.8%	Not Available	Not Available	0	0
Graduate Students	Total Graduate Students	0	32	34	29	36	29	24	35	35	38
	Number of Disabled	0	0	0	0	1	1	0	0	0	0
	Percentage of Disabled	0.0%	0.0%	0.0%	0.0%	2.8%	3.4%	0.0%	0.0%	0	0
	National Engineering Averages Percent of Disabled	Not Available	7.1%	Not Available	Not Available	Not Available	4.8%	Not Available	Not Available	0	0
Undergraduate Students	Total Undergraduate Students	0	41	48	52	63	123	137	112	50	100
	Number of Disabled	0	1	4	4	1	1	2	0	0	0
	Percentage of Disabled	0.0%	2.4%	8.3%	7.7%	1.6%	0.8%	1.5%	0.0%	0	0
	National Engineering Averages Percent of Disabled	Not Available	10.3%	Not Available	Not Available	Not Available	10.5%	Not Available	Not Available	0	0
REU Students	Total REU Students	0	27	20	26	26	19	26	23	25	22
	Number of Disabled	0	0	0	0	2	0	0	0	0	0
	Percentage of Disabled	0.0%	0.0%	0.0%	0.0%	7.7%	0.0%	0.0%	0.0%	0	0
	National Engineering Averages Percent of Disabled	Not Available	10.3%	Not Available	Not Available	Not Available	10.5%	Not Available	Not Available	0	0

[1] Data are for all personnel regardless of citizenship.

[2] Leadership Team includes Directors, Thrust Leaders, Education Program Leaders, Industrial Liason Officer, Administrative Director, and Research Thrust Management and Strategic Planning.

[3] Faculty includes personnel types from both research and curriculum. Leadership Directors, Thrust Leaders, and Education Program Leaders are counted as faculty for years in which the ERC reported demographics by group. During these years, the data collection system did not provide a way for ERCs to indicate that personnel fulfilled multiple roles such as leadership and faculty.

[4] Personnel may be reported under multiple categories, for example as an undergraduate student and a REU student.



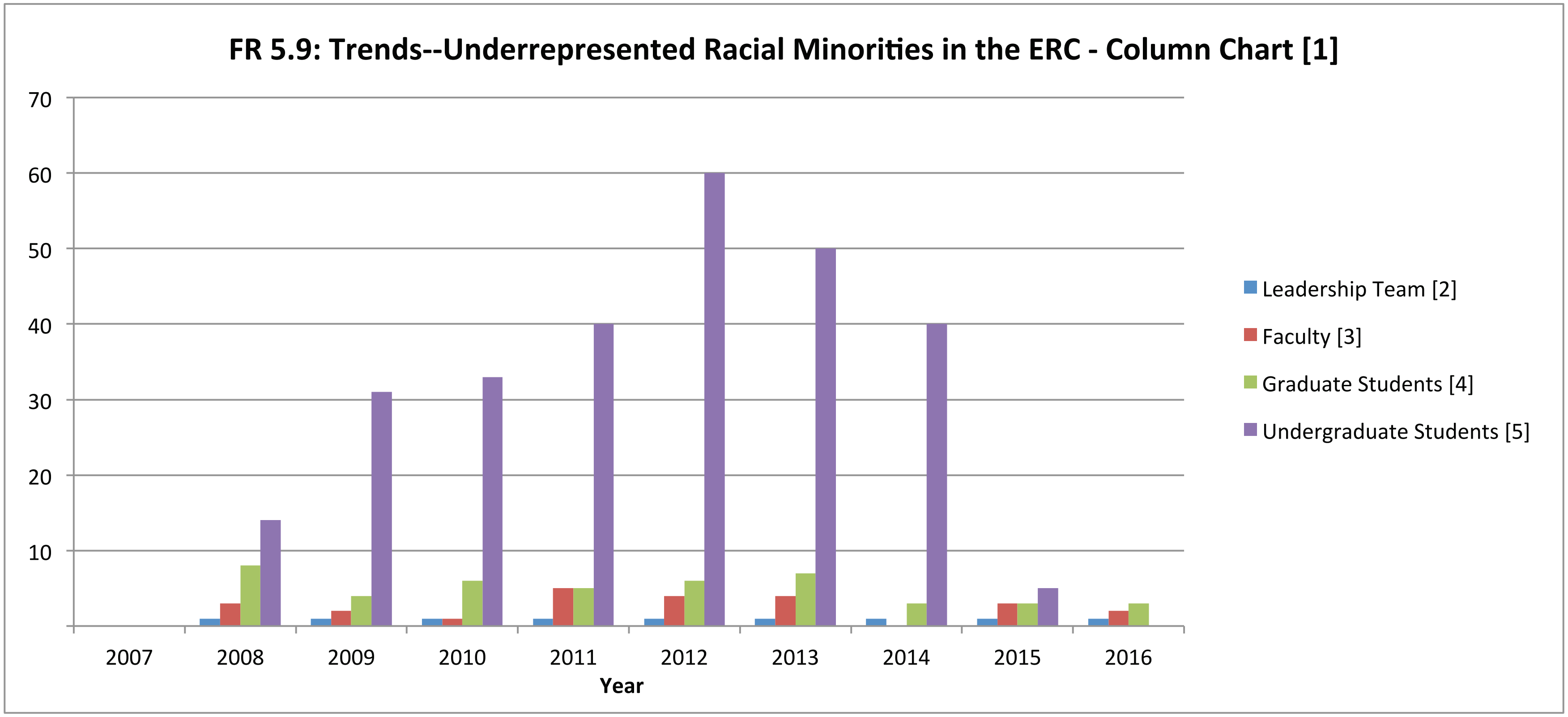
[1] Data are for all personnel regardless of citizenship.

[2] Leadership Team includes Directors, Thrust Leaders, Education Program Leaders, Industrial Liason Officer, Administrative Director, and Research Thrust Management and Strategic Planning.

counted as faculty for years in which the ERC reported demographics by group. During these years, the data collection system did not provide a way for ERCs to indicate that personnel fulfilled multiple roles such as leadership and faculty.

[4] Graduate Students include Research - Master's Students, Research - Doctoral Students, Curriculum Development and Outreach - Master's Students, Curriculum Development and Outreach - Doctoral Students

[5] Undergraduate Students include REU students and non-REU students.



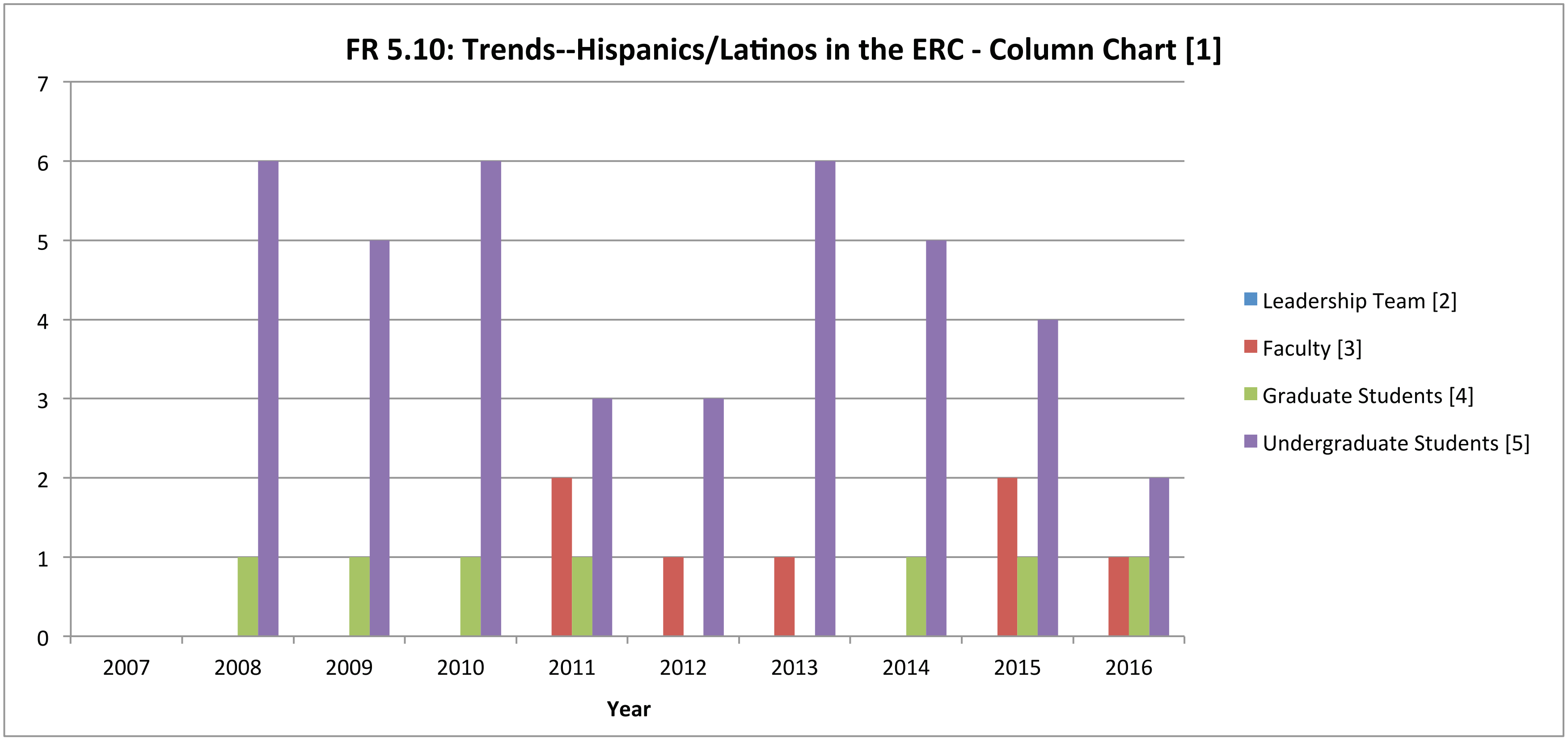
[1] Data are for U.S. citizens and permanent residents only.

[2] Leadership Team includes Directors, Thrust Leaders, Education Program Leaders, Industrial Liason Officer, Administrative Director, and Research Thrust Management and Strategic Planning.

counted as faculty for years in which the ERC reported demographics by group. During these years, the data collection system did not provide a way for ERCs to indicate that personnel fulfilled multiple roles such as leadership and faculty.

[4] Graduate Students include Research - Master's Students, Research - Doctoral Students, Curriculum Development and Outreach - Master's Students, Curriculum Development and Outreach - Doctoral Students

[5] Undergraduate Students include REU students and non-REU students.



[1] Data are for U.S. citizens and permanent residents only.

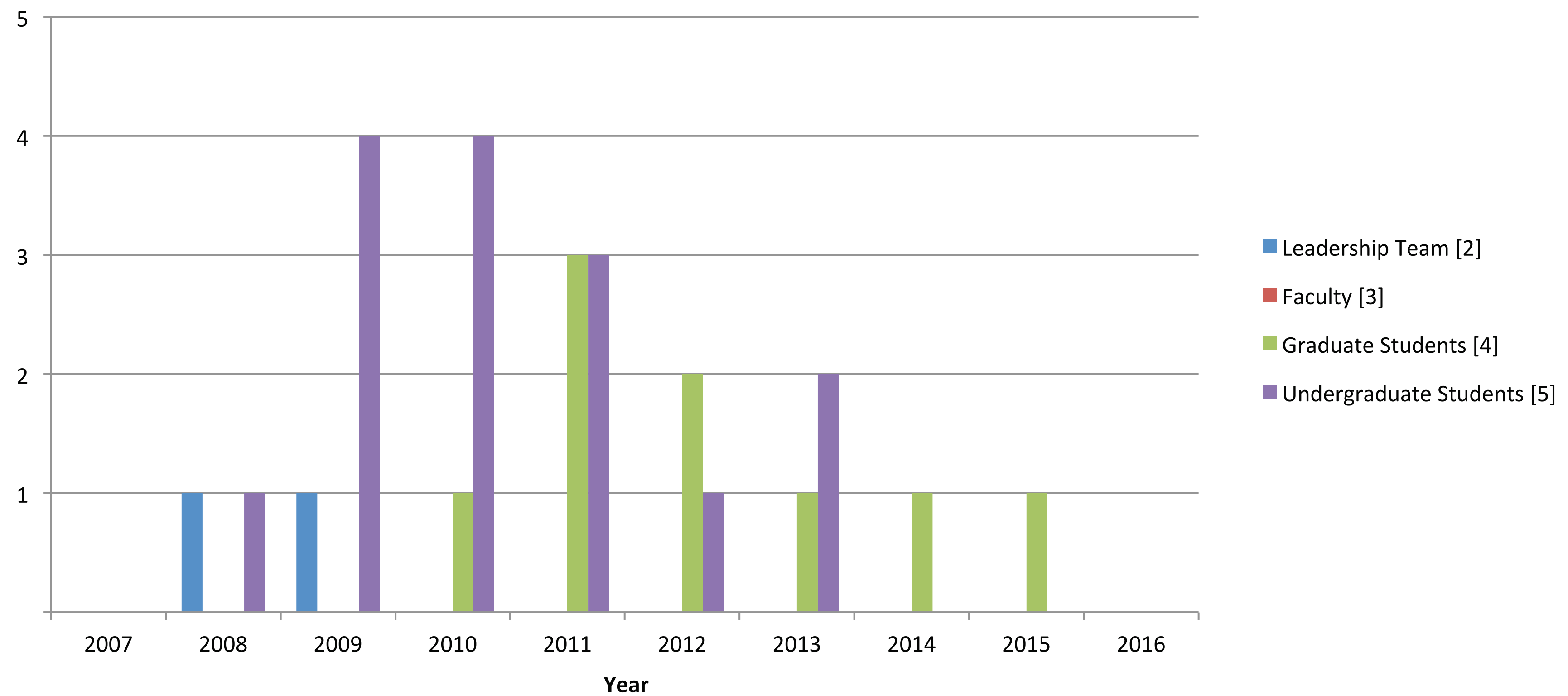
[2] Leadership Team includes Directors, Thrust Leaders, Education Program Leaders, Industrial Liason Officer, Administrative Director, and Research Thrust Management and Strategic Planning.

counted as faculty for years in which the ERC reported demographics by group. During these years, the data collection system did not provide a way for ERCs to indicate that personnel fulfilled multiple roles such as leadership and faculty.

[4] Graduate Students include Research - Master's Students, Research - Doctoral Students, Curriculum Development and Outreach - Master's Students, Curriculum Development and Outreach - Doctoral Students

[5] Undergraduate Students include REU students and non-REU students.

FR 5.11: Trends--Persons with Disabilities in the ERC - Column Chart [1]



[1] Data are for all personnel regardless of citizenship.

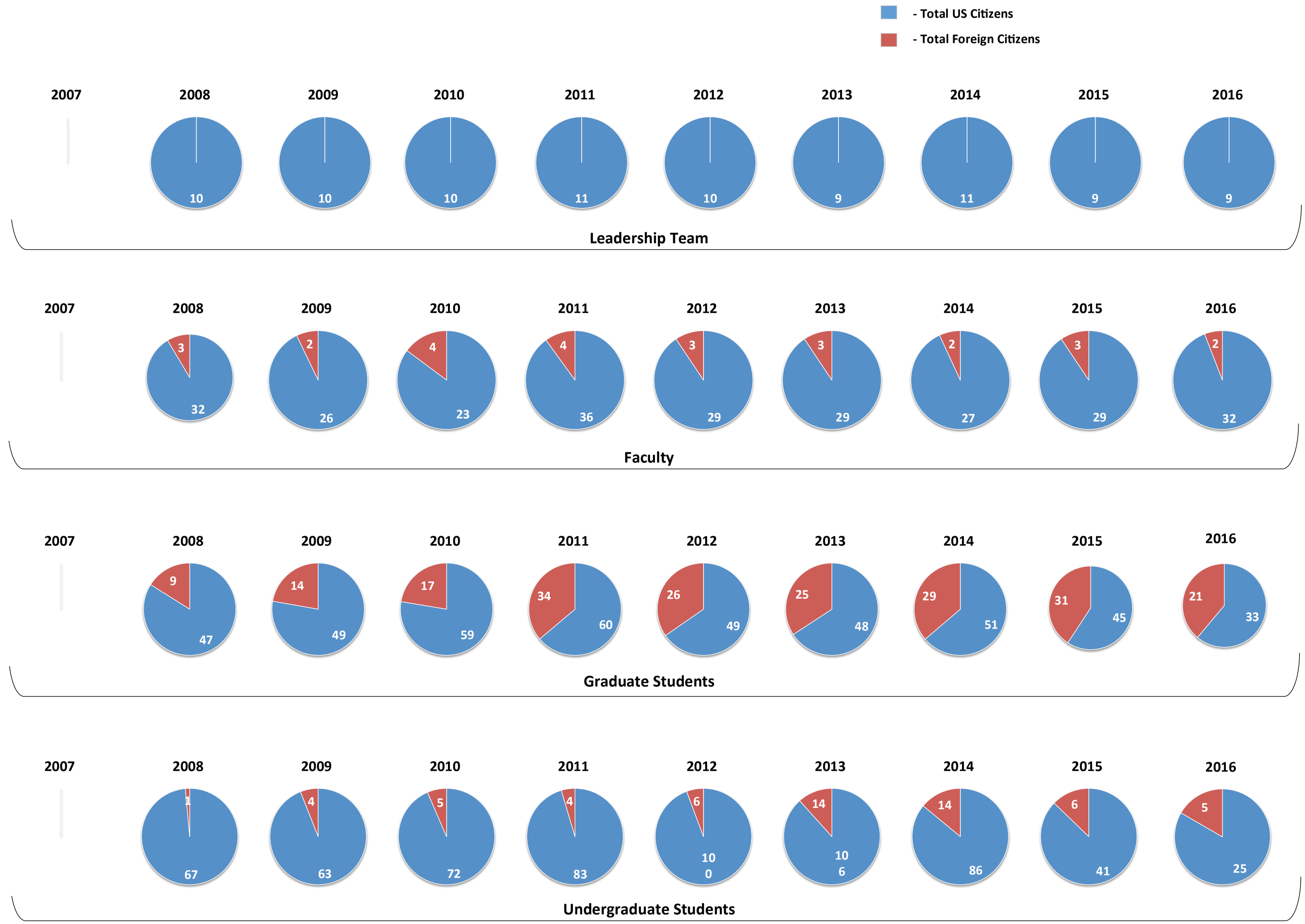
[2] Leadership Team includes Directors, Thrust Leaders, Education Program Leaders, Industrial Liason Officer, Administrative Director, and Research Thrust Management and Strategic Planning.

counted as faculty for years in which the ERC reported demographics by group. During these years, the data collection system did not provide a way for ERCs to indicate that personnel fulfilled multiple roles such as leadership and faculty.

[4] Graduate Students include Research - Master's Students, Research - Doctoral Students, Curriculum Development and Outreach - Master's Students, Curriculum Development and Outreach - Doctoral Students

[5] Undergraduate Students include REU students and non-REU students.

FR 5.12: Trends--U.S. Citizens and Foreign Citizens [1]



[1] Personnel who did not report citizenship are not included.

FR 5.13 shows Direct Sources of Support by Sector. Of note, the decrease in NSF funding in the last two years resulted in a corresponding decrease in University support. Also, the increase in “Other” support is offset by a corresponding decrease in “Industry” support due to the transition to the Pascal Society industry support agreement in year 9. $655,000 of Pascal Society support in both years 9 and 10, classified as “Other”, would have been previously classified as “Industry”.

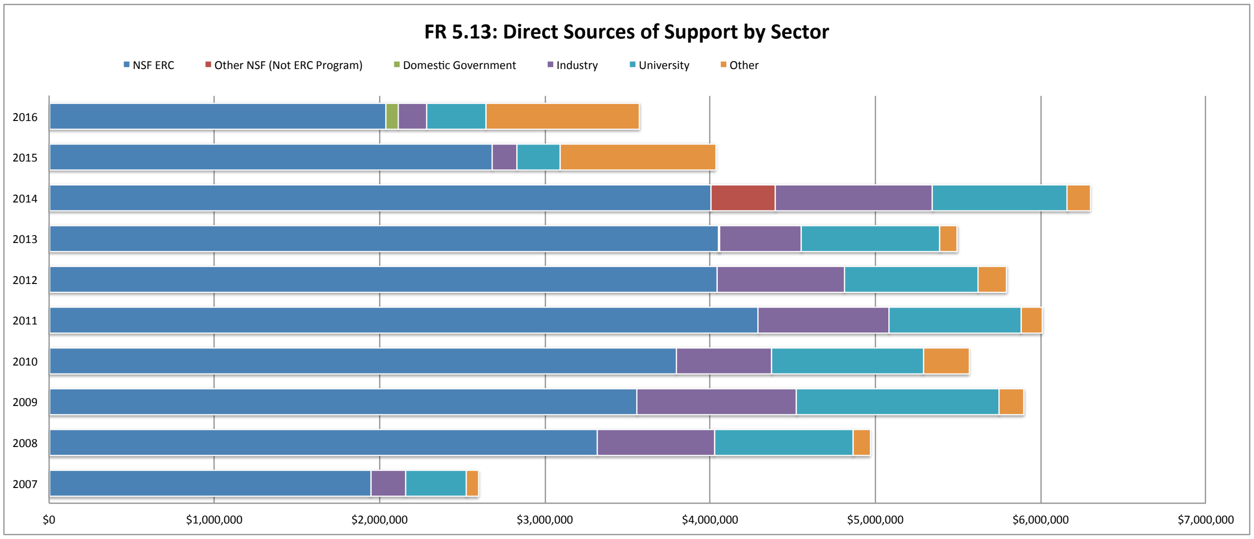


Figure FR 5.13: Direct Sources of Support by Sector

FR 5.14 Expenditures and Residuals shows the expense categories as a percentage of the total (expenditures and residuals). At a glance, it appears that expenses *as a percentage of the total* increased significantly in year 10. However, because the residual in year 10 is lower than year 9 and makes up a much smaller percentage of the total, the other expense category percentages increase accordingly.

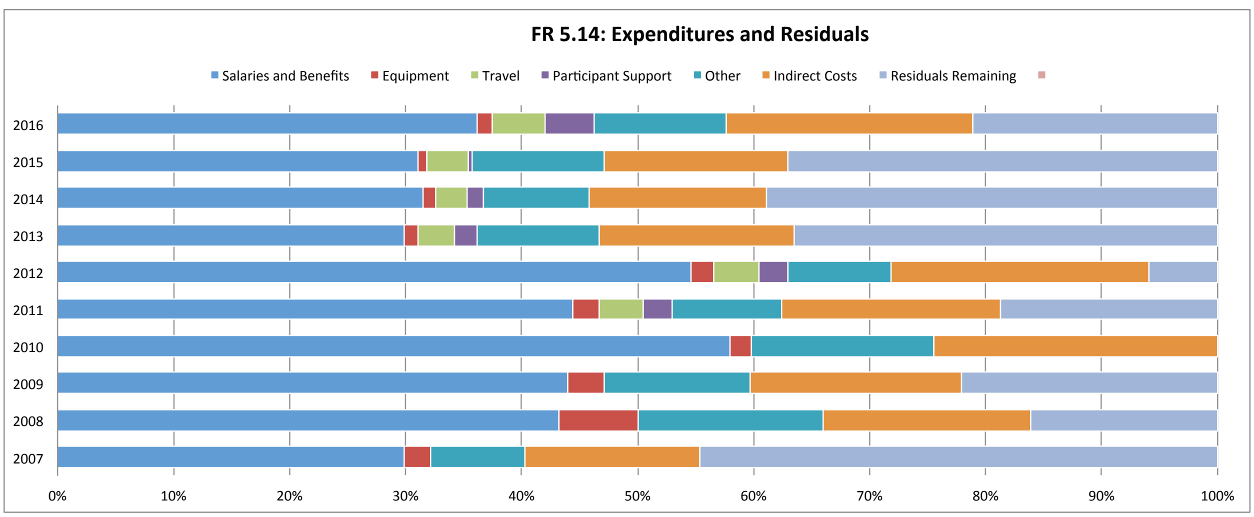


Figure FR 5.14: Expenditures and Residuals

FR 5.15 Budgets by Research, Educational and Functional Categories shows the functional category budgets as a percentage of the total budget. As with Table 5.13, because the residual funds remaining is smaller than in year 9 and makes up a smaller percentage of the total, the other category percentages are higher than in previous years.

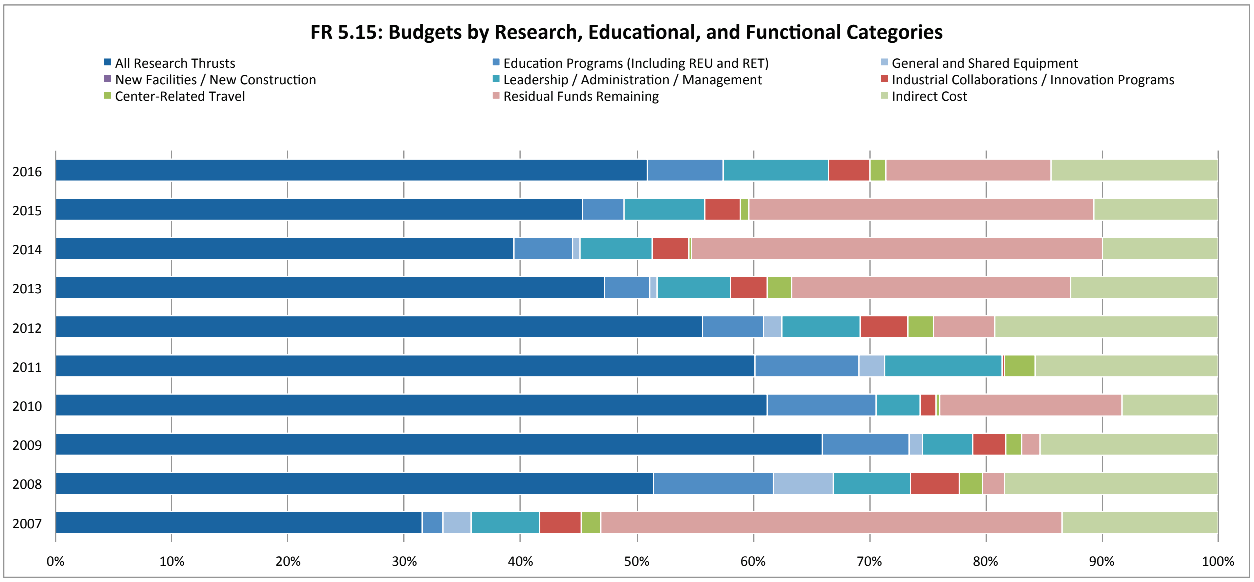


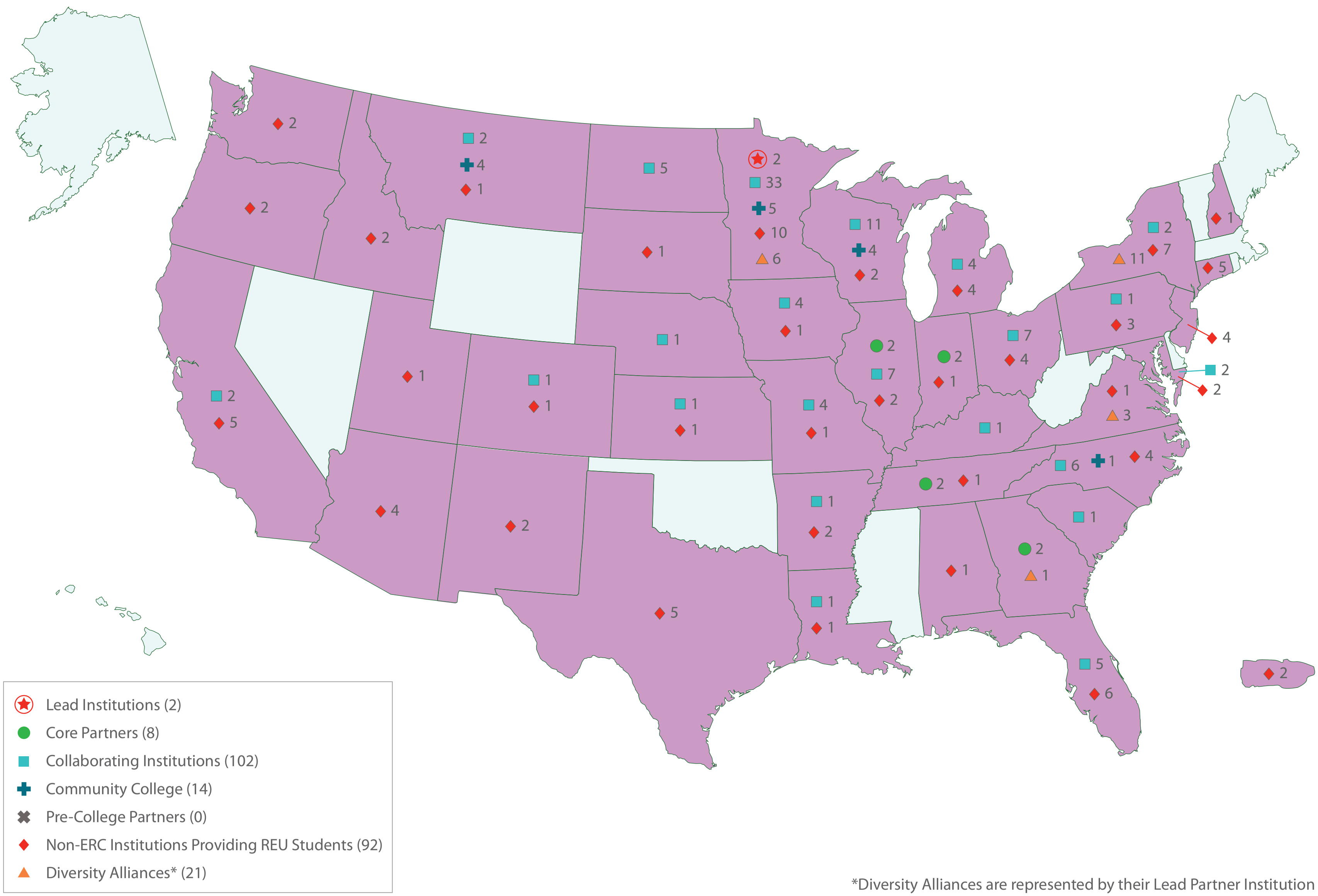
Figure FR 5.15: Budgets by Research, Educational, and Functional Categories

FR 5.16: Location of Participating Domestic Institutions

Center ID	State	Institution Type Display	Total
Minnesota	Minnesota	Lead Institution	2
Minnesota	Georgia	Core Partner	2
Minnesota	Illinois	Core Partner	2
Minnesota	Indiana	Core Partner	2
Minnesota	Tennessee	Core Partner	2
Minnesota	Arkansas	Collaborating Institution	1
Minnesota	California	Collaborating Institution	2
Minnesota	Colorado	Collaborating Institution	1
Minnesota	Florida	Collaborating Institution	5
Minnesota	Illinois	Collaborating Institution	7
Minnesota	Iowa	Collaborating Institution	4
Minnesota	Kansas	Collaborating Institution	1
Minnesota	Kentucky	Collaborating Institution	1
Minnesota	Louisiana	Collaborating Institution	1
Minnesota	Maryland	Collaborating Institution	2
Minnesota	Michigan	Collaborating Institution	4
Minnesota	Minnesota	Collaborating Institution	33
Minnesota	Missouri	Collaborating Institution	4
Minnesota	Montana	Collaborating Institution	2
Minnesota	Nebraska	Collaborating Institution	1
Minnesota	New York	Collaborating Institution	2
Minnesota	North Carolina	Collaborating Institution	6
Minnesota	North Dakota	Collaborating Institution	5
Minnesota	Ohio	Collaborating Institution	7
Minnesota	Pennsylvania	Collaborating Institution	1
Minnesota	South Carolina	Collaborating Institution	1
Minnesota	Wisconsin	Collaborating Institution	11
Minnesota	Alabama	Non-ERC Institution Providing REU Students	1
Minnesota	Arizona	Non-ERC Institution Providing REU Students	4
Minnesota	Arkansas	Non-ERC Institution Providing REU Students	2
Minnesota	California	Non-ERC Institution Providing REU Students	5
Minnesota	Colorado	Non-ERC Institution Providing REU Students	1
Minnesota	Connecticut	Non-ERC Institution Providing REU Students	5
Minnesota	Florida	Non-ERC Institution Providing REU Students	6
Minnesota	Idaho	Non-ERC Institution Providing REU Students	2
Minnesota	Illinois	Non-ERC Institution Providing REU Students	2
Minnesota	Indiana	Non-ERC Institution Providing REU Students	1
Minnesota	Iowa	Non-ERC Institution Providing REU Students	1
Minnesota	Kansas	Non-ERC Institution Providing REU Students	1
Minnesota	Louisiana	Non-ERC Institution Providing REU Students	1
Minnesota	Maryland	Non-ERC Institution Providing REU Students	2
Minnesota	Michigan	Non-ERC Institution Providing REU Students	4
Minnesota	Minnesota	Non-ERC Institution Providing REU Students	10
Minnesota	Missouri	Non-ERC Institution Providing REU Students	1
Minnesota	Montana	Non-ERC Institution Providing REU Students	1
Minnesota	New Hampshire	Non-ERC Institution Providing REU Students	1
Minnesota	New Jersey	Non-ERC Institution Providing REU Students	4
Minnesota	New Mexico	Non-ERC Institution Providing REU Students	2
Minnesota	New York	Non-ERC Institution Providing REU Students	7
Minnesota	North Carolina	Non-ERC Institution Providing REU Students	4
Minnesota	Ohio	Non-ERC Institution Providing REU Students	4
Minnesota	Oregon	Non-ERC Institution Providing REU Students	2
Minnesota	Pennsylvania	Non-ERC Institution Providing REU Students	3
Minnesota	Puerto Rico	Non-ERC Institution Providing REU Students	2
Minnesota	South Dakota	Non-ERC Institution Providing REU Students	1
Minnesota	Tennessee	Non-ERC Institution Providing REU Students	1
Minnesota	Texas	Non-ERC Institution Providing REU Students	5
Minnesota	Utah	Non-ERC Institution Providing REU Students	1
Minnesota	Virginia	Non-ERC Institution Providing REU Students	1
Minnesota	Washington	Non-ERC Institution Providing REU Students	2
Minnesota	Wisconsin	Non-ERC Institution Providing REU Students	2
Minnesota	Minnesota	Community College	5
Minnesota	Montana	Community College	4
Minnesota	North Carolina	Community College	1
Minnesota	Wisconsin	Community College	4
Minnesota		AGEP	1
Minnesota		LSAMP	11
Minnesota		TCUP	1
Minnesota	Minnesota	Alliance with NSF Diversity Awardees	5
Minnesota	Virginia	Alliance with NSF Diversity Awardees	3

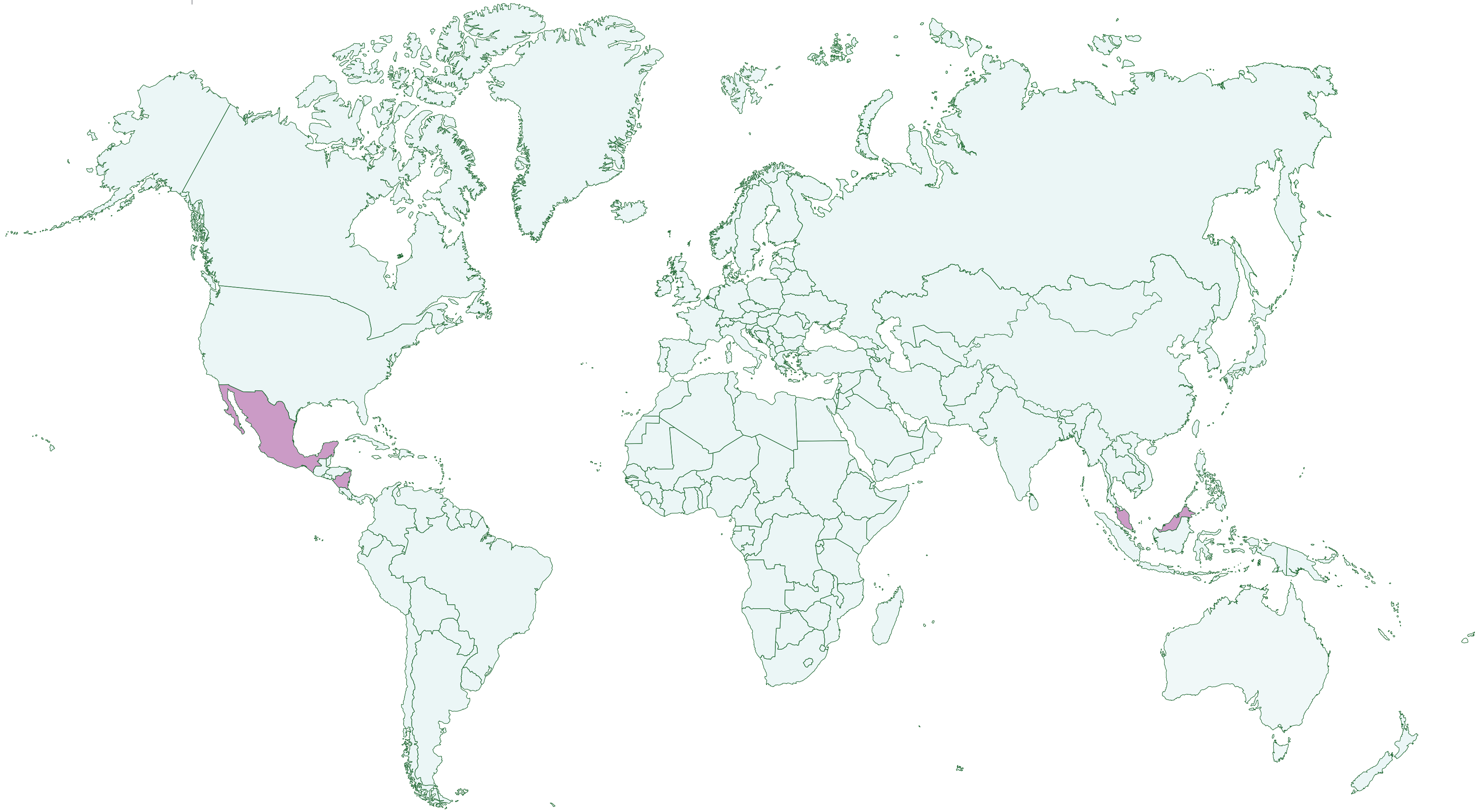
Figure FR 5.16: Location of Participating Domestic Institutions

FR 5.16 Location of Lead, Core Partner, and All Domestic Collaborating Institutions



*Diversity Alliances are represented by their Lead Partner Institution

FR 5.17 Location of Foreign Collaborating Institutions and/or Foreign Partner Institutions



= Number of institutions

	Number of institutions
Malaysia	1
Mexico	1
Nicaragua	1

FR 5.17: Location of Paricipating Foreign Institutions

Center ID	Institution Type Display	Country	Continent	Total
Minnesota	Collaborating Institution	Malaysia	ASIA	1
Minnesota	Collaborating Institution	Mexico	NORTH AMERICA	1
Minnesota	Collaborating Institution	Nicaragua	NORTH AMERICA	1

Figure FR 5.17: Location of Participating Foreign Institutions

Y10 CCEFP SLC SWOT

The Year 10 Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis of the CCEFP is based on the results of emailed responses from active student members of the Center as well as items that are still relevant and important from previous years SWOT analysis.

STRENGTHS

1. Connecting industry needs and desires with academic institutions abilities and resources
    a. Conferences, FPIRC and Industry Engagement Committee Summit
    b. Enlarging membership of the CCEFP through the partnership with NFPA
2. A lot of activities available to enhance student skill sets and encourage student participation
3. Valuable communication on the advancement of fluid power technology
    a. Webinars: present research progress to large group from industry and academia
    b. News stories: CCEFP and NFPA help get news of advancements out to world
4. Provide the potential career opportunities to the student member and help the industry acquire the sufficient talent from the universities
    a. Resume transfer and meeting with Industry made available at annual meetings offering a path to fluid power jobs
5. Outreach and education efforts:
    a. REU program (including boot camp)
    b. Travel grants
    c. Senior design project offshoots
    d. Extension of REU research beyond summer (e.g. Chainless Challenge) to universities that do not have fluid power or engineering curriculum

WEAKNESSES

1. Ability to engage and energize students as evidenced by:
    a. Lack of participation in the webcast presentation
    b. Difficulty attracting new students
    c. New students not aware they are part of the Center: providing new students (especially on associated projects or schools with a smaller CCEFP student base) with an introduction to the CCEFP policies, resources and organization
2. Start-up development and project commercialization:
    a. Disconnect between students and Center regarding interest in pursuing start-ups
    b. Benefits to students pursuing start-ups is not emphasized
    c. Source of funding and local resources for start-ups is not particularly clear
3. Inability to draw grad students into working in the fluid power field upon graduation from the center. Two examples of possible causes and sources include:
    a. The only PhDs at CCEFP events are those from academia: leads to the perception that there are no job opportunities for PhDs in the fluid power industry. Consequence: finding a second research thrust that is perceived as more useful when talking to employers
    b. Low success rate in incorporating research into industry platforms resulting in perception that industry is not actually excited about projects or that once students research is completed that will be the end of the technology/research
4. Finding new student officers and information transfer between SLC officers past, present and newly elected

OPPORTUNITIES

1. CCEFP is the only NSF ERC researching fluid power, use to Center's advantage for things like securing funding from sources outside of Pascal Society
2. Test beds can speed up on-the-fly research of fluid power related technologies
3. Encourage students who graduated from the Center to stay engaged
4. At future conferences or meetings showcase PhDs at current CCEFP industry partners so the current PhD students can see where they would fit within industry partners
5. Have companies demonstrate products which they have brought to market based off CCEFP research validating the value and impact of fluid power research through applications
6. Redesign of the CCEFP website making it more user friendly including ability to find documents
7. CCEFP-centered facilitation of technology and information transfer between projects, researchers, and industry
    a. Provide PI funding flexibility to allow for an overlap semester between students graduating from a project and students incoming to an existing or next phase project, or other creative ways to reduce or eliminate loss of information upon graduation
    b. Technology, hardware and information transfer between industry member resources and research project needs. For example, an online catalogue where companies can list products they may offer in kind and a request form where students can ask for part donations (in kind, not monetary) with the ability for companies to grant requests
8. Show that researchers in fluid power industries are appreciated and challenged: in addition to giving academics awards at conferences have awards for students (graduate and undergraduate) as well as industry members that are based on nominations for impacting fluid power

THREATS

1. Difference in goals and timelines between academia and industry including knowledge and demand gaps
2. Loss of learned skills (both via Center policies and Project development) due to graduation of students without overlap for incoming students resulting in policy and project delays
3. The expertise area of the CCEFP is very small in terms of number of professors and universities: there is a lack of growth in both limiting the Centers abilities and introduction of new ideas
    a. Definition for CCEFP student and faculty members as defined on the ccefp.org website: "Currently, membership in the CCEFP is only granted to faculty and students working on approved CCEFP projects at any of the seven consortium member institutions."
4. Inability to retain researchers' interest once they are out in industry
5. Projects are not given funding support via CCEFP when entering commercialization stage

DISCUSSION

With the CCEFP entering a structure transition period, many strengths and opportunities still exist and are sought after. A fundamental strength has repeatedly been industry connections and the interest it has generated at conferences with students. It has greatly impacted career opportunities for the Centers' students. A communication stream through webinars and news stories has helped to keep the participants of the center up-to-date with the proceedings of the center. Outreach events like the REU program have been successful in engaging undergraduate students in fluid power projects.

However, there exist a number of items that continue to appear from year to year particularly in weaknesses and threats. For example, weaknesses 1 and 2 as well as threats 1 and 2 have appeared in SWOT feedback across multiple years. These examples should receive more consideration in an effort to solve these problems.

Opportunities 1, 3, 6, and 8 are examples to help weaknesses 1 and 3. A user-friendly website can attract students to learn and explore more options with the center. An introduction to new students in the center in the CCEFP policies, resources, and organization is paramount. Increasing student participation and engagement is key as student commitment is a necessity for a sustainable model moving forward.

Further challenges may arise as the CCEFP progresses further with industry support through the Pascal Society, but this could also lead to more potential opportunities for the CCEFP as well. This marks a period where further weaknesses and threats could be solved now that the CCEFP is not limited to NSF guidelines and restrictions. Threats 1 and 2 could be solved during this restructuring period as the CCEFP transitions away from the NSF. Weakness 2 could also be addressed as the Pascal Society could look into the benefits of helping fund students with potential start-ups, as they want to commercialize their research.

In summary, threats and weaknesses that continue to resurface impact the student's needs. Helping to improve overlap in the research lab and having an answer for students who want to commercialize their research will alleviate their problems. Strategies need to be developed to further the engagement and recruitment of students in fluid power. Opportunities suggested can help ease these problems. With the restructuring of the CCEFP after year 10, lifted limitations from the NSF guidelines could spark a new plan for solving these needs.

CENTER MANAGEMENT RESPONSE

We appreciate the SLC's candid, thorough and thoughtful response. It is evident the student perspective and leadership is critical to assessing the successes and challenges of the Center. The CCEFP leadership agrees with areas of recommended focus: student engagement, emphasizing the need for prioritizing commercialization and startups, disconnect between academia's progress and industry's expectation and loss of knowledge when students graduate.

The Center is eager to comment on several of the threats and weaknesses in the report.

Student engagement: Tools and a guide have been created by the SLC to familiarize new and incoming students with the CCEFP. However, the on-boarding process continues to be a challenge in a geographically diverse ERC. CCEFP plans to redesign its on-boarding process in Y11 to be more synergistic with the academic calendar. The CCEFP's engagement strategy includes a call for a full Center website update and recalibration to reflect the changing environment of the Center. We are pleased to report CCEFP has redesigned it's website to be more user-friendly and engaging, to be launched June 1. We agree that broadening the definition of Center participants to include faculty and students outside the seven original institutions of the Center is critical to inclusion. The CCEFP will modify the definition of Center participants. This will be reflected on our website and literature. The expansion also includes associated research projects to be represented in the CCEFP Webcast Series and our annual technical conference, FPIRC. We plan on more emphasis on maintaining relationships with our graduates in our new collaboration with NFPA. Moving forward, the SLC will continue, but will be streamlined and share responsibilities for the on-boarding process.

Commercialization: It is helpful to understand that students are interested in start-ups and commercialization, so initiating a campaign to raise awareness is not a need. Rather, it is motivating students to begin investigating the entrepreneurial world on their own, with the support of their faculty mentor. It is a challenge to find the resources to support commercialization. The CCEFP is able to provide tools and make our community aware of the various resources for commercialization trainings and programs at our member universities and as provided by NSF and other government entities. It is the responsibility of the faculty and the inventing university's technology transfer department to overcome the challenges to commercialize technology. We recognize that this is a daunting task involving overcoming the well-known "valley of death." To motivate interest, we launched the Commercialization Pitch the Fluid Power Innovation & Research Conference (FPIRC). It was a success; we plan to continue hosting the session. Additionally, Industry Relations Committee members are creating a structured process for providing resources for commercialization of technology created by the Center.

SLC administration: We thank the SLC for updating the bylaws to be reflective of the CCEFP environment.

Timelines, goals and knowledge lost: This is a cultural challenge between academia and industry. The question is whether the timelines and expectations too high or if those goals and pressure to complete committed tasks are there to ensure progress? Both stakeholders could benefit from understanding each other. Students entering the workforce will be under deadlines but will also have resources not provided in their graduate experience. Likewise, industry expects progress and understands that setting a plan is the best approach to meeting those goals. It is a delicate balance. It would be beneficial for CCEFP researchers to be consistent (among projects) to provide SMART goals and to achieve them, however, citing risks and unanticipated problems along the way. It becomes suspicious when researchers are unable to submit plans for progress, although, it is worth noting, research is discovery, and at times, it is difficult to predict next steps. The CCEFP leadership is empathetic with this identified threat and will work towards setting reasonable expectations for both the research team and the industry advisory board set to review the progress.

The CCEFP commits to keeping current academic and industry members aware of its progress toward sustainability. Recent events, notably the Memo of Understanding between CCEFP and NFPA have greatly improved the likelihood of success. The Center will continue organizational improvements including communications, collaboration across Center institutions and research initiatives, and its research project review process.

This page is intentionally left blank

6. BEYOND GRADUATION

The Engineering Research Center for Compact and Efficient Fluid Power (CCEFP) is the premier fluid power research collaborative in North America and is among the best in the world. The Center fills a void in U.S. fluid power research that existed for decades. Prior to the establishing of the CCEFP, the U.S. had no major fluid power research center (compared with thirty centers in Europe and many others in Asia). Fluid power researchers, who were previously disconnected, are now linked through the CCEFP.

CCEFP's focus combines fluid power research and education with a strong industry partnership. From its inception in 2006, the Center's mission has been to change the way fluid power is researched, applied and taught and its goals have been to make fluid power compact, efficient and effective. CCEFP's mission and vision remain as vibrant and compelling today as they were in 2006. While great progress has been made by CCEFP, there is still work to do.

The National Science Foundation provides funding to ERCs for ten years. This section defines the plan for CCEFP to achieve sustainability. Sustainability means that the Center has sufficient funding, resources and partners to be self-sustaining after NSF funding ends.

The Engineering Research Center (ERC) funding from the National Science Foundation (NSF) has allowed the Center to build a core group of approximately 30 faculty members, 80 graduate students and 60 undergraduate students continually doing research at our seven member institutions. CCEFP has over 70 industry supporters. This critical mass of researchers and industry partners provides a strong foundation on which to build a sustainable Center that will be able to generate the resources required to continue its research, education and intellectual capital transfer on an ongoing basis.

The ultimate goal of the Center continues to be to combine the research, education and the transfer of intellectual capital to industry. This facilitates the commercialization of technologies, and provides components and systems that benefit the fluid power industry, its customers and society. Intellectual capital includes assets that a research university can provide to industry by way of giving access to qualified students (graduate and undergraduate) as university researchers and company employees. CCEFP also gives access to researchers and research facilities that improves the potential for licensing or creating intellectual property.

A critical key tenet for a sustainable Center is the preservation of the ERC "DNA" which includes systems thinking, interdisciplinary research and inter-University collaboration. The strategic plan recognizes these critical elements and focuses on preserving and expanding them. The strategic research plan for the self-sustaining CCEFP continues to focus the established expertise of its researchers on mobile hydraulics, but it also lays out plans for the investigation and inclusion of additional areas. The ongoing research structure will be organized in the following areas: off-highway vehicles, human scale fluid power, fluid power advanced manufacturing, industrial fluid power and fundamental fluid power research.

In December 2012, a groundbreaking report funded by the Department of Energy titled "Estimating the Impact (Energy, Emissions and Economics) of the U.S. Fluid Power Industry" was published. This report states that the energy to operate fluid power systems is 2-3% of all of the energy consumed in the U.S. It provides detail about the energy use and efficiency in major fluid power applications and strongly supports the case for continued fluid power research.

In summary, this plan proposes that the self-sustaining Center will:

- Strive to create an environment of inclusiveness for its industry supporters regardless of organizational size or technology focus. This mindset will allow for other US universities to join the post NSF funded Center.
- Cooperate closely with the National Fluid Power Association in both fundraising and administrative activities.
- Continue to provide an administrative organization to, among other things, foster communications and collaboration to nurture an inclusive, comprehensive strategy for fluid power research, promote pre-competitive and associated project research and provide a structure for bringing together broad groups of researchers with industry and government partners.
- Maintain the original Center mission and vision.
- Preserve the ERC culture by actively supporting systems level thinking, interdisciplinary research, and the use of appropriate test beds to demonstrate technologies, promoting multi-university research and fostering strong industry-university collaborations.
- Leverage the critical mass of researchers and industry partners and the outstanding reputation of the Center to seek new sources of funding for fluid power research.
- Leverage its strengths and those of its partners by further teaming with the National Fluid Power Association, a proven leader in public and pre-college outreach and technical education, to expand the Education and Outreach to include students from vocational schools and technical colleges. Increasing diversity and industry involvement are important aspects of workforce development.
- Focus on continuing to provide its industry members with a strong value proposition that includes:
    - Opportunities for commercialization of the research findings of Center researchers.
    - Opportunities to interact with a large number of students with strong fluid power education, as potential skilled employees.
    - Opportunities to advance fluid power research by interacting with customers, suppliers and competitors in a manner compliant with US anti-trust laws.
- Seek large grant funding from government agencies to support the Center's pre-competitive research activities. The DOE fluid power energy study provides strong support for continued and expanded fluid power research funding. In addition, the study and the combined knowledge of our partners offers an understanding of the government agencies whose mission aligns with the benefits that fluid power research can provide.

Sustainability planning has been the top priority of the CCEFP the past three years. The Center Director holds weekly sustainability meetings with key staff members and the two Deputy Directors during which strategies are discussed and tactics identified. It remains a key topic discussed at all major Center activities including IEC meetings, FPIRC annual meetings and "State of the Center" webcasts. Center strategies and progress is reviewed three times per year with the Center Steering Committee. Ideas are continuously vetted with internal academic and industry supporters to ensure alignment and understanding.

The Center sustainability plan calls for three major elements that we choose to represent as a three-legged stool shown below. The individual legs represent each of the key areas of support. They are (1) industry support for pre-competitive research (2) securing large multi-site block government grants and (3) growth in both the amount and breadth of sponsored associated research.

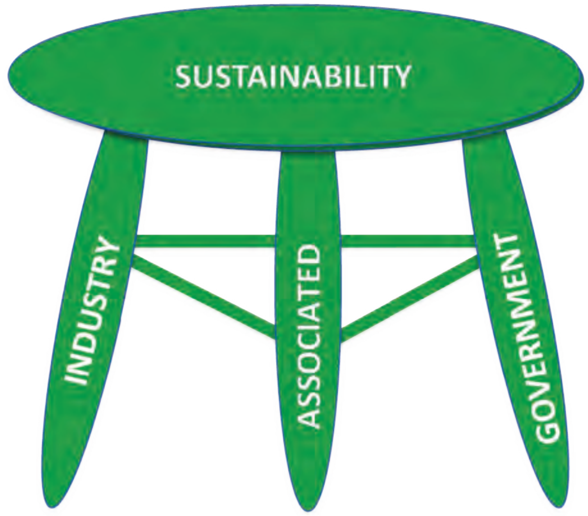


Figure 6.1: CCEFP's 3-Legged Stool Model for Center Sustainability

The industry leg of the plan is being fulfilled through a collaborative effort with the National Fluid Power Association (NFPA). NFPA will assume the responsibilities for raising industry sponsorship funds for pre-competitive fluid power research through their 501(c)(3) Foundation under a gifting program entitled the "Pascal Society". NFPA has signed a Grant Agreement with the lead university, University of Minnesota, which calls for NFPA to guarantee a minimum funding levels that are based on the funds raised by the Pascal Society efforts and backed up by their reserve fund. Every year the Grant Agreement is revisited and renewed in order to add another year of funding to allow for a minimum planning period of two years for the CCEFP management team. During these discussions longer term funding forecasts will be discussed as well as revised metrics and other possible improvements. CCEFP Operating Procedures (COPs) that provide a framework for all critical processes associated with the Center have been documented and approved. Both the Grant Agreement and the COPs are posted on the Center website (www.ccefp.org).

Membership and the corresponding giving levels in The Pascal Society are based on the size of companies, as measured by their annual global fluid power sales. These are summarized in table 6.1.

Table 6.1: Pascal Society Annual Giving Levels

		Membership and Annual Giving Levels		
Company size	**Annual global fluid power sales**	**Gold**	**Silver**	**Bronze**
Large	Above $250 million	$100,000 or more	At least $60,000	At least $6,000
Medium	Between $50 and $250 million	$50,000 or more	At least $30,000	At least $3,000
Small	Below $50 million	$25,000 or more	At least $15,000	At least $1,500

"Fluid power sales" are measured differently for different kinds of companies:

- For fluid power component or system manufacturers and distributors, it includes all of their sales.

- For OEMs, it includes the value of fluid power content in their machines, both purchased and manufactured.
- For suppliers, it includes all of their sales to the fluid power industry.

As previously mentioned these are charitable contributions, fully tax-deductible under the NFPA Foundation's 501(c)(3) status as a charitable organization.

Pascal Society members are invited to serve on our industry oversight committees. Each committee plays an important role in shaping and directing the CCEFP in a way that serves the long-term interests of our industry. The specific committees that a member is invited to serve on is based on their annual giving levels as defined in figure 6.2.

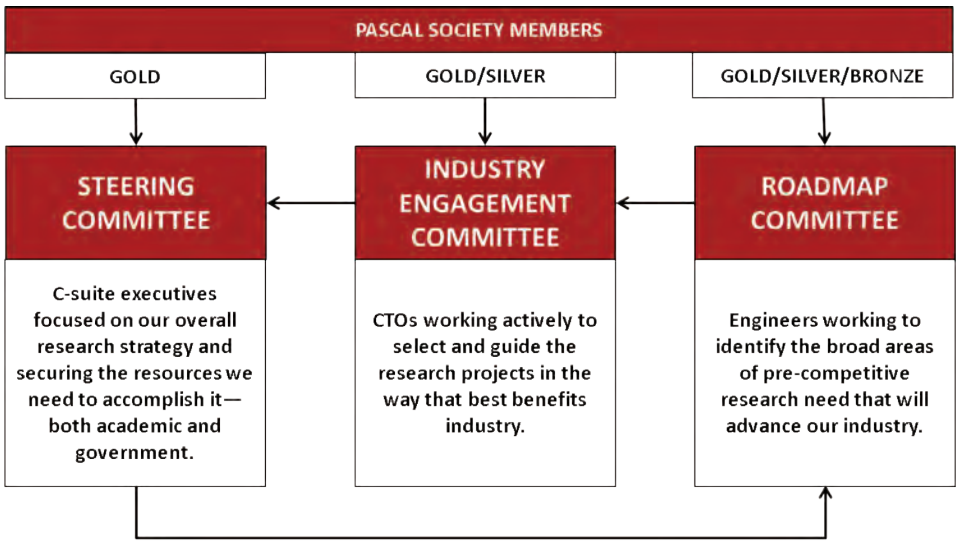


Figure 6.2: Pascal Society Member Representation in CCEFP Advisory Committees

A major goal of the CCEFP and the NFPA for the past year has been to convert the existing CCEFP industry members over to the Pascal Society. This goal has been largely accomplished with seventy-one industry sponsors, listed in table 6.2, currently committed to supporting the Pascal Society. In recognition of their previous support CCEFP industry members were given a one-time opportunity to join the Pascal Society at their current membership dues level in lieu of the higher Pascal Society levels as long as they committed to an annual increase until they reach the new support levels. Entirely new members to the Pascal Society will be required to reach the corresponding gifting levels upon joining.

GOLD		
Bimba Manufacturing	Eaton Corporation	Parker Hannifin
Caterpillar	Enfield Technologies	Proportion-Air
Daman Products Company	Hydra-Power Systems	
Danfoss Power Solutions	Pall Corporation	
SILVER		
Afton Chemical	ExxonMobil	Moog
Bobcat	Fluid Power World Magazine	Netshape Technologies
Chevron	Gates Corporation	Poclain Hydraulics
CNH	HYDAC/Schroeder Industries	Quality Control Corporation
Deltrol Fluid Products	Hydraquip	Simerics
Donaldson Company	Linde Hydraulics	Trelleborg Sealing Solutions
Evonik Oil Additives	Lubrizol	Woodward HRT
BRONZE		
Bosch Rexroth	HUSCO International	OEM Controls
Clippard Instrument Laboratory	Idemitsu Kosan	PARTsolutions
Concentric AB	IMI Precision Engineering	ROSS Controls
Czero	Industrial Hard Chrome	RYCO Hydraulics
Delta Computer Systems	Iowa Fluid Power	SMC USA
DunAn Microstaq	JCB	Stauff Corporation
Festo Corporation	Kaman Industrial Technologies	Steelhead Composites
FORCE America/Valve Division	KYB Japan	Sumitomo Heavy Industries
G. W. Lisk Company	Main Manufacturing Products	Sun Hydraulics
GS Global Resources	Master Pneumatic	The Toro Company
HAWE Hydraulik NA	Muncie Power Products	Walvoil Fluid Power
HECO Gear	National Tube Supply	White Drive Products
Hitachi	Nexen	Womack Machine Supply

Table 6.2: Pascal Society Membership

Additional recruitment is a continuous process with a focus on communicating the benefits of our Center to an ever-widening industry audience. This is another area of strong collaboration between the CCEFP and NFPA. CCEFP will be tasked with providing marketable content about its research progress, students, etc., which NFPA will promote to the industry through its already established marketing methods. Our ambitious communications plan discussed in section 4.1 is necessary to support this effort.

Our efforts to date have been fruitful. The Pascal Society supported CCEFP with $655,000 in year 10. They have pledged $805,000 for year 11. The amount for year 12 has not yet been determined but is expected to be larger than year 11. This has enabled the CCEFP to fund ten 2-year research projects in years 11 and 12. These projects are each funded at $80,000 per year. Because participating universities have agreed to 10% maximum indirect on pooled industry funding for pre-competitive research, this amount is effectively equivalent to the funding levels awarded under the NSF ERC grant.

NFPA has supported CCEFP in other ways including communications, recruiting, fund-raising and event planning. Beginning in year 11 the salaries of the Industry Liaison Officer and the Education and Outreach Director, $335,000 annually, will be covered by NFPA. Additional support for travel, subsidizing events, and external consultants exceeds $100,000 per year. With the $250,000 pledged by the University of Minnesota for years 11 and 12, the administrative costs of the Center will be fully covered. For yr11 the total funding from the Pascal Society, NFPA and the University of Minnesota is $1.5 million. This is adequate to support both administration of the Center and an active pre-competitive research program. We are anticipating a 10% annual increase in Pascal Society support over the next five years, assuring sustainability. These figures do not include associated projects from industry and government sources, in-kind donations, or large multi-site government grants. The CCEFP has plans to actively pursue these sources of funding.

The projected carry forward from year 10 to year 11 is $382,000. This includes $175,000 of supplemental funding for the 3D printed excavator project. The projected carry forward from year 11 to year 12 is $160,000.

To help define research areas that match Center and government interests, the Center partnered with a consulting company in 2014. The process included the following steps.

- Clearly define the expertise and interests of the Center's PIs
- Aggregate this information into focus areas and rank them by alignment with the needs and interests of government agencies and departments
- Propose future sources of funds that would require multi-site research
- Identify 4-8 multi-university projects
- Develop white papers for the 4-8 multi-university projects
- Provide examples of centers that won awards in specific areas
- Identify of potential competition for funds
- Create a SWOT of the Center's ability to achieve public funds
- Develop a roadmap for how to develop and implement a strategy for capturing the funding

The strategy developed is shown in figure 6.3.

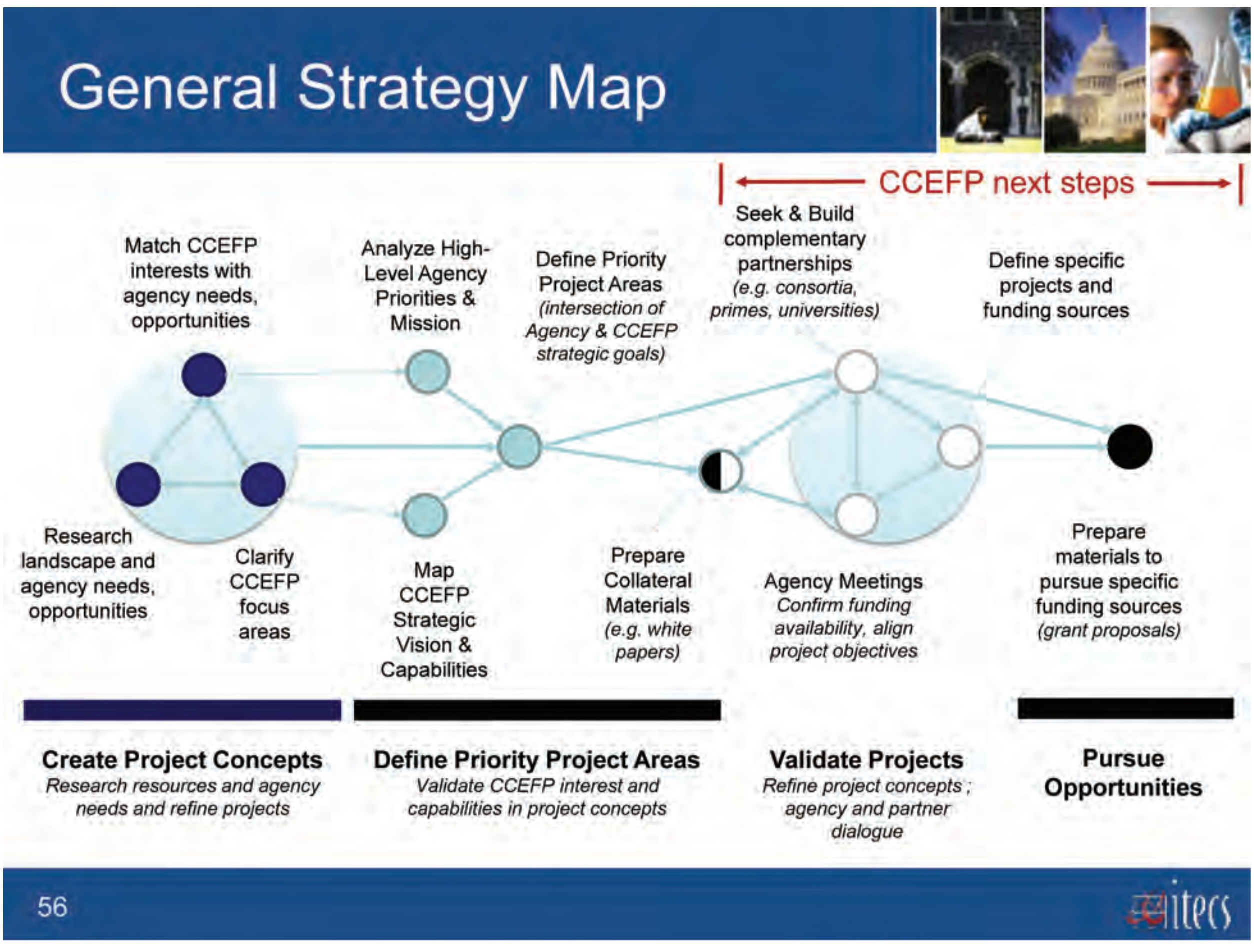


Figure 6.3: ITECS Innovative Consulting's Strategy Map

The agencies and department identified as providing the highest likelihood of CCEFP acquiring government grants were:

- DOE's Advanced Research Project Agency – Energy (ARPA-E)
- DOE's Office of Energy Efficiency and Renewable Energy (EERE)
- National Institute of Health
- Veteran's Administration
- DOE and DOD Advanced Manufacturing

The recommended funding sources and their interests fit naturally into five groups: off-highway vehicles, human scale fluid power, fluid power advanced manufacturing, industrial fluid power and fundamentals of fluid power. The leaders of these efforts are listed below.

Off Highway Vehicles - Prof. Zongxuan Sun, University of Minnesota

Human Scale Fluid Power - Prof. Eric Barth, Vanderbilt University

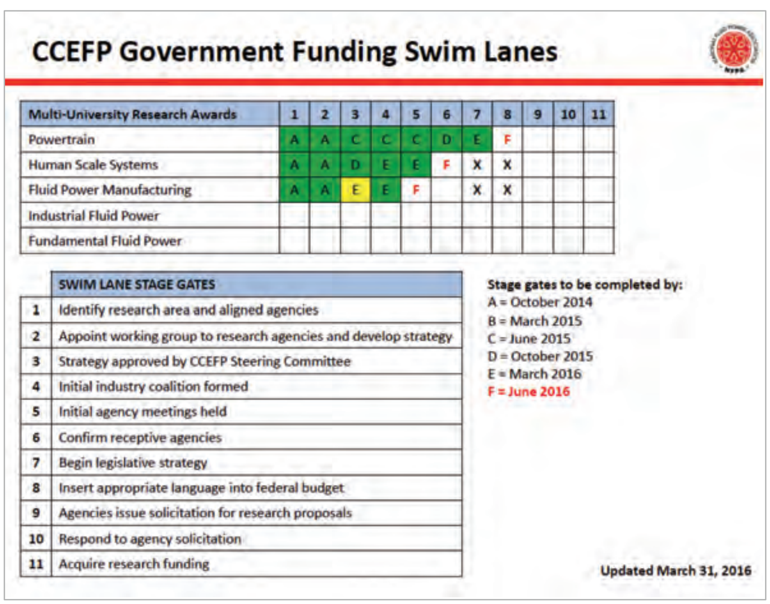
Fluid Power Advanced Manufacturing - Prof. Tom Kurfess, Georgia Tech

Industrial Fluid Power – Prof. Jose Garcia, Purdue University

Fundamentals of Fluid Power – Prof. Randy Ewoldt, University of Illinois Urbana-Champaign

The Center has limited resources so having all five efforts moving ahead at the same pace is unrealistic. Center management has decided to stage efforts in the following order: off-highway vehicles, human scale fluid power, and fluid power advanced manufacturing. Industrial fluid power and fundamental fluid power will commence in future years.

CCEFP management meets three times per year with its Steering Committee. All elements of the sustainability strategy are reviewed. Action plans are developed and progress is tracked. An example of progress tracking for government funding is shown is figure 6.4 below.


CCEFP Government Funding Swim Lanes

Multi-University Research Awards	1	2	3	4	5	6	7	8	9	10	11
Powertrain	A	A	C	C	C	D	E	F			
Human Scale Systems	A	A	D	E	E	F	X	X			
Fluid Power Manufacturing	A	A	E	E	F		X	X			
Industrial Fluid Power											
Fundamental Fluid Power											

	SWIM LANE STAGE GATES
1	Identify research area and aligned agencies
2	Appoint working group to research agencies and develop strategy
3	Strategy approved by CCEFP Steering Committee
4	Initial industry coalition formed
5	Initial agency meetings held
6	Confirm receptive agencies
7	Begin legislative strategy
8	Insert appropriate language into federal budget
9	Agencies issue solicitation for research proposals
10	Respond to agency solicitation
11	Acquire research funding

Stage gates to be completed by:
A = October 2014
B = March 2015
C = June 2015
D = October 2015
E = March 2016
F = June 2016

Updated March 31, 2016

Figure 6.4: CCEFP Government Funding Progress Tracking

Our efforts are producing results. In the past two years the Pascal Society has grown from 46 to 71 industry supporters. The resulting financial commitments are \$655K for year 10 and \$805K for year 11. Going forward our plans are to further increase industry supporters while increasing support levels.

In the past year significant progress in securing new government funding has been made. Several meetings with DOE labs and the EERE Vehicle Technologies Office convinced them that an off-highway vehicles research program was necessary. Because there are no government-funded programs in this area, industry and universities joined forces to inform targeted Representatives and Senators of the need. Requests have been submitted to the appropriations committees of both houses for a \$10 million program in fiscal year 2016.

In December 2015 the CCEFP held a workshop on human scale fluid power at Vanderbilt University. Twenty-seven industry and seventeen academic representatives attended. Outcomes of the workshop were identification of areas of mutual interest and the formation of teams to pursue these interests. Key CCEFP leaders attended the WearRAcon16 wearable robotics conference at Arizona State University in February. During the conference it became obvious that fluid power will be needed for most of the proposed applications. As a result, the CCEFP is submitting a response to a RFI for a Manufacturing Innovation Institute (MII) on “Soft and Assistive Robotics.”

The CCEFP in partnership with NFPA and the Association for Manufacturing Technology (AMT) were awarded a road-mapping grant from the NIST Advanced Manufacturing Technology Consortia (AMTech) Program. This program has two deliverables, a fluid power manufacturing roadmap and the organization of a sustainable industry consortium. The consortium has been organized and two workshops have been held in the past year. The draft roadmap will be ready June 2016 and circulated to industry for review. This roadmap will become the cornerstone of our fluid power manufacturing strategy. The consortium will meet again in Spring 2017 to finalize the roadmap. This activity will be strengthened by a NSF funded workshop on fluid power manufacturing research in May 2016. This workshop will focus on Manufacturing Readiness Level (MRL) 1-3 research.

APPENDIX I

Lessons Learned

This page is intentionally left blank

LESSONS LEARNED

1. Center Management

- Managing an ERC is complex. New management teams usually lack the required skills. We recommend that NSF provide training to new ERC leadership teams in best practices for strategic planning, project management, finance, progress reporting, etc.

- After a period of trial and error the CCEFP developed and documented processes for key management activities. These key functions are summarized below.

    1. ***Strategic Planning***: It is imperative that ERCs develop strategic plans early in their lifetime. The CCEFP has developed strategies for research, education and workforce development, engaging with industry, diversity and sustainability. These plans are used to drive the organization. Outputs from these strategies may reflect the need for specific projects, a new focus on membership, a required change in the organization or other factors affecting the center's ability to succeed. It may also identify areas where stronger leadership or a significant change of focus is required. Each year the strategies are reviewed and updated.
    2. ***Call for Project Proposals***: Perhaps the most important activity that an ERC must undergo is the selection of its research projects. The CCEFP process begins with the Center Director receiving market needs input from Industry via industry research and manufacturing roadmaps. The Director then meets with the CCEFP Steering Committee (SC) to review the CCEFP strategic plans and ensure these needs are incorporated. The Director next issues a strategic call for proposals to Center PIs citing areas of need.
    3. ***Project Selection***: The CCEFP IEC plays a critical role in project selection. They assign review teams made up of experts from their organizations to review every proposal. Each proposal had at least two industry reviewers. To ensure uniformity a standardized review template with fifteen distinct criteria is used. These criteria are separated into three subgroups: project risk, reward or alignment (strategic fit). The review results are discussed extensively during IEC teleconferences until a final outcome is reached and sent to the Center Director. The Director makes the final decision on which projects are funded. Non-funded proposals make up a "project funnel" for future consideration when other funding sources are made available.
    4. ***Project Funding***: The Center provides a two-year funding cycle. This allows more time to pursue higher impact research. It also provides more stability to plan graduate student funding.
    5. ***Progress Reporting***: Progress is reported twice per year at industry-university summits. Each funded project presents its progress. Industry is informed and encouraged to ask questions. This results in better engagement from our industry supporters.

- The burdensome data collection process for the annual report needs to be simplified. Annual report should be shorter and more informative. ERC policies should be regularized and clarified.

2. Research

- It is a new paradigm for PIs to focus their research on the needs of the test beds and to align with the three plane chart. A helpful practice is to define specific topics of interest in the call for proposals. More discussion on this below.

- The ERC test beds need to drive the research program. By this we mean that the test beds must identify the critical barriers to overcome. Furthermore, they should provide specification targets for individual research projects. Test bed leaders should to define the technology needs and interests of their test bed.

- It is important that the ERC provide a compelling vision of transformational research that industry can appreciate. This can set industry expectations at a higher level while encouraging long-range planning rather than concentrating on short-term incremental goals.

- Systems engineering knowledge is highly valued by industry. The test beds are a major source of systems engineering training, especially at the location of the test bed. The 3-plane diagram is an excellent communication tool for describing the systems nature of the research.

- Well-trained students for the next generation of researchers and practitioners are the most important product of ERC research programs. "Research is teaching." This means both research capability and communication skills. Our industry members tell us that our ERC students are "instantly effective" and have a one to two-year head start over other students.

- The Center should fund research projects in two year increments. This will cut down on the administrative load and also provide more certainty regarding funding for the PIs and their students.

- The most effective research projects have active industry participation. Advantages include market and product knowledge, design reviews, in-kind donations and access to industry facilities.

- The Center should work with industry to develop a technology roadmap that defines its future direction and priorities. A reasonable approach is for the road mapping to be Center-facilitated, but industry-focused. The roadmap is not a static document and should be reviewed and updated prior to the bi-annual call for research proposals at a minimum. Industry's suggestions for call topics generally flow from the technology roadmap.

- Center research should focus on industry wants and needs to the maximum extent. Using subject matter experts from industry to review and score project proposals on a rubric provided facilitates the process for industry making project funding recommendations to the Center Director. The Director makes the final decision of which proposals are funded, but we've found a strong correlation between the Director's and industry's priorities. Over three 2-year funding cycles totaling roughly 60 projects funded, the Director selected a project not recommended by industry just once and that was done in order to be in compliance with the ERC contract between the Center and NSF.

- Inter-university collaboration on research provides a "glue" that helps hold the Center together.

3. Education

- The external evaluator should be considered an intellectual partner in clarifying mission, vision strategy and objectives for E&O. The intellectual partner should be identified in the proposal stage of the ERC to ensure a common vision is established. A recommended objective of the external evaluator is to determine initiatives with the highest likelihood of sustainability. Implementing a focused approach to the education and outreach portfolio, quality versus quantity, will result in greater programmatic impact. Secondly, the ERC program should implement a simple common tool for assessment of national ERC impact -- recommend using the ATE Centers as a model.

- Within the first year, ERCs should invest in a third party longitudinal tracking process and procedure. Pay for the service and place Center personnel resources in program development and implementation.

- ERCs must partner with other organizations, including other NSF Centers, to increase impact. Where strategically aligned, it is better to build on existing programs rather than initiate new programs. CCEFP examples include our partnership with the Science Museum of Minnesota and the giida Native American program in Cloquet, MN.

- Allow ERCs flexibility with implementation of required education programs. Set the expectation for the engagement of a particular audience, provide a programmatic solution, and allow the ERC to select the best approach. For example, the CCEFP RET program ranked low in impact and likelihood for sustainability. However, CCEFP found great impact in teacher engagement through Project Lead The Way and an established industry-supported national engineering competition for middle and high school students. The required resources earmarked for the CCEFP RET program may have been better utilized in growing and expanding a program aligned with the CCEFP's long-range vision, goals, and objectives.

4. Diversity

- Diversity Supplements, through NSF or the ERC, are an excellent tool for diversifying graduate student population.

- The GEM-ERC collaborative model pioneered by CCEFP would benefit the ERC program if more widely practiced. The traditional GEM Fellow is sponsored, in part, by a corporate supporter, conducts research and participates in a summer industry internship. The GEM-ERC Fellow conducts ERC research, participates in an ERC-industry member internship and is supported in full through a variety of ERC, GEM and University sponsorship. The CCEFP model is differentiated from the traditional GEM Fellow in that the internship and the research are integrated. A worthwhile candidate for inclusion in every ERC diversity strategy.

5. Industry and Technology Transfer

- An industry trade association is an excellent partner to facilitate industry collaboration in an ERC. The National Fluid Power Association (NFPA) has been invaluable in recruiting industry supporters, communicating Center accomplishments and activities, and organizing events.

- Intellectual property (IP) is not the primary motivation for industry to support an ERC. It is better not to grant intellectual property rights in an industry management agreement. Our experience was that granting IP rights leads to lengthy and contentious discussions before joining. IP requires a significant amount of the ILO's time to manage with little prospect for licensing. In our experience, universal nondisclosure agreements do not work as our industry supporters refuse to sign them.

- Large industry supporters are unwilling to take the risks necessary to bring ERC research to the marketplace. Startups play a pivotal role in doing so. Developing an entrepreneurial culture is critical to technology transfer.

- Access to students is the number one reason industry joined our ERC. Graduating students are an excellent means to transfer technology to industry.

6. Sustainability

- Section 6 "Beyond Graduation" details the CCEFP sustainability plan.

- NSF could better help ERCs with sustainability. The I/UCRC program policies could be modified to be more flexible so that they are a possible mechanism for sustaining an ERC. The ERC Program could facilitate introductions to mission oriented government agencies that can lead to new partnerships with government.

This page is intentionally left blank

APPENDIX II

Bibliography of Publications

This page is intentionally left blank

Year 2 Annual Report Publications

Thrust 1 - Efficiency

*Hencey, B. and A. Alleyne, "A KYP Lemma for LMI Regions." IEEE Transactions on Automatic Control, 52 (10): 1926-1930 (2007).

*Hencey, B. and A. Alleyne, "A Robust Controller Interpolation Design Technique." 2007 American Controls Conference, New York, New York, 5347-5353 (2007).

*Hencey, B. and A. Alleyne, “"A Static Anti-Windup Compensator Design Technique for Robust Regional Pole Placement." Proceedings of the 2006 ASME IMECE, Chicago, Illinois, IMECE2006-14653 (2006).

Huang, C. and M. Ivantysynova, "An Advanced Gap Flow Model Considering Piston Micro Motion and Elastohydrodynamic Effect." Proceedings of the 4th FPNI Ph.D. Symposium, Sarasota, Florida (2006).

Ivantysynova, M., C. Huang, and A. Japing, "Determination of Gap Surface Temperature Distribution in Axial Piston Machines." Proceedings of the ASME International Mechanical Engineering Congress, Chicago, Illinois, IMECE2006-15249, (2006). *Best Paper Award*

*Kumar, R., M. Ivantysynova, and K. Williams, "Study of Energetic Characteristics in Power Split Drives for on Highway Trucks and Wheel Loaders." 2007 SAE International Commercial Vehicle Engineering Congress, Chicago, Illinois, SAE Technical Paper 2007-01-4193 (2007).

*Michael, P., "Study Reveals Factors that Affect Particle Counting Accuracy." Proceedings of Lubrication Excellence, Louisville, KY (2007).

*Michael, P. Herzog, S. and Marougy T., "Determining Hydraulic Fluid Viscosity Requirements." Machinery Lubrication, 7(1):40-42 (2007).

*Michael, P. Wanke, T. and McCambridge, M., "Additive and Base Oil Effects in Automatic Particle Counters." Journal of ASTM International 4(4):100941 (2007).

*Montgomery, A. and A. Alleyne, "Optimizing the Efficiency of Electro-Hydraulic Powertrains." Proceedings of the 2006 ASME IMECE, Chicago, Illinois, IMECE2006-16008 (2006).

Rannow, M., H. Tu, P. Y. Li, and T. R. Chase, "Software Enabled Variable Displacement Pumps – Experimental Studies," ASME-IMECE, Chicago, Illinois, IMECE2006-14973 (2006).

*Rannow, M. and P.Y. Li, "On/Off Valve Based Control of Linear Actuators with Ripple Cancellation." Proceedings of the ASME-IMECE, Seattle, Washington, IMECE2007-42590 (2007).

Tu, H., M. Rannow, M. Wang, J. Van de Ven, P.Y. Li and T.R. Chase, "High Speed Rotary Pulse Width Modulated On/Off Valve." ASME-IMECE, Seattle, November, IMECE2007-42559 (2007).

Williamson, C. and M. Ivantysynova, "The Effect of Pump Efficiency on Displacement Controlled Actuator Systems." Proceedings of the 10th Scandinavian International Conference on Fluid Power, (SICFP'07), Tampere, Finland (2007).

*Zimmermann, J., M. Pelosi, C. Williamson, and M. Ivantysynova, "Energy Consumption of an LS Excavator Hydraulic System." Proceedings of the ASME International Mechanical Engineering Congress, Seattle, Washington, IMECE2007-42267 (2007).

Thrust 2 - Compactness

Gulati, N. and E. J. Barth, "Dynamic Modeling of a Monopropellant-Based Chemofluidic Actuation System." ASME Journal of Dynamic Systems, Measurement, and Control, 129 (4): 435-445 (2007).

*Johnson, T.A., J.M. Jobe, C.J.J. Paredis, and R. Burkhart, "Modeling Continuous System Dynamics in SysML." Proceedings of the 2007 ASME International Mechanical Engineering Congress and Exposition, Seattle, Washington (2007).

*Li, Y., B. Hencey, and A. Alleyne, "Dimensional Analysis for Control for Planar Vehicle Dynamics." International Journal of Robust and Nonlinear Control, early view online version available (2007).

Li, P.Y., J.D. Van de Ven and C. Sancken, "Open Accumulator Approach for Compact Energy Storage." Proceedings of the ASME-IMECE, Seattle, Washington, IMECE2007-42580 (2007).

Malak, R.J. Jr. and C.J.J. Paredis, "Using Parameterized Pareto Sets to Model Design Concepts." Proceedings of the 2007 ASME International Mechanical Engineering Congress and Exposition, Seattle, Washington (2007).

Riofrío, J., and E. J. Barth, "A Free Piston Compressor as a Pneumatic Mobile Robot Power Supply: Design, Characterization and Experimental Operation." International Journal of Fluid Power, 8 (1): 17-28 (2007).

Riofrio, J.A. and E. J. Barth, "Design and Analysis of a Resonating Free Liquid-Piston Engine Compressor." Proceedings of the 2007 ASME International Mechanical Engineering Congress and Exposition (IMECE), Seattle, Washington, IMECE2007-42369 (2007).

*Zhu, Y. and, E J. Barth, "Energy-Based Control of a Pneumatic Oscillator with Application to Energy Efficient Hopping Robots." 2006 ASME International Mechanical Engineering Congress and Exposition (IMECE), Chicago, Illinois, IMECE2006-15015 (2006).

Thrust 3 - Effectiveness

Delpish, R., X. Jiang, **E.** Park, and S. Udoka, "A User-Centered Design for the Rescue Robot with Fluid Power." Proceedings of the Industrial Engineering Research Conference, Nashville, Tennessee (2007).

*Klop, R., K. Williams, D. Dyminski, and M. Ivantysynova, "A Simulation Study to Reduce Noise of Compact Power-Split-Drive Transmissions." Bath Workshop on Power Transmission and Motion Control PTMC 2007, Bath, United Kingdom (2007).

Kontz, M., M.C. Herrera, J.D. Huggins and W.J. Book, "Impedance Shaping for Improved Feel in Hydraulic Systems." Proceedings of 2007 ASME International Mechanical Engineering Congress and Exposition, Seattle, Washington, IMECE2007-41712 (2007).

Kontz, M.E., W.J. Book and J.G. Frankel, "Pressure Based Exogenous Force Estimation." Proceedings of the 2006 ASME International Mechanical Engineering Congress and Exposition, Chicago, Illinois, IMECE2006-14441 (2006).

Kontz, M. E. and W.J. Book, "Electronic Control of Pump Pressure for a Small Haptic Backhoe." International Journal of Fluid Power Research 8(2): 5-16 (2007).

Kontz, M. E. and W.J. Book, "Flow Control for Coordinated Motion and Haptic Feedback." International Journal of Fluid Power Research 8(3): (2007).

*Krauss, R. and W.J. Book, "A Module for Modeling and Control Design of Flexible Robots." Computing in Science and Engineering (IEEE CS and AIP), 9 (3): 41-45, (2007).

*Krauss, R. and W.J. Book, "A Python Software Module for Automated Identification of Systems Modeled with the Transfer Matrix Method," 2007 ASME International Mechanical Engineering Congress and Exposition, IMECE2007-42319, Seattle, Washington (2006).

*Krauss, R., W.J. Book and O. Brüls, "Transfer Matrix Modeling of Hydraulically Actuated Flexible Robots." International Journal of Fluid Power Research 8(1):51-58 (2007).

Salant, R.F. and B. Yang, "Elastohydrodynamic Model of Reciprocating Hydraulic Seals," Proceedings of the ROTRIB 2007 International Tribology Conference, Bucharest, Romania (2007).

Salant, R.F. and B. Yang, "Elastohydrodynamic Model of a Reciprocating Hydraulic Rod Seal with a Double Lip." Proceedings of the BHRG 19th Intl. Conference on Fluid Sealing, Poitiers, France (2007).

Salant, R.F. and B. Yang, "Numerical Modeling of Reciprocating Hydraulic Rod Seals," Proceedings of the XIth International Conference on Seals and Sealing Technology, Kudowa Zdroj, Poland (2007).

*Shenouda , A., "Anti-Cavitation Analysis in a Four-Valve Independent Metering Configuration Controlling a Hydraulic Cylinder." Proceedings of the Session 7, 4th Fluid Power Net Ph.D. Symposium, Sarasota, Florida (2006).

Yang, B. and R.F. Salant, "Numerical Model of a Reciprocating Rod Seal with a Secondary Lip," Proceedings of the 62nd Annual Meeting, STLE, Philadelphia, Pennsylvania (2007).

Yang, B. and R.F. Salant, "Numerical Model of a Tandem Reciprocating Hydraulic Rod Seal." Proceedings of the STLE/ASME International Joint Tribology Conference, San Diego, California (2007).

*Zhu, H. and W.J. Book, "Active Shielding for a Novel Sensor." Proceedings of the 2007 ASME International Mechanical Engineering Congress and Exposition, Seattle, Washington, IMECE2007-42574 (2007).

*Zhu, H., B. Paul, and W. J. Book, "Control Issues of Digital Clay – Massive Hydraulic Actuator Array for Man-Machine Communication." Proceedings of the 2006 ASME International Mechanical Engineering Congress and Exposition, Chicago, Illinois, IMECE2006-15340 (2006).

Test Beds

*Shorter, K.A., J.D. Polk, K.S. Rosengren, and E.T. Hsiao-Wecksler, "Detecting Asymmetries in Braced and Unbraced Limbs." Proceedings of the 31st Annual Meeting of the American Society of Biomechanics, Stanford, California (2007).

*Shorter, K.A, J.D. Polk, K.S. Rosengren, and E.T. Hsiao-Wecksler, "A New Method for Assessing Gait Symmetry." Proceedings of the 18th Meeting of the International Society of Posture and Gait Research, Burlington, Vermont (2007).

Year 3 Annual Report Publications

Thrust 1 - Efficiency

*Andruch, J. and Lumkes, J., "A Hydraulic System Topography with Integrated Energy Recovery and Reconfigurable Flow Paths Using High Speed Valves". Proceedings of the 51st National Conference on Fluid Power (NCFP), Las Vegas, NV, NCFP I08-24.1, 649-657 (2008).

Bair, S., and Michael, P., "Modeling the Pressure and Temperature Dependence of Viscosity and Volume for Hydraulic Fluids". Proceedings of the STLE/ASME International Joint Tribology Conference, Miami, Florida, IJTC2008-71028 (2008).

Baker, J. and Ivantysynova, M., "Investigation of Power Losses in the Lubricating Gap Between the Cylinder Block and Valve Plate of Axial Piston Machines". Proceedings of the 5th FPNI PhD Symposium, Cracow, Poland, pp. 302 – 319 (2008). *Best paper award.*

Bayer, I. and Biswas A., "Applications of Nanotextured Surfaces." Vacuum Technology and Coating 9(12): 20-24 (2008).

Bayer, I.S., Biswas, A., Tripathi, A., Avasthi, D. K., Singh, J. P., Megaridis, C. M., " Composite Thin Films of Poly(phenylene oxide)/Poly(styrene) and Poly(phenylene oxide)/Silver via Vapor Phase Deposition." Polymers for Advanced Technologies DOI:* 10.1002/pat.1315 (2009).

*Bayer, I.S., Tiwari, M. K., Megaridis, C. M. , "Biocompatible Poly(vinylidene fluoride)/Cyanoacrylate Composite Coatings with Tunable Hydrophobicity and Bonding Strength." Applied Physics Letters 93, 173902 (2008). *Featured in Virtual Journal of Biophysics, 2008*.

*Dorgan, A. and Loth, E., "Efficient Calculation of the History Force at Finite Reynolds Number." International Journal of Multiphase Flow 33: 833-848 (2007).

Fredrickson, A. and Ivantysynova, M., "A Study of Gap Flow Conditions Between the Piston and the Cylinder". Proceedings of the 5th FPNI Ph.D. Symposium, Cracow, Poland, pp. 273 – 285 (2008).

Herzog, S., Marougy, T., and Michael, P., "Guidelines for Hydraulic Fluid Viscosity Selection to Improve Equipment Fuel Economy and Productivity". Proceedings of the 51st National Conference on Fluid Power, Las Vegas, Nevada, NCFP I08-2.1 (2008).

Ivantysynova, M., "Innovations in Pump Design – What are Future Directions?" Proceedings of the 7th JFPS International Symposium on Fluid Power, Toyama, Japan, pp. 59 -64 (2008). *Invited lecture organized session agriculture and mining machinery.*

Jouini, N. and Ivantysynova, M., "Valve Plate Surface Temperature Prediction in Axial Piston Machines". Proceedings of the 5th FPNI Ph.D. Symposium, Cracow, Poland, pp. 95 – 110 (2008).

*Loth, E., "Drag of Non-Spherical Solid Particles of Regular and Irregular Shape." Powder Technology 182: 342-353 (2008).

*Loth, E., "Review: Lift of a Spherical Particle Subject to Vorticity and/or Spin." American Institute of Aeronautics and Astronautics Journal 46:801-809 (2008).

*Loth, E. and Wang, C., "Quasi-Steady Shape and Drag of Deformable Bubbles and Drops". International Conference on Multiphase Flow, Leipzig, Germany (2007).

*Loth, E., "Quasi-Steady Shape and Drag of Deformable Bubbles and Drops." International Journal of Multiphase Flow 34: 523-546 (2008).

*Loth, E., March, J. and Krishnan, K., "Predicting Droplet-Droplet Collision Regimes". AIAA Aerospace Sciences Meeting, Reno, Nevada, AIAA-2008-1022 (2008).

*Martini, A., Hsu, H.Y., Patankar, N.A., and Lichter, S., "Slip at High Shear Rates." Physical Review Letters 100: 206001 (2008).

Meyer, J. J., Stelson, K.A., Hencey, B. and Alleyne, A.G., "Optimization of the Power Management Strategy for a Hydraulic Hybrid Vehicle". Fifth Fluid Power Net International Ph.D. Symposium Proceedings, Krakow, Poland, pp. 371-380 (2008).

*Michael P., Bergesen, A., Blazel, B., Kimball A., and Wanke, R., "Hydraulic Motor Lubrication and Wear Particle Analysis". Proceedings of the 51st National Conference on Fluid Power, Las Vegas, Nevada, NCFP I08-21.3 (2008).

Michael, P. and Herzog, S., "Hydraulic Fluid Viscosity Selection for Improved Fuel Economy". Proceedings of the STLE/ASME International Joint Tribology Conference, Miami, Florida, IJTC2008-71305 (2008).

Pelosi, M. and Ivantysynova, M., "A New Fluid-Structure Interaction Model for the Slipper-Swashplate Interface". Proceedings of the 5th FPNI Ph.D. Symposium, Cracow, Poland, pp. 219 – 236 (2008).

*Seeniraj, G. and Ivantysynova, M., "Multi-Objective Optimization Tool for Noise Reduction in Axial Piston Machines". SAE International Commercial Vehicle Engineering Congress & Exhibition, Rosemont, Illinois, 01-2723 (2008).

*Seeniraj, G. and Ivantysynova, M., "Noise Reduction in Axial Pison Machines Based on Multi-Objective Optimization". Proceeding of the 5th FPNI Ph.D. Symposium, Cracow, Poland, pp. 111 – 123 (2008).

*Song, X., Mohd Zulkefli, A., Sun, Z. and Miao, H., "Transmission Clutch Fill Control Using an Improved Dynamic Programming Method". Proceedings of the Dynamic Systems and Control Conference, Ann Arbor, Michigan (2008).

Steele, A., Bayer,I. and Loth, E., "Inherently Superoleophobic Nanocomposite Coatings by Spray Atomization." Nano Letters 9(1): 501-505 (2009).

Steele, A., Moran, S., Cannon, A., King, W., Bayer, I., and Loth, E., "Conformal Nano-Composite Spray Coatings on Micro-Patterned Surfaces for Super-Hydrophobicity". Proceedings of the ASME Fluids Engineering Conference, Jacksonville, FL, FEDSM2008-55051 (2008).

Wang, M. and Li, P.Y., "Event Based Kalman Filter Observer for Rotary High Speed On/Off Valve". Proceedings of the 2008 American Control Conference, Seattle, WA (2008).

Williamson, C. and Ivantysynova, M., "Pump Mode Prediction for Four-quadrant Velocity Control of Valveless Hydraulic Actuators". Proceedings of the 7th JFPS International Symposium on Fluid Power, Toyama, Japan, Vol. 2, pp.323-328 (2008).

Williamson, C., Zimmerman, J. and Ivantysynova, M., "Efficiency Study of an Excavator Hydraulic System Based on Displacement-Controlled Actuators". Proceedings of the Bath/ASME Symposium on Fluid Power and Motion Control (FPMC), pp. 291-307 (2008).

Zimmerman, J. and Ivantysynova, M., "The Effect of System Pressure Level on the Energy Consumption of Displacement Controlled Actuator Systems". Proceedings of the 5th FPNI Ph.D. Symposium, Cracow, Poland, pp. 77-92 (2008).

Thrust 2 - Compactness

"CCEFP Research Focus: Project 2B: Free-Piston Engine Compressor". An interview with Eric Barth, Professor, Vanderbilt University, Fluid Power Journal (trade magazine), p. 46, November/December (2008).

Alleyne, A., "Ask the Experts: Fluid Power." IEEE Control Systems, December:19-20 (2007).

Hencey, B. and Alleyne, A., "An Anti-Windup Technique for LMI Regions with Applications to a Fluid Power System". American Controls Conference, Seattle, WA, 1519-1524 (2008).

*Hencey, B. and Alleyne, A., "Robust Controller Interpolation with Applications to Electrohydraulic Systems". Proceedings of the ASME Dynamic Systems & Control Conference, Ann Arbor, MI (2008).

*Jobe, J.M., Johnson, T.A. and Paredis, C.J.J., "Multi-Aspect Component Models: A Framework for Model Reuse in SysML". Proceedings of the ASME Computers and Information in Engineering Conference, Brooklyn, New York (2008).

*Johnson, T.A., Paredis, C.J.J., and Burkhart, R., "Integrating Models and Simulation in Continuous Dynamics into SysML". Proceedings of the 6th International Modelica Conference, Bielefeld, Germany (2008).

Malak, R.J. Jr. and Paredis,C.J.J., "Modeling Design Concepts under Risk and Uncertainty using Parameterized Efficient Sets". Proceeding of the SAE World Congress, Detroit, Michigan (2008).

Malak, R.J. Jr., Aughenbaugh, J.M., and Paredis,C.J.J., "Multi-Attribute Utility Analysis in Set-Based Conceptual Design". Computer Aided Design, doi:10.1016/j.cad.2008.06.004 (2008).

Malak, R.J. Jr., Tucker, L. and Paredis, C.J.J., "Composing Tradeoff Models fro Multi-Attribute System-Level Decision Making". Proceedings of the ASME Computers and Information in Engineering Conference, Brooklyn, New York (2008).

Malak, R.J. Jr., Tucker, L. and Paredis, C.J.J., "Compositional Modeling of Fluid Power Systems Using Predictive Tradeoff Models". Proceedings of the Bath/ASME Symposium on Fluid Power and Motion Control, Bath, United Kingdom (2008).

Morgan, B., Manwaring, S. and Alleyne, A., "Dynamic Design Criteria via Dimensional Analysis of Electrohydraulic 2-stage Servovalves". Proceedings of the ASME Dynamic Systems and Control Conference, Ann Arbor, Michigan (2008).

Paredis, C.J.J., "An Open-Source Modelica Library of Fluid Power Models". Proceedings of the Bath/ASME Symposium on Fluid Power and Motion Control, Bath, UK (2008).

Riofrio, J.A., Al-Dakkan, K., Hofacker, M.E., Barth, E.J., "Control-Based Design of Free-Piston Sterling Engines". Proceedings of the American Control Conference, Seattle, Washington, pp. 1533-1538 (2008).

Riofrio, J.A. and Barth, E.J., "Experimental Assessment of a Free Elastic-Piston Engine Compressor with Separated Combustion Chamber". Bath/ASME Symposium on Fluid Power and Motion Control, Bath, United Kingdom, pp. 233-244 (2008). *Winner of the BEST PAPER AWARD for the entire Symposium.*

*Shen, X. and Goldfarb, M., "Energy Saving in Pneumatic Servo Control Utilizing Inter-Chamber Cross-Flow." ASME Journal of Dynamic Systems, Measurement, and Control 129 (3): 303-311 (2007).

*Shen, X. and Goldfarb, M., "Simultaneous Force and Stiffness Control of a Pneumatic Actuator." ASME Journal of Dynamic Systems, Measurement, and Control 129 (4): 425-434 (2007).

*Tyson, S., and Alleyne, A., "Feedback Frameworks for Active Suspensions with Electrohydraulic Actuator Dynamics". Proceedings of the 2008 ASME Dynamic Systems & Control Conference, Ann Arbor, MI (2008).

Yong, C., Riofrio, J.A. and Barth, E.J., "Modeling and Control of a Free-Liquid-Piston Engine Compressor". Bath/ASME Symposium on Fluid Power and Motion Control, Bath, United Kingdom, pp. 245-257 (2008).

Thrust 3 - Effectiveness

Bair, S., "Rheology and High Pressure Models for Quantitative Elastohydrodynamics." Institution of Mechanical Engineers Part J Journal of Engineering Tribology 223: (2009).

Bair, S. and Cassalini, R., "A Scaling Parameter and Function for the Accurate Correlation of Viscosity with Temperature and Pressure across Eight Orders-of-Magnitude of Viscosity." Journal of Tribology 130: 041802: 1-7 (2008).

Bair, S. and Michael, P., "Modeling the Pressure and Temperature Dependence of Viscosity and Volume for Hydraulic Fluids". ASME paper IJTC2008-71028 (2008).

*deMattos, P., Park, E., Seong, Y., and Udoka, S., "An Application of Multivariate Profile Analysis in Healthcare". Proceedings of the Industrial Engineering Research Conference, Vancouver, Canada (2008).

*deMattos, P., Park, E., Udoka, S., Seong, Y., and Jiang, X., "Training and Job Satisfaction to Improve Nursing Retention". Proceedings of the 14th Annual Conference on Industry, Engineering and Management Systems, Cocoa Beach, Florida (2008).

*Desai, Y., Park, E., deMattos, P., and Park, J., "Process Improvement in the Emergency Department at Moses Cone Hospital". Proceedings of the 14th Annual Conference on Industry, Engineering and Management Systems, Cocoa Beach, Florida (2008).

*Desai, Y., Park, E., and Johnson, K., "Operational Improvement in the Emergency Department at Moses Cone Hospital". Proceedings of the Industrial Engineering Research Conference, Vancouver, Canada (2008).

Hughes, K., Jiang, X., "Modeling Human Performance of a Hydraulic Excavator Using Micro Saint". Proceedings of the Industrial Engineering Research Conference, Vancouver, Canada (2008).

Jenkins, Q., Delpish, R., Jiang, X., "A Review of Literature Towards a Model of Trust in Human Robotics Interaction". Proceedings of the Human Interaction with Complex Systems, Norfolk, Virginia (2008).

Jenkins, Q., Jiang, X., "Developing a Tool for Measuring Human Operator Trust in New Generation Rescue Robots". Proceedings of the Industrial Engineering Research Conference, Vancouver, Canada (2008).

*Jiang, X., Osafo-Yeboah, B., and Park, E., "Using the Callsign Acquisition Test (CAT) to Investigate the Impact of Background Noise, Gender, and Bone Vibrator Location on the Intelligibility of Bone-Conducted Speech." International Journal of Industrial Ergonomics 39:246-254 (2009).

*Jiang, X., Rice, B., Watson, G., and Park, E., "A Multivariate Statistical Approach to Analyze Nursing Errors". Proceedings of the 14th Annual Conference on Industry, Engineering and Management Systems, Cocoa Beach, Florida (2008).

*Kim, Daebum, Park, E., Ntuen, C., and Seong, Y., "An AGV Dispatching Algorithm with Look-Ahead Procedure for a Tandem Multiple-load AGV System." The Journal of Management and Engineering Integration (2009).

Krupka, I., Bair, S., Kumar, P., Khonsari, M. and Hartl, M., "An Experimental Validation of the Recently Discovered Scale Effect in Generalized Newtonian EHL." Tribology Letters, OnlineFirst (2008).

Li, P.Y. and Durbha, V., "Passive Control of Fluid Powered Human Power Amplifiers". Proceedings of the 7th JFPS International Symposium on Fluid Power, Toyama, Japan (2008).

Ntuen, C. and Park, E., "Predicting Human Reliability under Workload and Skill". Proceedings of the 10th IFAC Symposium on Information Control Problems in Manufacturing, Seoul, Korea (2007).

*Opdenbosch, P., Nader, S. and Wayne, B., "Learning Control Applied to an Electro-Hydraulic Poppet Valve". American Control Conference, pp. 1525 – 1532 (2008).

Park, E., Jenkins, Q. and Jiang, X., "Measuring Trust of Human Operators in New Generation Rescue Robots". 2008 JFPC International Symposium on Fluid Power, Toyama, Japan (2008).

*Park, E., Park, J., Ntuen, C., Kim, D., and Johnson, J., "Forecast Driven Simulation Model for Service Quality Improvement of the Emergency Department in the Moses H. Cone Memorial Hospital." The Asian Journal on Quality 9(3): (2009).

*Park, J., Park, E., Seong, Y., and deMattos, P., "Forecasting Patient Load Cycle of Emergency Department at a Hospital". Proceedings of the Industrial Engineering Research Conference, Vancouver, Canada (2008).

Ritson, D., Jiang, X., Udoka, S. and Park, E., "A User-Centered Design for the Rescue Robot with Fluid Power". Proceedings of the 2007 Human Computer Interaction International Conference, Beijing, China (2007).

*Roland, Bogoslovov, Casalini, Ellis, Bair, Rzosca, Czuprynski, and Urban, "Thermodynamic Scaling and the Characteristic Relaxation Time at the Phase Transition of Liquid Crystals." Journal of Chemical Physics 28(224506): 1-9 (2008).

Salant, R. F. and Yang, B., "Numerical Modeling of Reciprocating Fluid Power Seals". 7th JFPS International Symposium on Fluid Power, Toyama, Japan (2008).

Salant, R. F. and Thatte, A., "Transient Model of a Hydraulic Rod Seal". 15th International Sealing Conference, Stuttgart, Germany (2008).

*Seong, Y., and Park, E., "Analysis on Medication Errors to Understand the Trends: A Case Study at a Large Hospital". Proceedings of the Industrial Engineering Research Conference, Vancouver, Canada (2008).

*Shenouda, A., and Wayne, B., "Optimal Mode Switching for a Hydraulic Actuator Controlled with Four-Valve Independent Metering Configuration." International Journal of Fluid Power 9(1): 35-46 (2008).

*Shin, D., Park, H., Seong, Y., Park, E., and Nteun, C., "Development of A New Evacuation Strategy Based on Occupants Density and Exit Door Capacity". Proceedings of the Industrial Engineering Research Conference, Vancouver, Canada (2008).

*Sim, T.P., and Li, P.Y., "On Coordination and Stabilization of Two Xerographic Printers". Proceedings of the American Control Conference, Seattle, Washington (2008).

Thatte, A. and Salant, R. F., "Transient EHL Analysis of an Elastomeric Hydraulic Seal". Nordtrib 2008, 13th Nordic Symposium on Tribology, Tampere, Finland (2008).

*Watson, G., and Park, E., “Errors Made in Healthcare - Causes, Costs and Potential Solutions”. Proceedings of the Industrial Engineering Research Conference, Vancouver, Canada (2008).

Yang, B. and Salant, R. F., “Effects of Speed and Pressure on Hydraulic Rod Seal Behavior”. 62nd Annual Meeting, Society of Tribologists and Lubrication Engineers, Cleveland, Ohio (2008).

Yang, B. and Salant, R. F., “Numerical Model of a Reciprocating Rod Seal with a Secondary Lip.” Tribology Transactions 51: 119-127 (2008).

Yang, B. and Salant, R. F., “Numerical Model of a Tandem Reciprocating Hydraulic Rod Seal.” Journal of Tribology 130: 032201-1 – 032201-7 (2008).

Yang, B. and Salant, R.F., “Soft EHL Analysis of a Reciprocating Hydraulic Step Seal”. STLE/ASME Tribology Conference, Miami, Florida, IJTC2008-71043 (2008).

*Young, R., Park, E., Naveiro, R., and Lohani, V., “The Development of a Global Engineering Certification Program ”. Proceedings of the Industrial Engineering Research Conference, Vancouver, Canada (2008).

Test Beds

Enes, A. and Book, W., "A Hardware-in-the-Loop Simulation Testbed for Emulating Hydraulic Loads Representing the Complete Dig Cycle of a Construction Machine". In International Mechanical Engineering Congress and Exposition, Boston, Massachusetts (2008).

Chin, R., Hsiao-Wecksler, E.T., Loth, E., Alleyne, A., Manwaring, S., Shorter, K.A., Tyson, S.N. and Kogler, G., “Portable Pneumatic Ankle-Foot-Orthosis for Foot Drop Connection”. Proceedings of the ASME 2008 Summer Bioengineering Conference, Marco Island, Florida (2008).

Chin, R., Loth, E. and Hsiao-Wecksler, E.T., “Fluid-Power Harvesting Through Use of a Bellow with Application in Advanced Orthotic Braces”. ASME Fluids Engineering Division Summer Conference, 8th International Symposium on Fluid Power, Jacksonville, FL (2008).

*Hsiao-Wecksler, E.T., Shorter, K.A., and DiBerardino, L.A., “New Methods for Quantifying Asymmetric Gait”. 45th Annual Society of Engineering Science Conference, Urbana, IL (2008).

*Klop, R. and Ivantysynova, M., ”Influence of Line Length Concerning Noise Source Generation in Hydrostatic Transmissions”. SAE International Commercial Vehicle Engineering Congress & Exhibition, Rosemont, Illinois, 01-2722 (2008).

*Klop, R. and Ivantysynova, M., “Investigation of Noise Source Reduction Strategies in Hydrostatic Transmissions”. Proceeding of the 5th FPNI Ph.D. Symposium, Cracow, Poland, pp. 63 – 76 (2008).

Kumar, R. and Ivantysynova, M., ”Towards and Optimal Energy Management Strategy for Hybrid Hydraulic Powertrains Based on Output-Coupled Power Split Principle”. Proceeding of the 5th FPNI Ph.D. Symposium, Cracow, Poland, pp. 41 – 51 (2008).

*Shorter, K.A, Polk, J.D., Rosengren, K.S., and Hsiao-Wecksler, E.T., “A New Approach for Detecting Asymmetries in Gait.” Clinical Biomechanics 23(4): 459-467 (2008).

*Shorter, K.A., Polk, J.D., Rosengren, K.S., and Hsiao-Wecksler, E.T., “Tracking Gait Asymmetries During Rehabilitation Using Regions of Deviation Measures: a Case Study”. North American Congress of Biomechanics and 32nd Annual Meeting of the American Society of Biomechanics, Ann Arbor, Michigan (2008).

Stelson, K. A., Meyer, J.J., Alleyne, A.G., and Hencey, B., “Energy Saving Control of a Hydraulic Hybrid Passenger Vehicle”. Proceedings of the Seventh Japan Society of Fluid Power International Symposium on Fluid Power, Toyama, Japan, pp. 143-148 (2008).

Wait, K.W., and Goldfarb, M.A., “Biologically Inspired Approach to the Coordination of Hexapedal Gait”. IEEE International Conference on Robotics and Automation, pp. 275-280 (2007).

Van de Ven, J.D., Olson, M. and Li, P.Y., “Development of a Hydro-Mechanical Hydraulic Hybrid Drive Train with Independent Wheel Torque Control for an Urban Passenger Vehicle”. International Fluid Power Exposition, Las Vegas, Nevada (2008).

Wait, K.W., Dalley, S.A., and Goldfarb, M., “The Design and Control of a Biomimetic Hexapedal Walker”. IEEE International Conference on Biomedical Robotics and Biomechatronics, pp. 270-275 (2008).

Wait, K.W., and Goldfarb, M., “A Biologically Inspired Approach to the Coordination of Hexapedal Gait”. IEEE International Conference on Robotics and Automation, pp. 275-280 (2007).

*Williams, K. and Ivantysynova, M., “Towards and Optimal Energy Management Strategy for Hybrid Hydraulic Powertrains Based on Dual Stage Power Split Principle”. Proceeding of the 5th FPNI Ph.D. Symposium, Cracow, Poland, pp. 27 – 40 (2008).

General

Stelson, K. A., “Engineering Research Center for Compact and Efficient Fluid Power (CCEFP).” in D. N. Johnston and A. R. Plummer, eds., Fluid Power and Motion Control, Bath, England, pp. 265-275.H (2008).

Year 4 Annual Report Publications

<u>**Thrust 1 - Efficiency**</u>

A. Steele, Bayer, I. Allen, K & Loth, E., “Effect of Carbon Nanotube Additives on Drag Reduction in Pipe Flows." ASME Engineering Fluids Division Summer Meeting FEDSM2009-78122, Vail, Colorado, April 2009.

Baker, J. and Ivantysynova, M., "Advanced surface design for reducing power losses in axial piston machines." Proceedings 11th Scandinavian International Conference on Fluid Power, SICFP’09, Linköping, Sweden, June 2-4, 2009.

Batdorff, M., and Lumkes, J., “High fidelity magnetic equivalent circuit in an axisymmetric electromagnetic actuator.” <u>IEEE Transactions on Magnetics</u>, 45(8):3064-3072 (2009).

*Chandan, V., A. Alleyne, and G. Zak, “Modeling and Control of Hydronic Systems for Energy Efficient Operation.” 2009 ASME Dynamic Systems and Control Conference, Los Angeles, CA, October 2009.

*Gillella, P. and Sun, Z., “Modeling and Control Design for a Camless Valve Actuation System.” Proceedings of the 2009 American Control Conference, St. Louis, MO, pp. 2696-2701, June, 2009.

*Gupta, V., Zhang, Z. and Sun, Z., “A Novel Pressure Control Mechanism for Common Rail Fuel Injection Systems." Proceedings of the 2009 Dynamic Systems and Control Conference, Hollywood, CA, DSCC2009-2174, Oct. 2009.

H. Tu, M. Rannow, M. Wang, P. Y. Li, and T. R. Chase, "Modeling and Validation of a High Speed Rotary PWM On/Off Valve." Proceedings of the ASME 2009 Dynamic Systems and Control Conference #2763, DSCC2009/Bath Symposium PTMC, Hollywood, 2009.

*He, X., Durret, R. and Sun, Z., “Late Intake Valve Closing as an Emission Control Strategy at Tie 2 Bin 5 Engine-Out NO_x Level.” SAE International Journal of Engines, 1(1), pp.427-443, 2008.
Hencey, B. and A. Alleyne, “A Robust Controller Interpolation Design Technique.” <u>IEEE Transactions on Control System Technology</u>, Vol 18, No. 1, pp. 1-10, Jan 2010.

*Hencey, B. and A. Alleyne, “An Anti-Windup Technique for LMI Regions.” <u>Automatica</u>, Vol 45, No. 10, pp. 2344-2349, Oct 2009.

*Hencey, B. and A. Alleyne, “Robust Controller Interpolation via Convex Optimization.” 2009 American Control Conference, June 2009.

Herzog, S. Zink, M. and Michael, P., “Hydraulic Fluid Viscosity Selection for Improved Fuel Economy.” SAE Commercial Vehicle Conference, Paper 2009-01-2845, Chicago, IL (2009).

I. Bayer, A. Steele, P. Martorana, Loth, E. & Miller, L., "Superhydrophobic cellulose-based bio-nanocomposite films from Pickering emulsions." <u>Applied Physics Letters</u> Vol. 94, April 2009.

I. Bayer, A. Steele, P. Martorana, Loth, E. & S. Robinson & D. Stevenson, "Biolubricant induced phase inversion and superhydrophobicity in rubber-toughened biopolymer/ organoclay nanocomposites." <u>Applied Physics Letters</u> Vol. 95, 2009.

I. Bayer, Brown, A., Steele, A., & E. Loth, “Transforming Anaerobic Adhesives into Highly Durable and Abrasion Resistant Superhydrophobic Organoclay Nanocomposite Films: A New Hybrid Spray Adhesive for Tough Superhydrophobicity.” <u>Applied Physics Express</u> 2:125003 (2009).

Ivantysynova, M., "Hydraulic Hybrid Power Trains - an Opportunity and Challenge for Fluid Power." 7th International Conference on Fluid Power, Hangzhou, China, April 7-10, 2009.

Ivantysynova, M. and Baker, J., "Power Loss in the Lubricating Gap Between Cylinder Block and Valve Plate of Swash Plate Type Axial Piston Machines." International Journal of Fluid Power, Vol. 10, No. 2, pp. 29 - 43 (2009).

*Kumar, R. and Ivantysynova, M., "An Optimal Power Management Strategy for Hydraulic Hybrid Output Coupled Power-Split Transmission." Bath ASME Symposium on Fluid Power and Motion Control (FPMC2009), [DSCC2009-2780] (2009).

*Loth, E. and Dorgan, A.J. "An equation of motion for particles of finite size and Reynolds number in a liquid." Environmental Fluid Mechanics (invited article), Vol. 9, pp. 187-214 (2009).

Lumkes, J., Batdorff, M., and Mahrenholz, J. "Characterization of losses in virtually variable displacement pumps." International Journal of Fluid Power, 10(3) pp. 17-27 (2009).

M. Rannow and P. Y. Li, "Soft Switching Approach to Reducing Transition Losses in an On/Off Hydraulic Valve." Proceedings of the ASME 2009 Dynamic Systems and Control Conference #2617, DSCC2009/Bath Symposium PTMC, Hollywood, 2009.

Mahrenholz, J. and Lumkes, J., "Coupled Dynamic Model for a High Speed Pressure Balanced 3-way On/Off Hydraulic Valve." J. Dyn. Sys., Meas., Control, 132, 011005, 10p. (2010).

Michael, P. Burgess, K. Kimball, A. and Wanke, T., "Hydraulic Fluid Efficiency Studies in Low-Speed High-Torque Motors." SAE Commercial Vehicle Conference, Paper 2009-01-2848, Chicago, IL (2009).

*Michael, P. Jelinski, C. Schick, D. and Whittaker, K., "Compatibility and Filterability of Hydraulic Fluids." SAE Commercial Vehicle Conference, Paper 2009-01-2851, Chicago, IL (2009).

*Mohd Zulkefli, M., Song, X., Sun, Z. and Miao, H., "A Novel Automotive Transmission Clutch Control Mechanism." Proceedings of the 2009 Dynamic Systems and Control Conference, Hollywood, CA, DSCC2009-2173, Oct. 2009.

P. Martorana, Bayer, I. Steele, A. & Loth, E., "Effect of Nano-scale Additives on Gear Pump Performance." ASME Engineering Fluids Division Summer Meeting FEDSM2009-78149, Vail, Colorado, April 2009.

Pelosi, M. and Ivantysynova, M., "A Novel Thermal Model for the Piston/Cylinder Interface of Piston Machines." Bath ASME Symposium on Fluid Power and Motion Control (FPMC2009), [DSCC2009-2782] (2009).

Pelosi, M. and Ivantysynova, M., "A Novel Fluid-structure Interaction Model for Lubricating Gaps of Piston Machines." Proceedings of the Fifth Fluid Structure Interaction Conference, eds. C.A. Brebbia, WIT Press, Southampton, pp.13-24, 2009.

*Song, X., Mohd Zulkefli, A., Sun, Z. and Miao, H., "Modeling, Analysis, and Design of the Transmission Ball Capsule System." Proceedings of the 2009 American Control Conference, St. Louis, MO, pp. 1379-1384, June, 2009.

*Song, X., Sun, Z., Yang, X. and Zhu, G., "Modeling, Control, and Hardware-in-the-Loop Simulation of an Automated Manual Transmission." Proceedings of the IMechE, Part D, Journal of Automobile Engineering, Vol. 224, No.2, pp.143-160, 2010.

Steele, A., I. Bayer, & E. Loth, "Inherently Superoleophobic Nanocomposite Coatings by Spray Atomization." Nano Letters 9(1): 501-505 (2009).

*Sun, Z., "Electro-Hydraulic Fully Flexible Valve Actuation System with Internal Feedback." ASME Transactions on Journal of Dynamic Systems, Measurement and Control, Vol. 131, 024502, 2009.

*Sun, Z., Zhang, Z. and Tsao, T.-C., "Trajectory Tracking and Disturbance Rejection for Linear Time-Varying Systems: Input/Output Representation." Systems and Control Letters, 58, pp.452-460, 2009.

Tu, Haink C., Rannow, Michael B., Wang, Meng, Li, Perry Y., and Chase, Thomas R., "Modeling and Validation of a High Speed Rotary PWM On/Off Valve." Proceedings of the ASME 2009 Dynamic Systems and Controls Conference, Paper No. MoBT7.1, Hollywood, CA (2009).

*Wang, Y., Sun, Z. and Stelson, K., "Modeling and Tracking Control of a Hydrostatic Dynamometer." Proceedings of the 2009 American Control Conference, pp. 1391-1396, St. Louis, MO, June, 2009.

*Zhang Z. and Sun, Z., "A Novel Internal Model-Based Tracking Control for a Class of Linear Time-Varying Plants." ASME Transactions on Journal of Dynamic Systems, Measurement and Control, Vol. 132, 011004, January, 2010.

*Zhang, Z. and Sun, Z., "A Novel Internal Model-Based Tracking Control for a Class of Linear Time-Varying Plants." Proceedings of the 2009 American Control Conference, pp. 5339-5344, St. Louis, MO, June, 2009.

*Zhang, Z. and Sun, Z., "Rotational Angle Based Control of Common Rail Fuel Injection Systems for Internal Combustion Engines." Proceedings of the 2009 American Control Conference, pp. 2690-2695, St. Louis, MO, June, 2009.

Zimmerman, J. and Ivantysynova, M., "Effect of Installed Hydraulic Corner Power on the Energy Consumption and Performance of Multi-Actuator Displacement Controlled Mobile Machines." Bath ASME Symposium on Fluid Power and Motion Control (FPMC2009), [DSCC2009-2781] (2009).

Thrust 2 - Compactness

A. Pedchenko and E. J. Barth, "Design and Validation of a High-Energy Density Elastic Accumulator Using Polyurethane." 2009 ASME Dynamic Systems and Control Conference & Bath/ASME Symposium on Fluid Power and Motion Control. DSCC2009-2719, pp. 1-8, Hollywood, CA, October 12-14, 2009.

*Braun, D. and Goldfarb, M., "A Control Approach for Dynamic Walking in Bipedal Robots." IEEE International Conference on Intelligent Robots and Systems, pp. 2916-2921, 2009.

*Braun, D. and Goldfarb, M., "Actuated Dynamic Walking in Biped Robots: Control Approach, Robot Design and Experimental Validation." IEEE International Conference on Humanoid Robots, pp. 237-242, 2009.

*Braun, D., and Goldfarb, M. "Eliminating Drift in the Numerical Simulation of Constrained Dynamical Systems." Computer Methods in Applied Mechanics and Engineering, vol. 198, no. 37-40, pp. 3151-3160, 2009.

*Braun, D.J. and Goldfarb M., "A Controller for Dynamic Walking in Biped Robots." IEEE Transactions on Robotics, vol. 25, no. 6, pp. 2192-1303, 2009.

C. Sancken and P. Y. Li, "Optimal Efficiency-Power Relationship for an Air Motor-Compressor in an Energy Storage and Regeneration System." Proceedings of the ASME 2009 Dynamic Systems and Control Conference #2749, DSCC2009/Bath Symposium PTMC, Hollywood, 2009.

*C. Yong, and E. J. Barth, "Modeling and Control of a High Pressure Combined Air/Fuel Injection System." 2009 ASME Dynamic Systems and Control Conference & Bath/ASME Symposium on Fluid Power and Motion Control. DSCC2009-2769, pp. 1-8, Hollywood, CA, October 12-14, 2009.

Conigliaro, R.A., A.A. Kerzhner and C.J.J. Paredis, “Model-Based Optimization of a Hydraulic Backhoe using Multi-Attribute Utility Theory.” SAE International Journal of Materials & Manufacturing, 2(1): 298-309 (2009).

Conigliaro, R.A., A.A. Kerzhner and C.J.J. Paredis, “Model-Based Optimization of a Hydraulic Backhoe using Multi-Attribute Utility Theory.” 2009 SAE World Congress, Detroit, Michigan (2009).

J. A. Willhite and E. J. Barth, “Reducing Piston Mass in a Free Piston Engine Compressor by Exploiting the Inertance of a Liquid Piston.” 2009 ASME Dynamic Systems and Control Conference & Bath/ASME Symposium on Fluid Power and Motion Control, DSCC2009-2730, pp. 1-6, Hollywood, CA, October 12-14, 2009.

J. Van de Ven and P. Y. Li, "Liquid Piston Gas Compression." Applied Energy, Vol. 86, Issue 10, pp. 2183-2191, October, 2009.

Kangude A, Burgstahler B, Kakastys J, Durfee W, "Single channel hybrid FES gait system using an energy storing orthosis: preliminary design." Annual International Conference of the IEEE Engineering in Medicine and Biology Society, 6798-6801, 2009.

Kerzhner, A.A. and C.J.J. Paredis, “Using Domain Specific Languages to Capture Design Synthesis Knowledge for Model-Based Systems Engineering.” Proceedings of ASME International Design Engineering Technical Conferences & Computers and Information in Engineering 2009, San Diego, California (2009).

M. E. Hofacker, J. Kong, E. J. Barth, “A Lumped-Parameter Dynamic Model of a Thermal Regenerator for Free-Piston Stirling Engines.” 2009 ASME Dynamic Systems and Control Conference & Bath/ASME Symposium on Fluid Power and Motion Control, DSCC2009-2741, pp. 1-8, Hollywood, CA, October 12-14, 2009.

Malak, R.J. and C.J.J. Paredis, “Modeling Design Concepts under Risk and Uncertainty using Parameterized Efficient Sets.” SAE International Journal of Materials and Manufacturing, 1(1): 339-352 (2009).

Malak, R.J., L. Tucker and C.J.J. Paredis, “Compositional Modeling of Fluid Power Systems using Predictive Tradeoff Models.” International Journal of Fluid Power, 10(2): 45-56 (2009).

Manwaring, S. and A. Alleyne, “Dimensionless Design of Variable Displacement Pumps." 2009 ASME Dynamic Systems and Control Conference, Los Angeles, CA, October 2009.

Manwaring, S. and A. Alleyne, “Modeling And Control Of Interconnected Dimensionles Dynamic Systems.” 2009 ASME Dynamic Systems and Control Conference, Los Angeles, CA, October 2009.

Moore, R.A. and C.J.J. Paredis, “Variable Fidelity Modeling as Applied to Trajectory Optimization for a Hydraulic Backhoe.” Proceedings of ASME International Design Engineering Technical Conferences & Computers and Information in Engineering 2009, San Diego, California (2009).

*N. Gulati, E. J. Barth, “A Globally Stable, Load Independent Pressure Observer for the Servo Control of Pneumatic Actuators.” IEEE/ASME Transactions on Mechatronics, vol. 14, issue 3, pp.295 – 306, DOI 10.1109/TMECH.2008.2009222, June 2009.

Shah, A.A., D. Schaefer, and C.J.J. Paredis, “Enabling Multi-View Modeling with SysML Profiles and Model Transformations.” Proceedings of the 6th International Conference on Product Lifecycle Management, Bath, UK (2009).

Sup, F., Varol, A.H., Mitchell, J.E., Withrow, T.J., and Goldfarb, M., "Preliminary Evaluations of a Self-Contained Anthropomorphic Transfemoral Prosthesis." IEEE Transactions on Mechatronics, vol. 14, no. 6, pp. 667-676, 2009.

*Sup, F.C., Varol, H.A., Mitchell, J., Withrow, T.J., and Goldfarb, M., "Self-Contained Powered Knee and Ankle Prosthesis: Initial Evaluation on a Transfemoral Amputee." IEEE International Conference on Rehabilitation Robotics, (Awarded ICORR 2009 Best Paper Award), pp. 638-644, 2009.

Tian L, Kittelson DB, Durfee WK, "Miniature HCCI free-piston engine compressor for orthosis application." Proceedings of the SAE Small Engine Technology Conference, 2009-32-0176/20097176, 2009.

Tian, Lei, David B. Kittelson, William K. Durfee, "Miniature HCCI Free-Piston Engine Compressor for Orthosis Application." JSAE paper number 20097176 (2009).

*V.R. Gervasi, D. Cook, "Reduction Of Complex Objects Into Manufacturable Elements Using The Shell-Slice Approach." Solid Freeform Fabrication Symposium Proceedings, Austin, Texas, August 2009.

*Varol, H.A., Sup, F.C., and Goldfarb, M., "Powered Sit-to-Stand and Assistive Stand-to-Sit Framework for a Powered Transfemoral Prosthesis." IEEE International Conference on Rehabilitation Robotics, pp. 645-651, 2009.

Thrust 3 - Effectiveness

Black, B. and W. Book, "Dynamic Compensating Controller for Passive Haptic Manipulators in Teleoperation." 2009 IEEE International Conference on Robotics and Automation, Kobe, Japan, paper ThD11.5 (May 12-17, 2009).

*DeMattos, Policarpo, Eui Park, and Celestine Ntuen, "Sensemaking Approaches to Decision Making Processes in Healthcare Industries." Proceedings of 2009 Industrial Engineering Research Conference, Miami, Florida (May 2009).

DeMattos, Policarpo, Eui Park, and Celestine Ntuen, "The Applications of Sensemaking Processes in Healthcare Industries." Proceedings of the 15th International Conference on Industry, Engineering, & Management Systems, Cocoa Beach, Florida, (March 2009).

*Desai, Yogeeta, Eui Park**,** Mark Maxwell, and Kendall Johnson, "Improvement of OR Operational Efficiency at Moses Cone Hospital." Proceedings of 2009 Industrial Engineering Research Conference, Miami, Florida (May 2009).

Enes, Aaron and Wayne Book, "A Hardware-in-the-Loop Simulation Testbed for Emulating Hydraulic Loads Representing the Complete Dig Cycle of a Construction Machine." 2008 ASME International Mechanical Engineering Conference and Exposition, Boston, MA (Nov. 2008).

Enes, Aaron and Wayne Book, "A Virtual Reality Operator Interface Station with Hydraulic Hardware-in-the-Loop Simulation for Prototyping Excavator Control Systems." 2009 IEEE/ASME International Conference on Advanced Intelligent Mechatronics, Singapore, pp250-255 (July 14-17, 2009).

*Gao, Dalong and Wayne Book, "Steerability in Planar Dissipative Passive Robots." International Journal of Robotics Research, (ijr.sagepub.com), May 19, 2009.

Hughes, K., Jiang, X., "An Integrative Framework to Model Hydraulic Excavator Operator Performance." Proceedings of the Annual Industrial Engineering Research Conference, Miami, Florida (2009).

Hughes, K., Jiang, X., "Quantification Of Operator Workload In Existing & Emergent Fluid Power Systems." Proceedings of the Annual Symposium on Human Interaction with Complex Systems, Greenbelt, MD (2009).

Humphreys, Heather, Wayne Book and James Huggins, "Modeling of Biodynamic Feedthrough in Backhoe Operation." 2009 ASME Dynamic Systems and Control Conference, Hollywood, CA, paper TuBT1.4, (October 12-14, 2009).

Jenkins, Q., Jiang, X., Park, E., Seong, Y., “Development of an Instrument to Measure Operator Trust for Fluid Powered Rescue Robots.” Proceedings of the Annual Industrial Engineering Research Conference, Miami, Florida (2009).

Jenkins, Q., Jiang, X., Seong, Y., Park, E., “Empirical Study Assessing a Survey Instrument Measuring Trust in Human-Robot Interaction.” Proceedings of the Annual Symposium on Human Interaction with Complex Systems, Greenbelt, MD (2009).

*Klop, R. and Ivantysynova, M., "A Method of Characteristics Based Coupled Pump/Line Model to Predict Noise Sources of Hydrostatic Transmissions." Bath ASME Symposium on Fluid Power and Motion Control (FPMC2009), [DSCC2009-2779] (2009).

Lee, Antonio, X. Jiang, Z Jiang, and E. Park, “Using Human Performance Modeling Tool to Predict Fluid Powered Rescue Robot Operator Performance.” Proceedings of the 17th World Congress on Ergonomics, Beijing, China (August 2009).

Liu, Y., Jiang, Z., Jiang, X., “Development of digital Human Model to Evaluate Excavator Operator Performance.” The Journal of Management and Engineering Integration, 2(2): 67-74 (2009).

Maciejewski, N. J., R. B. Sefkow and B. E. Klamecki, “Composite Structure Design of O-Rings Using Material Behavior to Decrease Strain Energy and Permanent Deformation.” ASME Journal of Tribology, 131(4): 042202-1 – 042202-10 (2009).

*Michael, P. Wanke, T. Kimball, A. and Blazel, B., “Atomic Force Microscopy of Geroler Motor Wear Debris Ferrograms;” Journal of ASTM International, 6(1): Paper ID JAI101628, (2009).

*Ngoo, Cheng Shu and Wayne Book, “Digital Clay Force Observer Design and Shape Editing Concept.” 2009 ASME Dynamic Systems and Control Conference, paper TuCT7.2, Hollywood, CA, (October 12-14, 2009).

Ntuen, C. and E. Park, “Predicting Human Reliability under Workload and Skill.” Proceedings of the 10th IFAC Symposium on Information Control Problems in Manufacturing, Seoul, Korea (2009).

*Opdenbosch, Patrick, Nader Sadegh, Wayne Book, Todd Murray and Roger Yang, “Modeling an Electro-Hydraulic Poppet Valve.” International Journal of Fluid Power, Vol 10, No. 1, pp 7-15 (March, 2009).

Osafo-Yeboah, B., Jiang, X., “Human interaction with multimodal Human Machine Interface: Current Status and Research Perspective.” Proceedings of the Annual Symposium on Human Interaction with Complex Systems, Greenbelt, MD (2009).

Osafo-Yeboah, B., Jiang, X., “Usability Evaluation of a Haptically Controlled Excavator Simulation.” Proceedings of the Annual Industrial Engineering Research Conference, Miami, Florida (2009).

*Park, S., Eui Park, and Celestine Ntuen, “New Paradigm of Six Sigma; Knowledge-based Six Sigma." Journal of Total Quality Management & Business Excellence, Taylor & Francis (2009).

R. Wang and P. Y. Li, "Duty Ratio Control of a Rotary PWM valve with Periodic Measurement Error." Proceedings of the 2009 American Control Conference, (Best presentation in session), St. Louis, MO, 2009.

*Rainey, D., Eui Park, Steve Oneyear, and Daniel Mountjoy, “Improving Throughput via Overall Equipment Efficiency (OEE) to Reach Production and Financial Goals.” Proceedings of the 15th International Conference on Industry, Engineering, & Management Systems, Cocoa Beach, Florida (March 2009).

*Rothwell, Rothwell, Eui Park, and Daebeom Kim, “A Sampling Policy for the Reduction of Quality Cost and Improvement of Accepted Percentage in Company L,.” The Asian Journal on Quality, Vol. 10, No 4 (2009).

Salant, R. F. and Yang, B., “Hydraulic Rod Seal with a Mico-Patterned Sealing Surface – Simulation Results.” Ecotrib 09, 2nd European Conference on Tribology, Pisa, Italy, 2009.

Thatte, A. and Salant, R. F., “Elastohydrodynamic Analysis of an Elastomeric Hydraulic Seal during Fully Transient Operation,” Journal of Tribology, Vol. 131, pp. 031501-1 - 031501-11, 2009.

Thatte, A. and Salant, R. F., “Transient EHL Analysis of an Elastomeric Hydraulic Seal.” Tribology International, Vol. 42, pp. 1424-1432, 2009.

V. Durbha and P. Y. Li, "Passive Bilateral Tele-Operation and Human Power Amplification With Pneumatic Actuators." Proceedings of the ASME 2009 Dynamic Systems and Control Conference #2751, DSCC2009/Bath Symposium PTMC, Hollywood, 2009.

Wang, Longke, Wayne Book and James Huggins, “A Control Approach with Applications to Variable Displacement Pumps.” 2009 IEEE/ASME International Conference on Advanced Intelligent Mechatronics, Singapore, pp1862-1867, July 14-17, 2009.

Wang, Longke, Wayne Book and James Huggins, “Adaptive Robust Control of Hydraulic Robots with Recursive Least Squares.” 2009 ASME Dynamic Systems and Control Conference, Hollywood, CA, paper WeAT7.6, (October 12-14, 2009).

Williamson, C., Lee S. and Ivantysynova, M., "Active Vibration Damping for an Off-Road Vehicle with Displacement Controlled Actuators." International Journal of Fluid Power, Vol. 10, No. 3, pp. 5 - 16, (2009).

*Winck, Ryder, Steve Dickerson, Wayne Book and James Huggins, “A Novel Approach to Fabric Control for Automated Sewing.” 2009 IEEE/ASME International Conference on Advanced Intelligent Mechatronics, Singapore, pp. 53-58 (July 14-17, 2009).

Yang, B. and Salant, R. F., “Soft EHL Simulations of U-cup and Step Hydraulic Rod Seals.” Journal of Tribology, Vol. 131, pp. 021501 -1 – 021501-7, 2009.

Yang, B. and Salant, R. F., "Numerical Analysis of a Reciprocating Hydraulic Rod Seal with a Micro-Scale Surface Pattern.” Proceedings of 20th International Conference on Fluid Sealing, BHRG, pp. 109-118, 2009.

Test Beds

R. Chin, E. T. Hsiao-Wecksler, E. Loth, G. Kogler, S. D. Manwaring, S. N. Tyson, K. A. Shorter and J. N. Gilmer, “A pneumatic power harvesting ankle-foot orthosis to prevent foot-drop.” Journal of Neuro-Engineering and Rehabilitation Vol. 6, No. 19, June 2009.

T. P. Sim and P. Y. Li, "Analysis and Control Design of a Hydro-Mechanical Hydraulic Hybrid Passenger Vehicle." Proceedings of the ASME 2009 Dynamic Systems and Control Conference #2763, DSCC2009/Bath Symposium PTMC, Hollywood, CA, 2009.

*** All entries marked with an asterisk represent publications derived from Associated Projects***

Year 5 Annual Report Publications

Thrust 1- Efficiency

Bayer, I., A. Steele, P.F. Martorana and E. Loth "Fabrication of superhydrophobic polyurethane/layered silicate nano-structured composites from cyclomethicone-in-water emulsions." Applied Surface Science , pp. 823-826, Vol. 257, (2010).

*Campanella G., Vacca A. , "Modeling and Optimization of the Control Strategy for the Hydraulic System of an Articulated Boom Lift", Proceedings of SAE 2010 Commercial Vehicle Engineering Congress, October 5-6, 2010, Rosemont, Illinois, USA (2010).

*Casoli P., Vacca A., Anthony A., Berta G.L., "Numerical and Experimental Analysis of the Hydraulic Circuit for the Rear Hitch Control in Agricultural Tractors", Proceedings of 7IFK International Fluid Power Conference, 22-24 March 2010, Aachen, Germany, (2010).

*Casoli P., Vacca A., Greco M., Berta G.L., "Analisi sperimentale e numerica del funzionamento di macchine volumetriche ad ingranaggi esterni" *(in italian),* Proceedings of 65° Congresso Nazionale ATI, 13-17 Settembre 2010, Domus de Maria,Cagliari, Italy (2010).

*Cristofori D., Vacca A., "Analysis of the Dynamics of a Proportional Valve Operated by an Electronic Controller", Proceedings of 6th FPNI – PhD Symposium, June 15-19 2010, West Lafayette (IN), USA (2010).

Deppen, T.O., A.G. Alleyne, K.A. Stelson, J.J. Meyer, "Model Predictive Energy Management of a Hybrid Hydraulic Vehicle," Proceedings of the 6th FPNI PhD Symposium. (2010).

Deppen, T.O., A.G. Alleyne, K.A. Stelson, J.J. Meyer, "Predictive Energy Management for Parallel Hydraulic Hybrid Passenger Vehicle," Proceedings of the ASME Dynamic Systems and Control Conference. DSCC (2010).

Garcia J, A. Martini, and J. Lumkes, "Experimental Measurement of Surface and Lubricant Effects on Static Friction for Metal Contacts." Tribology and Lubrication Technology p 17 (2010).

*Greco M., Vacca A., Casoli P., "Experimental Measurement and Numerical Simulation of the "Inter-Teeth Space Pressure" in External Gear Pumps", Proceedings of 6th FPNI – PhD Symposium, June 15-19 2010, West Lafayette (IN), USA (2010).

*Hencey, B., and A.G. Alleyne, "A Robust Controller Interpolation Design Technique," IEEE Transactions on Control Systems Technology, 18(1): 1-10, (2010)

*Hencey, B., and A.G. Alleyne, "Robust gain-scheduled control," Proceedings of the American Controls Conference, Baltimore, MD (2010).

Kumar, R. and M. Ivantysynova, "The Hydraulic Hybrid Alternative for Toyota Prius - A Power Management Strategy for Improved Fuel Economy," Proceedings of the 7th International Fluid Power Conference Aachen 2010 (7IFK), Vol. 2, pp.329-341, (2010).

Kumar, R. and M. Ivantysynova, "Investigation of Various Power Management Strategies for a Class of Hydraulic Hybrid Powertrains: Theory and Experiments," Proceedings of the 6th FPNI PhD Symposium, West Lafayette, USA, pp 87 – 99, (2010).

Li, P.Y. and F. Mensing, "Optimization and Control of a Hydro-Mechanical Transmission based Hydraulic Hybrid Passenger Vehicle", Proceedings of the 7th International Fluid Power Conference, Aachen, Germany (2010).

Martorana, P., I. S. Bayer, A. Steele, and E. Loth, “Effect of Graphite and Carbon Nanofiber Additives on the Performance Efficiency of a Gear Pump Driven Hydraulic Circuit Using Ethanol” Industrial and Engineering Chemistry Research Vol. 49, pp. 11363–11368 (2010).

Merrill, K., M. Holland, and J. Lumkes, “Efficiency Analysis of a Digital Pump Motor as Compared to a Valve Plate Design,” Proceedings of the 7th International Fluid Power Conference (7.IFK), Aachen, Germany, March 22-24 (2010).

Merrill, K. and J. Lumkes, “Operating Strategies and Valve Requirements for Digital Pump/Motors,” Proceedings of 6th FPNI-PhD Symp. West Lafayette 2010, pp. 249-258 (2010).

Meyer, J. J., K. A. Stelson, A. G. Alleyne and T. O. Deppen, “Energy Management Strategy for a Hydraulic Hybrid Vehicle using Stochastic Dynamic Programming.” In M. Ivantysynova, ed., Sixth Fluid Power Net International Ph.D. Symposium Proceedings, West Lafayette, IN, 15-19 June (2010).

Meyer, J. J., K. A. Stelson, B. Hencey and A. G. Alleyne, “Power Management Strategy for a Hydraulic Hybrid Passenger Vehicle Using Stochastic Dynamic Programming,” Proceedings of the 7th International Fluid Power Conference, Aachen, Germany, 22-24 March (2010).

Michael P., K. Burgess, A. Martini, J.M. Garcia, S. Bair, and M. Devlin, “Lubricant Effects in Hydraulic Motor Starting Efficiency.” Proceedings of the STLE/ASME 2010 International Joint Tribology Conference, San Francisco, California, October 17-20, (2010).

Pelosi, M. and M. Ivantysynova, “A Simulation Study on the Impact of Material Properties on Piston/Cylinder Lubricating Gap Performance,” Proceedings of the 6th FPNI PhD Symposium, West Lafayette, USA, pp 373 – 386, (2010).

Pelosi, M., M. Zecchi, and M. Ivantysynova, “A Fully Coupled Thermo-Elastic Model for the Rotating Kit of Axial Piston Machines,” ASME/ Bath International Symposium on Fluid Power and Motion Control (FPMC2010), pp. 217 – 234, (2010).

Rannow, M., P. Li, T. Chase, H. Tu, and M. Wang, “Optimal design of a high-speed on/off valve for a hydraulic hybrid vehicle application,” Proceedings of the 7th International Fluid Power Conference, Aachen, Germany, (2010).

Steele, A., I. Bayer, A. Cannon, W. King, E. Loth and A. Steele, "Conformal ZnO nanocomposite coatings on micro-patterned surfaces for superhydrophobicity." Thin Solid Films, Vol. 518, pp. 5426-5431 (2010).

Stelson, K. A. and F. Wang, “A Simple Model of Piston-Cylinder Gap Efficiency in Positive-Displacement Hydraulic Pumps and Motors,” Bath/ASME Symposium on Fluid Power & Motion Control (FPMC 2010), 15-17 September 2010, Bath, UK, pp. 417-429 (2010).

*Vacca, A., R. Klop, and M. Ivantysynova, “A numerical approach for the evaluation of the effects of air release and vapour cavitation on effective flow rate of axial piston machines.” International Journal of Fluid Power, Vol. 11, No. 1, pp. 33 – 46 (2010).

Vassena A., Vacca A., “Design Optimization of the Sliding Elements of External Gear Machines”, Proceedings of 6th FPNI – PhD Symposium, June 15-19 2010, West Lafayette (IN), USA (2010).

*Wang, Y., Z. Sun and K. A. Stelson. “Modeling, Nonlinear Tracking Control and Experimental Investigation of a Transient Hydrostatic Dynamometer,” Proceedings of the 2010 American Control Conference, Baltimore, MD 30 June-July 2, (2010).

Wilfong, G., M. Batdorff, and J. Lumkes, “Design and Dynamic Analysis of High Speed on/off Poppet Valves for Digital Pump/Motors,” Proceedings of 6th FPNI-PhD Symposium West Lafayette 2010, pp. 259-269 (2010).

Williamson, C. and M. Ivantysynova, "Power Optimization for Multi-Actuator Pump-Controlled Systems," Proceedings of the 7th International Fluid Power Conference Aachen 2010 (7IFK), Vol 1. pp. 91-102, (2010).

Williamson, C. and M. Ivantysynova, "Stability and Motion Control of Inertial Loads with Displacement Controlled Hydraulic Actuators," Proceedings of the 6th FPNI PhD Symposium, West Lafayette, USA, pp 499 – 514, (2010). Recognized paper.

Zecchi M., Vacca A., Casoli P., "Numerical analysis of the lubricating gap between bushes and gears in external spur gear machines", Proceedings of FPMC 2010 Bath/ASME Symposium on Fluid Power and Motion Control, September 15-17 2010, Bath, UK (2010).

Zimmerman, J. and M. Ivantysynova, "Reduction of Engine and Cooling Power by Displacement Control," Proceedings of the 6th FPNI PhD Symposium, West Lafayette, USA, pp 339 – 352, (2010). Recognized paper.

Thrust 2- Compactness

*Cook, D., B. Knier, V. Gervasi and D. Stahl, "Automatic Generation of Strong, Light, Mutli-Functional Structures from FEA Output," Solid Freeform Fabrication Symposium, Austin, Texas, USA, August (2010).

Kerzhner, A.A. and C.J.J. Paredis, "Model-Based System Verification: A Formal Framework for Relating Analyses, Requirements, and Tests." Proceedings of the Workshop on Multi-Paradigm Modeling (MPM'10), Satellite Event for MODELS'10, Oslo, Norway, October 3 (2010).

Malak, R. J.Jr, and C.J.J. Paredis, "Using Parameterized Pareto Sets to Model Design Concepts." Journal of Mechanical Design 132(4) 041007 (2010).

Malak, R.J. Jr, and C.J.J. Paredis, "Using Support Vector Machines to Formalize the Valid Input Domain of Predictive Models for Systems Design Problems." Journal of Mechanical Design 132(10): 101001 (2010).

Shah, A.A, A.A. Kerzhner, D. Schaefer and C.J.J. Paredis, "Multi-View Modeling to Support Embedded Systems Engineering in SysML." in Gregor Engels, Claus Lewerentz, Wilhelm Schäfer, Andy Schürr, Bernhard Westfechtel (Eds.): Graph Transformations and Model-Driven Engineering - Essays Dedicated to Manfred Nagl on the Occasion of his 65th Birthday, LNCS 5765, Springer-Verlag, Berlin/Heidelberg (2010).

Shah, A.A., C.J.J. Paredis, R. Burkhart, and D. Schaefer, "Combining Mathematical Programming and SysML for Component Sizing of Hydraulic Systems." Proceedings of the ASME 2010 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference (IDTEC/CIE 2010), paper no. DETC2010-28960, Montreal, Quebec, Canada, August 15-18 (2010).

Tian, L., Kittelson, D.B. and Durfee, W.K., "Experimental Tests and Simulations of A 1.5 cc Miniature Glow-Ignition Two-Stroke Engine," Society of Automotive Engineers, #2010-32-0018 (2010).

Vikberg, G. and D. Cook, "Voronoi Diagrams and Stress-Directed Lattice Structures Applied to Weight Reduction," Proceedings of the 6th Fluid Power Net International (FPNI) PhD Symposium. West Lafayette, Indiana (2010).

Wait, K.W. and M. Goldfarb, "Enhancing Performance in Pneumatic Servosystems with Supplemental Mechanical Damping." ASME Journal of Dynamic Systems, Measurement, and Control vol. 132, no. 4, pp. 041012-1-8 (2010).

Willhite, J. A. and Barth, E. J., "Optimization of Liquid Piston Dynamics for Efficiency and Power Density in a Free Liquid Piston Engine Compressor," *Bath/ASME Symposium on Fluid Power and Motion Control (FPMC 2010)*, pp. 461-473, September 15-17. Bath, U K (2010).

Willhite, J. A. and Barth, E. J., “Experimental Characterization of Critical Dynamic Model Parameters for a Free Liquid Piston Engine Compressor”. *6th Fluid Power Net International Ph.D. Symposium.* Vol. 2, Session 7, pp.425-433, June 15-19, West Lafayette, ID (2010).

Zhu, Y. and Barth, E. J., “Accurate Sub-millimeter Servo-Pneumatic Tracking using Model Reference Adaptive Control (MRAC)”. *International Journal of Fluid Power*, vol. 11, no. 2, pp. 43-55 (2010).

Thrust 3- Effectiveness

Bair, S., “The Dependence of the Dynamic Properties of Elastohydrodynamic Liquids on Temperature and Pressure (Volume).” Proc. I. Mech. E., Part C, Journal of Engineering Science 224(12): 2568-2576 (2010).

Bair, S and P. Michael, “Modeling the Pressure and Temperature Dependence of Viscosity and Volume for Hydraulic Fluids.” International Journal of Fluid Power 11: 37-42 (2010).

Chung, C., X. Jiang, Z. Jiang, and S. Udoka, “Using Digital Human Modeling to Predict Operator Performance of a Compact Rescue Crawler,” Proceedings of the 2010 Industrial Engineering Research Conference, Cancun, Mexico, June 5-9, (2010).

Daepp, H., W. Book, T.Y. Kim and P. Radecki “An Interactive Simulation for a Fluid-Powered Legged Search and Rescue Robot,” Proceedings of 2010 International Symposium on Flexible Automation, Tokyo, Japan, July 12-14, (2010).

Delpish, R., X. Jiang, E. Park, S. Udoka, and Z. Jiang, “Development of a User-Centered Framework for Rescue Robot Interface Design,” Proceedings of the 2010 Industrial Engineering Research Conference, Cancun, Mexico, June 5-9, (2010).

Durbha V. and P. Y. Li, “Independent Metering of Pneumatic Actuator for Passive Human Power Amplification,” Proceedings of the 2010 American Control Conference, Baltimore MD (2010).

Earnhart, N, K. Marek, and K.A. Cunefare, “Evaluation of hydraulic silencers,” Proceedings of Noise-Con 2010, joint with the 159th Meeting of the Acoustical Society of America, Baltimore, MD, U.S.A, 19-23 April, (2010).

Elton, M. and W. Book, “Operator Efficiency Improvements From Novel Human-Machine Interfaces,” Proceedings of the 6th FPNI-PhD Symposium, West Lafayette, Indiana, June 15-19 2010, pp.315-322.

Enes, A., "Towards Shared Control of Hydraulic Excavators," in Fluid Power Net International 6th Annual PhD Symposium, West Lafayette, IN, July 2010.

Enes, A. and W. Book, “Blended Shared Control of Zermelo's Navigation Problem,” Proceedings, 2010 American Control Conference, Baltimore, MD, June 30-July 1, (2010).

Enes, A. and W. Book, “Optimum Point to Point Motion of Net Velocity Constrained Manipulators,” 2010 IEEE Conference on Decision and Control, Atlanta, GA, Dec. 15-17 (2010).

Franklin, C. and Z. Jiang, "Applying the Learning Curve to the Haptic Feedback Controller." Proceedings of the 16th International Conference on Industry, Engineering, & Management Systems, Cocoa Beach, FL (2010).

Hughes, K., X. Jiang, Z. Jiang, D. Mountjoy, and E. Park, “A Preliminary Study of an Integrated Human Performance Model“, Proceedings of the 2010 Industrial Engineering Research Conference, Cancun, Mexico, June 5-9, (2010).

Hughes, K., and X. Jiang, “Using Discrete Event Simulation to Model Excavator Operator Performance.” International Journal of Human Factors and Ergonomics in Manufacturing and Service Industries 20(5), 408-423 (2010).

Humphreys, H. C. and W. J. Book, "Possible Methods for Biodynamic Feedthrough Compensation in Backhoe Operation," in Fluid Power Net International 6th Annual PhD Symposium West Lafayette, IN, July (2010).

Jenkins, Q., X. Jiang, “Measuring Trust and Application of Eye Tracking in Human Robotic Interaction,” Proceedings of the 2010 Industrial Engineering Research Conference, Cancun, Mexico, June 5-9, (2010).

*Klop, R. and M. Ivantysynova, “Sound Intensity Measurements to Investigate Noise Generation of Hydrostatic Transmissions,” Proceedings of the 7th International Fluid Power Conference Aachen 2010 (7IFK), Vol. 2, 229-242, (2010).

*Klop, R. and M. Ivantysynova, “Validation of a Coupled Pump-Motor-Line Model to Predict Noise Sources of Hydrostatic Transmissions,” Proceedings of the 6th FPNI PhD Symposium, West Lafayette, USA, pp 665 – 680, (2010).

Kumar, P., S. Bair and I. Krupka, “Newtonian Elastohydrodynamic Film Thickness with Linear Piezoviscosity.” Tribology International 43(11): 2159-2165 (2010).

Kumar, P., M.M. Khonsari and S. Bair, “Anharmonic Variations in Elastohydrodynamic Film Thickness Resulting from Harmonically Varying Entrainment Velocity.” Proc. I. Mech. E., Part J, Journal of Engineering Tribology 224(J3): 239-248 (2010).

Liu, Y., X. Jiang, Z. Jiang, and E. Park, “Predicting Backhoe Excavator Operator Performance Using Digital Human Modeling,” Proceedings of the 2010 Industrial Engineering Research Conference, Cancun, Mexico, June 5-9, (2010).

Marek, K., N. Earnhart, and K.A. Cunefare, “Numerical model for a hydraulic in-line silencer,” Proceedings of Noise-Con 2010, 159th Meeting of the Acoustical Society of America, Baltimore, MD, U.S.A., 19-23 April, (2010).

Martini, A. and S. Bair, “The role of Fragility in EHL Entrapment.” Tribology International 43: 277–282 (2010).

Osafo-Yeboah, B., M. Elton, X. Jiang, W. Book, and E. Park, “Usability Evaluation of a Coordinated Excavator Controller with Haptic Feedback,” Proceedings of the 2010 Industrial Engineering Research Conference, Cancun, Mexico, June 5-9, (2010).

Salant, R. F., B. Yang and A. Thatte, “Simulation of Hydraulic Seals.” Journal of Engineering Tribology 224: 865-876 (2010).

Thatte, A. and R.F. Salant, “Visco-Elastohydrodynamic Model of a Hydraulic Rod Seal During Transient Operation.” Journal of Tribology 132: 041501-1 – 041501-13 (2010).

Yang, B. and R.F. Salant, “EHL Simulation of O-ring and U-cup Hydraulic Seals,” Proceedings of Nordtrib 2010, 14th Nordic Symposium on Tribology, Lulea, Sweden (2010).

Young, A. and S. Bair, “Experimental Investigation of Friction in Entrapped Elastohydrodynamic Contacts.” Tribology International 43(9): 1615–1619 (2010).

Test Beds and General

Hsiao-Wecksler, E. T., E. Loth, G.F. Kogler, K.A. Shorter, J.A. Thomas, and J.N. Gilmer, “Portable Active Pneumatically Powered Ankle-Foot Orthosis,” United States Patent Pending (12/898,519).

Ivantysynova, M., “Maha Fluid Power Research Center – Future Trends in Fluid Power.” Journal of the Japan Fluid Power System Society, Vol. 41, No 1, pp. 31 – 34 (2010). – invited paper.

Stelson, K. A., “Center for Compact and Efficient Fluid Power (CCEFP), A National Science Foundation Engineering Research Center, United States,” Journal of the Japan Fluid Power Society, Vol. 41, No. 1, Jan. 2010, pp. 60-63.

Li, Y., K.A. Shorter, T. Bretl, and E.T. Hsiao-Wecksler, “Modeling and Control of a Portable Powered Ankle Foot Orthosis,” 6th Annual FPNI – PhD Symposium, West Lafayette, Indiana, June 15-19, (2010).

Morris, E.A., and E.T. Hsiao-Wecksler, “Time normalizing gait data based on gait events,” 34th Annual Meeting of the American Society of Biomechanics, Providence, RI, August 18-21, (2010).

Shorter, K.A., G.F. Kogler, E. Loth, W.K. Durfee, and E.T. Hsiao-Wecksler, “A pneumatically powered portable ankle-foot orthosis,” 34th Annual Meeting of the American Society of Biomechanics, Providence, RI, August 18-21, (2010).

Shorter, K.A., E.A. Morris, Y. Li, and E.T. Hsiao-Wecksler, “A Pneumatically Powered Portable Ankle-Foot Orthosis,” presented at the 4th Annual Symposium of the Center on Health, Aging and Disability, University of Illinois, Urbana, IL, December 9, 2010.

Year 6 Annual Report Publications

Thrust 1 – Efficiency

Burgess, K; Michael, P; Wanke, T; Ziemer, C; "Starting Efficiency in Hydraulic Motors," Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 9.1 (2011)

*Campanella, G; and Vacca, A; "Modellazione numerica di un distributore Flow Sensing," Oleodinamica e Pneumatica, Tecniche Nuove, Milano, Italy (2011).

*Casoli, P; Greco, M; Vacca, A; and Lettini, A; "Sistema telemetrico per acquisizione della pressione nel vano," Oleodinamica e Pneumatica, Tecniche Nuove, Milano, Italy (2011).

Chase, T; and Fikru, N; "A Review of MEMS Based Pneumatic Valves," Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 11.2 (2011)

*Cristofori, D; Vacca, A; "Electro-Hydraulic Proportional Valve Modeling Comprehending Magnetic Hysteresis," Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 28.1 (2011)

Cross, M; and Ivantysynova, M; "Practical Considerations for Pump / Motor Selection in Hydraulic Hybrid Vehicles," Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 11-2.3 (2011).

Deppen, T; Alleyne, A; Stelson, K; and Meyer, J; "A Model Predictive Control Approach for a Parallel Hydraulic," Proceedings of the American Control Conference, ACC (2011).

Deppen, T; Alleyne, A; Stelson, K; and Meyer, J; "Model Predictive Control of An Electro-Hydraulic Powertrain with Energy Storage," Proceedings of the ASME Dynamic Systems and Control Conference, DSCC (2011).

*Ganesh, K; Minming, Z; and Ivantysynova, M; "Effect of Combining Precompression Grooves, PCFV and DCFV on Pump Noise Generation," International Journal of Fluid Power, 12 (3):53-64 (2011)

Garcia, J; Lumkes, J; Heckaman, B; and Martini, A; "Viscosity dependence of static friction in lubricated metallic line contacts," Tribology Transactions, 54:333 (2011)

Garcia, J; Lumkes, J; and Martini, A; "Static friction characterization of metallic contacts with hydraulic fluids," Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 39.2 (2011)

Habchi, W; Vergne, P; Fillot, N; Bair, S; and Morales-Espejeld, G; "A Numerical Investigation of the Local Behavior of TEHD Highly Loaded Circular Contacts," Tribology International, 44:1987-1996 (2011)

*Ivantysynova, M; and Seeniraj, G; "A Multi-Parameter Multi-Objective Approach to Reduce Pump Noise Generation," International Journal of Fluid Power, 12(1):7-17 (2011)

*Klop, R; and Ivantysynova, M; "Investigation of Noise Sources on a Series Hybrid Transmission," International Journal of Fluid Power, 12(3):17-30 (2011)

Kumar, R; and Ivantysynova, M; "Instantaneous Optimization Based Power Management Strategy to Reduce Fuel Consumption in Hydraulic Hybrids," International Journal of Fluid Power, 12 (2):15-25 (2011)

Li, P; Loth, E; Simon, T; and Van de Ven, J; "Compressed Air Energy Storage for Offshore Wind Turbines," 2011 International Fluid Power Exhibition (IFPE) (2011)

Merrill, K; Holland, M; and Lumkes, J; "Analysis of Digital Pump/Motor Operating Strategies," Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 1.1 (2011)

Meyer, J; Stelson, K; “Developing an Energy Management Strategy for a Four-Mode Hybrid Passenger Vehicle,” Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 6.2 (2011)

Michael, P; Guevremont, JK; Devlin, M; and Ziemer, C; “Tribological Film Formation in Hydraulic Motors,” Proceedings of the STLE/ASME International Joint Tribology Conference, Paper IJTC2011-61029 (2011)

Pedchencko, A. V.; Barth, E. J.; "Finite Element Model-based Design of a Hyperelastic Strain Energy Hydraulic Accumulator"; Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 14.3 (2011)

Rice, A; Li, P; “Optimal Efficiency-Power Tradeoff for an Air Motor/Compressor with Volume Varying Heat Transfer Capability,” ASME DSCC 2011/Bath Symposium on PTMC, Arlington, VA, (2011)

*Rose, J; and Ivantysynova, M; “A Study of Pump Control Systems for Smart Pumps,” Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; I11-27.1 (2011)

Schenk, A; Ivantysynova, M; “An Investigation of the Impact of Elastohydrodynamic Deformation on Power Loss in the Slipper Swashplate Interface,” Proceedings of 8th JFPS Int Symp on Fluid Power, Okinawa, Japan. (2011)

Schenk, A; Ivantysynova, M; “Design and Optimization of the Slipper-Swashplate Interface Using an Advanced Fluid-Structure-Interaction Model,” Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 4.2. (2011)

*Schweiger, W., Schoefmann, W., and Vacca, A., "Gerotor Pumps for Automotive Drivetrain Applications: A Multi Domain Simulation Approach," SAE Int. J. of Passeng. Cars – Mech. Syst. 4(3):1358-1376, doi:10.4271/2011-01-2272 (2011).

Stelson, K; “Saving Energy by Advancing Fluid Power Technology,” Fluid Power Journal, March/April, 4 (2011)

Thul, B.; Dutta, R.; Stelson, K.; “Hydrostatic Transmission for Mid-Size Wind Power,” Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 40.2 (2011)

Tu, H; Rannow, M; Wang, M; Li, P; Chase, T; “High-speed 4 way rotary on/off valve for virtually variable displacement pump/motor applications,” ASME DSCC 2011/Bath Symposium on PTMC, Arlington, VA (2011)

Tu, H; Rannow, M; Wang, M; Li, P; and Chase, T; “The Advantages and Feasibility of Externally Actuating a High-speed Rotary On/Off Valve,” Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 20.3 (2011)

*Vacca A; Dhar S; and Opperwall T; “A Coupled Lumped Parameter and CFD Approach for Modeling External Gear Machines,” Proceedings of The Twelfth Scandinavian International Conference on Fluid Power, May 18-20, Tampere, Finland (2011)

*Vacca, A; and Guidetti, M; “Modelling and Experimental Validation of External Spur Gear Machines for Fluid Power Applications,” Elsevier Simulation Modelling Practice and Theory, 19 (2011)

Wang, F.; Randan, M.; and Stelson, K.; “Comparison between Hydraulic Hybrid and Electric Hybrid Passenger Vehicle using ADVISOR 2004,” Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 2.2 (2011)

Wang, M; Li, P; Tu, H; and Rannow, M; “Direct Displacement Control of Hydraulic Actuators Based on a Self-Spinning Rotary On/Off Valve,” 2011 International Fluid Power Exhibition (IFPE) (2011)

Wilfong,G; Holland, M; and Lumkes, J; "Design and Analysis of Pilot Operated High Speed On/Off Valves for Digital Pump/Motors," Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 20.1 (2011)

Yong, Chao; Barth, Eric J.; "A Virtual-Cam Control Methodology for Free-Piston Engines", ASME DSCC 2011/Bath Symposium on PTMC, Arlington, VA; TuAT1.2 (2011)

Yong, C.; Willhite, J. A.; Barth, E. J; "A Virtual-Cam Control Methodology for a Novel Free-Liquid-Piston Engine Compressor"; Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 3.3 (2011)

Zecchi, M; and Ivantysynova, M; "A Novel Fluid Structure Interaction Model for the Cylinder Block/Valve Plate Interface of Axial Piston Machines," Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; I11-9.2 (2011)

Zimmerman, J.; Busquets E.; and Ivantysynova, M.; "40% Fuel Savings by Displacement Control Leads to Lower Working Temperatures: A Simulation Study and Measurements," Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 27.2 (2011)

Zimmerman, J; Hippalgaonkar, R; and Ivantysynova, M; "Optimal Control for the Series-Parallel Displacement Controlled Hydraulic Hybrid Excavator," ASME/Bath Symposium on Fluid Power and Motion Control, Arlington, VA; TuBT1.4 (2011)

Thrust 2 – Compactness

Comber, D; Barth, E; "Precision Position Tracking of MR-Compatible Pneumatic Piston-Cylinder Using Sliding Mode Control," Proceedings of the 4th Annual Dynamic Systems and Control Conference, Arlington, VA; TuAT1.1 (2011).

Cook, D; Vito, G; "High-Performance, Multi-Functional, Fluid-Power Components Using Engineered Materials," 52nd National Conference on Fluid Power, Las Vegas, NV; 36.4 (2011)

Kerzhner, A; and Paredis, C; "A Formal Framework for Capturing Knowledge for Transforming Structural Models into Analysis Models," Journal of Simulation, 5: 202-216 (2011)

Kerzhner, A; and Paredis, C; "Model-Based System Verification: A Formal Framework for Relating Analyses, Requirements and Tests," Workshops and Symposia at MODELS 2010, Reports & Revised Selected Papers, Springer-Verlag, Berlin/Heidelberg, 6627:279-292 (2011)

Li, K; Sun, Z; "Modeling and Control of a Hydraulic Free Piston Engine with HCCI Combustion," Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 21.1 (2011)

Li, K; Sun, Z; "Stability Analysis of a Hydraulic Free Piston Engine with HCCI Combustion," Proceedings of the 4th Annual Dynamic Systems and Control Conference, Arlington, VA; WeAT2.4 (2011)

Min, B; Kerzhner, A; and Paredis, C; "Process Integration and Design Optimization for Model-Based Systems Engineering with SysML," Proceedings of ASME IDETC/CIE; Aug 28; DETC2011-48453 (2011)

Moore, R; Paredis, C; and Romero, D; "A Rational Design Approach to Gaussian Process Modeling for Variable Fidelity Models," Proc ASME IDETC/CIE, DETC2011-48227 (2011)

Turkseven, M; Ueda, J; "Design of an MRI Compatible Haptic Interface," Proceedings of the 2011 IEEE International Conference on Intelligent Robots and Systems, San Francisco, CA; pp.2139 – 2144, 10.1109/IROS.2011.6095170 (2011)

Ueda, J; Turkseven, M; “Development of a Pneumatically Driven MRI-compatible Haptic Device,” Proceeding of the 29th Annual Conference of the Robotics Society of Japan, Tokyo, Japan (2011)

Thrust 3 – Effectiveness

Bair, S; and Laesecke, A; “High Pressure Viscosity Measurements of 1, 1, 1, 2-Tetrafluoroethan,” International Journal of Thermophysics, 32(5):925-941 (2011)

Bair, S; and Laesecke, A; “Normalized Ashurst-Hoover Scaling and a Comprehensive Viscosity Correlation for Compressed Liquids,” ASME J. Tribol (2011)

Casoli, P; Vacca, A; Anthony, A; and Berta, G; “Modellazione della Valvola di Controllo di un Sollevatore Agricolo,” Oleodinamica e Pneumatica, Tecniche Nuove, Milano, Italy (2012)

*Cook, D; Newbauer, S; Pettis, S; Knier, B; Kumpaty, S; “Effective Thermal Conductivities of Unit-Lattice Structures for Multi-Functional Components,” Proceedings of the 22nd Annual International Solid Freeform Fabrication Symposium (2011)

Cristofori, D; and Vacca, A; “The Modeling of Electro-Hydraulic Proportional Valves,” ASME Journal of Dynamic Systems, Measurement and Control, 134 (2): 13 (2011)

Cunefare, K; Earnhart, N; and Marek K; “Novel, compact devices for reducing fluid-borne noise,” Proceedings of the SAE 2011 Noise and Vibration Conference and Exhibition (2011)

Cunefare, K; Earnhart, N; and Marek K; “Passive Noise Control in Fluid Power,” Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV (2011)

Cunefare, K; Earnhart, N; Marek K; Walsh, M; and Edirisinghe, R; “Noise control devices for fluid systems,” Noise-Con Proc. 129:877 (2011)

Earnhart, N; and Cunefare, K; “Cancelling noise at its source,” Hydraulics & Pneumatics (2011)

Elton, M; and Book, W; “An Excavator Simulator for Determining the Principles of Operator Efficiency for Hydraulic Multi-DOF Systems,” Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 18.3 (2011)

Elton, M; and Book, W; “Comparison of Human-Machine Interfaces Designed for Novices Teleoperating Multi-DOF Hydraulic Manipulators,” 20th IEEE International Symposium on Robot and Human Interactive Communication (2011)

Franklin, C.; Jiang, Z; and Jiang, X; “Learning Curve Analysis of a Haptic Controller,” The journal of Management and Engineering Integration, 4(1):63-70 (2011)

Hughes, K; Jiang, S; Jiang, Z; Park, E; and Mountjoy, D; “Assessment of Excavator Operator Performance Using an Integrated Human Performance Model,” The journal of Management and Engineering Integration, 4(1): 88-98 (2011)

Humphreys, H.; Book, W.; Huggins, J.; “Biodynamic Feedthrough Compensation and Experimental Results Using a Backhoe” Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 22.3 (2011)

Humphreys, H.; Book, W.; Huggins, J.; “Compensation for Biodynamic Feedthrough in Backhoe Operation by Cab Vibration Control,” Proceedings of the IEEE International Conference on Robotics and Automation, Shanghai, China; (2011)

*Michael, P; Blazel, B; Reuchel, R; Harville, X; “Hydraulic Fluid Compatibility and Filterability,”; Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 35.2, (2011) Mizumoto, H; Daepp, H; Book, W; Matsuno, F; "Teleoperation system using past image records for legged robot," 9th IEEE International Symposium on Safety, Security, and Rescue Robotics (2011)

*Newbauer, S; Cook, D; and Pettis, D; "Multifunctional Components Using Engineered Lattice Structures as Materials," Proceedings of the 2011 COMSOL Conference in Boston (2011)

Yang, B; and Salant, R; "EHL Simulation of O-ring and U-cup Hydraulic Seals," Journal of Engineering Tribology, 225:603-610 (2011)

Testbeds and General

Cheong, K; Li, P; Chase. T; "Optimal Design of Power-Split Transmission for Hydraulic Hybrid Passenger Vehicles," Proceedings of the 2011 American Control Conference, San Francisco, CA; pp. 3295 – 3300, (2011)

Cheong, K; Li, P; Sedler, S; Chase. T; "Comparison between input coupled and output coupled power-split configurations in hybrid vehicles," Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 10.3 (2011)

Chipalkatty,R; Daepp, H; Egerstedt, M; Book, W; "Human-in-the-Loop: MPC for Shared Control of a Quadruped Rescue Robot," IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) (2011)

Daepp, H; Book, W; "Modeling and Simulation of a Pneumatically-Actuated Rescue Robot," Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 3.2 (2011)

Durfee, W.K; Kogler, G.; Morris, E.; Hsiao-Wecksler, E.; "Actuation Timing Strategies for a Portable Powered Ankle-Foot Orthosis," Proceedings of the ASME Dynamic Systems and Control Conference (2011).

Li, D; Becker, A; Shorter, K; Bretl, T; and Hsiao-Wecksler, E; "Estimating System State During Human Walking with a Powered Ankle-Foot Orthosis," IEEE/ASME Transactions on Mechatronics (2011).

Li, Y; Morris, E; Shorter, K; Hsiao-Wecksler, E; "Energy Efficiency Analysis of A Pneumatically-Powered Ankle-Foot Orthosis," Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 3.1 (2011)

Mensing, F; Li, P; "Sizing and Optimal Operation of a Power Split Hydraulic Hybrid Drive Train," Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 10.2 (2011)

Michael, P; Wanke, T; "Hydraulic Fluid and System Standards, Chapter 7," Handbook of Hydraulic Fluid Technology, 2nd Edition, (2012)

Mishler, L; Garcia, J; Lumkes, J; "Engaging Pre-College Students in Engineering Using Hands-on Micro-Processor Controlled Portable Fluid Power Demonstrators," ASABE Annual International Meeting, Louisville, KY; 1111500; (2011)

Shorter, K; Hsiao-Wecksler, E; Kogler, G; Loth, E; and Durfee, W; "A Portable Powered Ankle-Foot-Orthosis for rehabilitation," Journal of Rehabilitation Research & Development (2011).

Shorter, K; Li, Y; Morris, E; Kogler, G; Hsiao-Wecksler, E; "Experimental Evaluation of a Portable Powered Ankle-Foot Orthosis," 33rd Annual International IEEE EMBS Conference, Boston, MA; pp. 624 – 627; 10.1109/IEMBS.2011.6090138 (2011)

Year 7 Annual Report Publications

Thrust 1 – Efficiency

Bair, S. and Michael, P. "Modeling the Pressure and Temperature Dependence of Viscosity and Volume for Hydraulic Fluids." International Fluid Power Journal, 2: No. 11: 37-42 (2010)

Bayer, I.; Steele A.; Martorana P.F.; Loth E.; "Fabrication of Superhydrophobic Polyurethane/Layered Silicate Nano-Structured Composites from Cyclomethicone-in-Water Emulsions." Applied Surface Science, 257: 823-826 (2010).

Burgess, K; Michael, P; Wanke, T; Ziemer, C; "Starting Efficiency in Hydraulic Motors," Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 9.1 (2011)

*Campanella, G; and Vacca, A; "Modellazione numerica di un distributore Flow Sensing," Oleodinamica e Pneumatica, Tecniche Nuove, Milano, Italy (2011).

*Casoli, P; Greco, M; Vacca, A; and Lettini, A; "Sistema telemetrico per acquisizione della pressione nel vano," Oleodinamica e Pneumatica, Tecniche Nuove, Milano, Italy (2011).

Chase, T; and Fikru, N; "A Review of MEMS Based Pneumatic Valves," Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 11.2 (2011)

Cristofori D; Vacca A; "Adaptive Vibration Damping Method for Hydraulic Machines: the Case of a Hydraulic Crane," 7th FPNI PhD Symposium on Fluid Power, 27-30 June (2012)

Cristofori, D; Vacca, A; "Electro-Hydraulic Proportional Valve Modeling Comprehending Magnetic Hysteresis," Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 28.1 (2011)

Cross, M; and Ivantysynova, M; "Practical Considerations for Pump / Motor Selection in Hydraulic Hybrid Vehicles," Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 11-2.3 (2011)

Cunefare K; Skow, E; Erturk A; Savor J; Verma N; Cacan M; "Energy harvesting from hydraulic pressure fluctuations," Smart Mater. Struct. 22 025036 (2013)

Deppen, T; Alleyne, A; Stelson, K; and Meyer, J; "A Model Predictive Control Approach for a Parallel Hydraulic Hybrid Powertrain," Proceedings of the American Control Conference, ACC (2011).

Deppen, T; Alleyne A; Stelson K; Meyer J; "An Energy Management Strategy for a Hydraulic Hybrid Vehicle," Proceedings of the American Control Conference, ACC (2012)

Deppen, T; Alleyne, A; Stelson, K; and Meyer, J; "Model Predictive Control of An Electro-Hydraulic Powertrain with Energy Storage," Proceedings of the ASME Dynamic Systems and Control Conference, DSCC (2011).

Deppen, T; Alleyne A; Stelson K; Meyer J; " Model Predictive Energy Management of a Hybrid Hydraulic Vehicle," Proceedings of the 6th Fluid Power Net International Ph.D. Symposium (2010)

Deppen, T; Alleyne A; Stelson K; Meyer J; "Optimal Energy Use In a Light Weight Hydraulic Hybrid Passenger Vehicle", Journal of Dynamic Systems, Measurements and Control, 134: No. 4 (2012)

Deppen, T; Alleyne A; Stelson K; Meyer J; "Predictive Energy Management for Parallel Hydraulic Hybrid Passenger Vehicle" Proceedings of the ASME Dynamic Systems and Control Conference, DSCC (2010)

Deppen, T; Alleyne A; Stelson K; Meyer J; "Sensitivity Analysis of Energy Management Strategies For Hydraulic Hybrid Vehicles," Proceedings of the ASME Dynamic Systems and Control Conference, DSCC (2012)

Devendran, R; Vacca, A; “Fuel Savings of a mini-excavator through a hydraulic hybrid displacement controlled system,” FPMC 2012 Bath/ASME Symposium on Fluid Power and Motion Control (2012)

Dhar S; Vacca A; Lettini A; “A Fluid Structure Interaction Model to Analyze Axial Balance in External Gear Machines,” 8IFK International Fluid Power Conference, 26th - 28th March (2012)

Dhar S; Vacca A; Lettini A; “A Novel Elastohydrodynamic Model for the Lubricating Gaps in External Gear Machines: Evaluation of Axial Balance,” 7th FPNI PhD Symposium on Fluid Power, 27-30 June (2012)

Dutta, R; Wang, F; Bohlmann, B; Stelson, K; “Analysis of Short-term Energy Storage for Mid-Size Hydrostatic Wind Turbine,” ASME Dynamic Systems and Control Conference (2012)

*Ganesh, K; Minming, Z; and Ivantysynova, M; “Effect of Combining Precompression Grooves, PCFV and DCFV on Pump Noise Generation,” International Journal of Fluid Power, 12 (3):53-64 (2011)

Garcia, J; Lumkes, J; Heckaman, B; and Martini, A; "Viscosity dependence of static friction in lubricated metallic line contacts,” Tribology Transactions, 54:333 (2011)

Garcia, J; Lumkes, J; and Martini, A; “Static friction characterization of metallic contacts with hydraulic fluids,” Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 39.2 (2011)

Habchi, W; Vergne, P; Fillot, N; Bair, S; and Morales-Espejeld, G; “A Numerical Investigation of the Local Behavior of TEHD Highly Loaded Circular Contacts,” Tribology International, 44:1987-1996 (2011)

Herzog, S.N. and Michael, P. “Hydraulic Fluids That Improve Fuel Economy.” Machine Design Vol. 82: No. 16: 2-55 (2010)

Hippalgaonkar, R; Ivantysynova, M; Zimmerman, J; “Fuel Savings of a mini-excavator through a hydraulic hybrid displacement controlled system,” Proceedings of the 8th International Conference on Fluid Power, 2:39-54 (2012)

Hippalgaonkar, R; Ivantysynova, M; Zimmerman, J; “Investigation Of Power Management Strategies For A Multi-Actuator Hydraulic Hybrid Machine System,” SAE 2011 Commercial Vehicle Engineering Congress (2011)

Holland, M; Lumkes, J. J; “Test Stand Development for Investigating Digital Pump/Motor Operating Strategies,” Proceedings of the 6th FPNI - PhD Symposium (2010)

Holland, M; Wilfong, G; Merrill,K; Lumkes, J. Jr; “Experimental Evaluation of Digital Pump/Motor Operating Strategies with a Single-Piston Pump/Motor,” Proceedings of the 52nd National Conference on Fluid Power (2012)

Ivantysynova, M; Pelosi, M; “Heat Transfer and Thermal Elastic Deformation Analysis on the Piston/Cylinder Interface of Axial Piston Machines (2012)

Ivantysynova, M; and Seeniraj, G; “A Multi-Parameter Multi-Objective Approach to Reduce Pump Noise Generation,” International Journal of Fluid Power, 12(1):7-17 (2011)

*Klop, R; and Ivantysynova, M; “Investigation of Noise Sources on a Series Hybrid Transmission,” International Journal of Fluid Power, 12(3):17-30 (2011)

Kumar, R; and Ivantysynova, M; “Instantaneous Optimization Based Power Management Strategy to Reduce Fuel Consumption in Hydraulic Hybrids,” International Journal of Fluid Power, 12 (2):15-25 (2011)

Li, P; Loth, E; Simon, T; and Van de Ven, J; “Compressed Air Energy Storage for Offshore Wind Turbines,” 2011 International Fluid Power Exhibition (IFPE) (2011)

Merrill, K; Lumkes, J; “Operating Strategies and Valve Requirements of Digital Pump/Motors,” Proceedings of the 6th Fluid Power Net International PhD Symposium (2010)

Merrill, K; Holland, M; Batdorff, M; Lumkes, J; “Comparative Study of Digital Hydraulics and Digital Electronics,” International Journal of Fluid Power, 11:3:45-51 (2010)

Merrill, K; Holland, M; and Lumkes, J; “Analysis of Digital Pump/Motor Operating Strategies,” Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 1.1 (2011)

Merrill, K; Holland, M; and Lumkes, J; “Efficiency Analysis of a Digital Pump/Motor as Compared to a Valve Plate Design,” Proceedings of the 7th International Fluid Power Conference (2010)

Meyer, J; Stelson, K; “Developing an Energy Management Strategy for a Four-Mode Hybrid Passenger Vehicle,” Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 6.2 (2011)

Meyer, J; Stelson, K; Alleyne, A; Deppen, T; “Energy Management Strategy for a Hydraulic Hybrid Vehicle Using Stochastic Dynamic Programming,” Proceedings of the 6th Fluid Power Net International Ph.D. Symposium (2010)

Meyer, J; Stelson, K; Alleyne, A; Deppen, T; “Power Management Strategy for a Parallel Hydraulic Hybrid Passenger Vehicle Using Stochastic Dynamic Programming,” Proceedings of the 7th International Fluid Power Conference (2010)

Michael, P; Burgess, K; Martini, A; Garcia, J; Bair, S; “Effects in Hydraulic Motor Starting Efficiency.” Proceedings of the STLE/ASME International Joint Tribology Conference, Paper IJTC2010-41262 (2010)

Michael, P; Guevremont, JK; Devlin, M; and Ziemer, C; “Tribological Film Formation in Hydraulic Motors,” Proceedings of the STLE/ASME International Joint Tribology Conference, Paper IJTC2011-61029 (2011)

Michael, P; Garcia, J; Bair, S; Devlin M; Martini, A; “Lubricant Chemistry and Rheology Effects on Hydraulic Motor Starting Efficiency,” STLE Tribology Transactions (2012)

Michael, P; Khalid, H; Wanke, T; “An Investigation of External Gear Pump Efficeincy and Stribeck Values,” Proceedings of SAE Commercial Vehicle Conference (2012)

Michael, P. Wanke, T. Devlin, M. et.al. “An Investigation of Hydraulic Fluid Properties and Low-Speed Motor Efficiency” Proceedings of the 7th International Fluid Power Conference, Aachen, Germany, Vol. 3: 341-353 (2010)

Pedchencko, A. V.; Barth, E. J.; "Finite Element Model-based Design of a Hyperelastic Strain Energy Hydraulic Accumulator"; Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 14.3 (2011)

Ramesh, A; Polycarpou, A; King, W; “Friction characteristics of microtextured surfaces under mixed and hydrodynamic lubrication,” Tribology International (2012)

Rannow, M; Li, P; “Soft Switching Approach to Reducing Transition Losses in an On/Off Hydraulic Valve,” ASME Journal of Dynamic Systems Measurement and Control (2012)

Rannow, M; Tu, H; Wang, M; Li, P; Chase, T; “Optimal Design of a High-Speed On/off Valve for a Hydraulic Hybrid Vehicle Application,” Proceedings of the 7th International Fluid Power Conference, Aachen (2010)

Rice, A; Li, P; “Optimal Efficiency-Power Tradeoff for an Air Motor/Compressor with Volume Varying Heat Transfer Capability,” ASME DSCC 2011/Bath Symposium on PTMC, Arlington, VA, (2011)

*Rose, J; and Ivantysynova, M; “A Study of Pump Control Systems for Smart Pumps,” Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; I11-27.1 (2011)

Saadat, M; Li, P; “Modeling and Control of a Novel Compressed Air Energy Storage System for Offshore Wind Turbine,” American Control Conference (2012)

Schenk, A; Ivantysynova, M; “An Investigation of the Impact of Elastohydrodynamic Deformation on Power Loss in the Slipper Swashplate Interface,” Proceedings of 8th JFPS Int Symp on Fluid Power, Okinawa, Japan. (2011)

Schenk, A; Ivantysynova, M; “Design and Optimization of the Slipper-Swashplate Interface Using an Advanced Fluid-Structure-Interaction Model,” Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 4.2. (2011)

Schenk, A; Ivantysynova, I; “The influence of swashplate elastohydrodynamic deformation,” Proc. of the 7th FPNI PhD Symposium (2012)

*Schweiger W; Scheofman W; Vacca A; “A Omni-Comprehensive Approach for the Design and Simulation of Gerotor Pumps,” 8IFK International Fluid Power Conference, 26th - 28th March (2012)

*Schweiger, W., Schoefmann, W., and Vacca, A., "Gerotor Pumps for Automotive Drivetrain Applications: A Multi Domain Simulation Approach," SAE Int. J. of Passeng. Cars – Mech. Syst. 4(3):1358-1376, doi:10.4271/2011-01-2272 (2011).

Stelson, K; “Saving Energy by Advancing Fluid Power Technology,” Fluid Power Journal, March/April, 4 (2011)

Stelson, K; Wang, F; “A simplified model to optimize positive-displacement hydraulic pump and motor efficiency,” in Proc. Bath/ASME Symp. Fluid Power Motion Control, Bath, UK, (2010)

Stelson, K; Wang, F; “Minimizing the power dissipation in the piston-cylinder gap using a barrel-shaped piston,” Proc. Bath/ASME Symp. Fluid Power Motion Control, Bath, U.K (2012)

Thul, B.; Dutta, R.; Stelson, K.; “Hydrostatic Transmission for Mid-Size Wind Power,” Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 40.2 (2011)

Tu, H; Rannow, M; Wang, M; Li, P; Chase, T; “High-speed 4 way rotary on/off valve for virtually variable displacement pump/motor applications,” ASME DSCC 2011/Bath Symposium on PTMC, Arlington, VA (2011)

Tu, H; Rannow, M; Wang, M; Li, P; and Chase, T; “The Advantages and Feasibility of Externally Actuating a High-speed Rotary On/Off Valve,” Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 20.3 (2011)

Tu H; Rannow M.B; Wang M; Li P; Chase T.R; Van de Ven J; “Design, Modeling and Validation of a High-Speed Rotary PWM On/Off Valve for Use in Virtually Variable Displacement Pumps,” ASME JDSMC 134: 6:061002 (2012)

Tu H; Rannow M.B; Wang M; Li P; Chase T.R; Van de Ven J; “Design, Modeling, and Validation of a High-Speed Rotary Pulse-Width-Modulation On/Off Hydraulic Valve,” ASME Journal of Dynamic Systems, Measurement, and Control 2012; 134:6::061002 (2012)

Vacca, A; Dhar S; “Axial motion coupled model for the axial balance of lateral bushings in external gear machines,” Simulation Modeling Practice and Theory: 26:60–76 August (2012)

Vacca A; Dhar S; and Opperwall T; “A Coupled Lumped Parameter and CFD Approach for Modeling External Gear Machines,” Proceedings of The Twelfth Scandinavian International Conference on Fluid Power, May 18-20, Tampere, Finland (2011)

Vacca, A; and Guidetti, M; “Modelling and Experimental Validation of External Spur Gear Machines for Fluid Power Applications,” Elsevier Simulation Modelling Practice and Theory, 19 (2011)

Wang, F.; Randan, M.; and Stelson, K.; “Comparison between Hydraulic Hybrid and Electric Hybrid Passenger Vehicle using ADVISOR 2004,” Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 2.2 (2011)

Wang, F; Ramdan, M; Stelson, K; “Comparison between hydraulic hybrid and electric hybrid in passenger vehicles using ADVISOR 2004,” in Proc. 52nd National Conf. Fluid Power, Las Vegas, USA, 2011, NCFP I11-2.2 (2011)

*Wang, Y; Sun, Z; Stelson, K; “Modeling, Control and Experimental Validation of a Transient Hydrostatic Dynamometer,” I.E.E.E. Transactions on Control Systems Technology (2011)

Wang, F; Trietch, B; Stelson, K; “Mid-sized wind turbine with hydro-mechanical transmission demonstrates improved energy production,” Proc. 8th International Conference on Fluid Power Transmission and Control, Hangzhou, China (2013)

Wang M; Tu H; Rannow M; Li P; Chase T; “CFD Analysis of a Novel High Speed Rotary ON/Off Valve,” Proc. of 6th FPNI-PhD Symposium (2010)

Wang, M; Li, P; “Displacement Control of Hydraulic Actuators Using a Passivity Based Nonlinear Controller,” Proceedings of the 2012 ASME Dynamic Systems and Conference, DSCC2012-MOVIC2012-8784 (2012)

Wang, M; Li, P; Tu, H; and Rannow, M; “Direct Displacement Control of Hydraulic Actuators Based on a Self-Spinning Rotary On/Off Valve,” 2011 International Fluid Power Exhibition (IFPE) (2011)

Wilfong,G; Holland, M; and Lumkes, J; “Design and Analysis of Pilot Operated High Speed On/Off Valves for Digital Pump/Motors,” Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 20.1 (2011)

Yong, Chao; Barth, Eric J.; "A Virtual-Cam Control Methodology for Free-Piston Engines", ASME DSCC 2011/Bath Symposium on PTMC, Arlington, VA; TuAT1.2 (2011)

Yong, C.; Willhite, J. A.; Barth, E. J; "A Virtual-Cam Control Methodology for a Novel Free-Liquid-Piston Engine Compressor"; Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 3.3 (2011)

Zecchi, M; and Ivantysynova, M; “A Novel Fluid Structure Interaction Model for the Cylinder Block/Valve Plate Interface of Axial Piston Machines,” Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; I11-9.2 (2011)

Zecchi, M. and Ivantysynova, M; “An investigation of the impact of micro surface shaping on the cylinder block/valve plate inter-face performance through a novel thermo-elasto-hydrodynamic model,” Proc. of the 7th FPNI PhD Symposium, Reggio Emilia, Italy, 589 – 610 (2012)

Zecchi, M; and Ivantysynova, M; “Cylinder block/valve plate interface - a novel approach to predict thermal surface loads,” Proceedings of 8th IFK International Conference on Fluid Power, Dresden, Germany, 1:285-298 (2012)

Zimmerman, J; Ivantysynova, M; “Reduction of Engine and Cooling Power by Displacement Control,” Proc. of 6th FPNI-PhD Symp (2010)

Zimmerman, J.; Busquets E.; and Ivantysynova, M.; “40% Fuel Savings by Displacement Control Leads to Lower Working Temperatures: A Simulation Study and Measurements,” Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 27.2 (2011)

Zimmerman, J; Hippalgaonkar, R; and Ivantysynova, M; “Optimal Control for the Series-Parallel Displacement Controlled Hydraulic Hybrid Excavator,” ASME/Bath Symposium on Fluid Power and Motion Control, Arlington, VA; TuBT1.4 (2011)

Thrust 2 – Compactness

Barth, E; Willhite, J; “High Inertance Liquid Piston Engine-Compressor and Method of use Thereof,” US Patent (2012)

*Berg, D; Li, P; “Achieving Dexterous Manipulation for Minimally Invasive Surgical Robots Through the Use of Hydraulics,” ASME Dynamic Systems and Control Conference (2012)

Cardona, D; “A MRI Compatible Concentric Tube Continuum Robot With Pneumatic Actuation,” MS Thesis, Vanderbilt University (2012)

Comber, D; Barth, E; “Precision Position Tracking of MR-Compatible Pneumatic Piston-Cylinder Using Sliding Mode Control,” Proceedings of the 4th Annual Dynamic Systems and Control Conference, Arlington, VA; TuAT1.1 (2011).

Comber, D; Cardona, D; Webster, R III; Barth, E; “Precision Pneumatic Robot for MRI-Guided Neurosurgery,” Design of Medical Devices Conference (2012)

Comber, D; Cardona, D; Webster, R III; Barth, E; “Precision Pneumatic Robot for MRI-Guided Neurosurgery,” ASME Journal of Medical Devices (2012)

Comber, D; Cardona, D; Webster, R III; Barth, E; “Sliding mode control of a MRI-compatible pneumatically actuated robot,” Bath/ASME Symposium on Fluid Power & Motion Control (2012)

*Cook, D; Vito, G; “High-Performance, Multi-Functional, Fluid-Power Components Using Engineered Materials,” 52nd National Conference on Fluid Power, Las Vegas, NV; 36.4 (2011)

*Cook, D; Knier, B; Gervasi, V; Stahl, D; “Automatic Generation of Strong, Light, Multi-Functional Structures from FEA Output,” Proceedings of the 21st Annual International Solid Freeform Fabrication Symposium (2010)

*Henderson, G; Ueda, J; “Pneumatically-Powered Robotic Exoskeleton to Exercise Specific Lower Extremity Muscle Groups in Humans,” Pneumatically-Powered Robotic Exoskeleton to Exercise Specific Lower Extremity Muscle Groups in Humans (2012)

Hofacker, M; Sun, M; Barth, E; “Design of a Figure-Eight Free-Liquid-Piston Engine Compressor for Compact Robot Power,” Bath/ASME Symposium on Fluid Power and Motion Control (2012)

Kerzhner, A; and Paredis, C; “A Formal Framework for Capturing Knowledge for Transforming Structural Models into Analysis Models,” Journal of Simulation, 5: 202-216 (2011)

Kerzhner, A; and Paredis, C; “A Mathematical Programming-Based Framework for Architecture Selection,” Proceedings of the ASME 2012 IDETC/CIE Computer and Information in Engineering Conference (2012)

Kerzhner, A; and Paredis, C; “A SysML-Based Language for Modeling System-Level Architecture Decisions,” Proceedings of the ASME 2012 IDETC/CIE Computer and Information in Engineering Conference (2012)

Kerzhner, A; and Paredis, C; "Model-Based System Verification: A Formal Framework for Relating Analyses, Requirements and Tests," Workshops and Symposia at MODELS 2010, Reports & Revised Selected Papers, Springer-Verlag, Berlin/Heidelberg, 6627:279-292 (2011)

Li, K; Sadgihi, A; Sun, Z; "Motion Control of a Hydraulic Free Piston Engine," Proceedings of the 2012 American Control Conference (2012)

Li, K; Sun, Z; "Modeling and Control of a Hydraulic Free Piston Engine with HCCI Combustion," Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 21.1 (2011)

Li, K; Sun, Z; "Stability Analysis of a Hydraulic Free Piston Engine with HCCI Combustion," Proceedings of the 4th Annual Dynamic Systems and Control Conference, Arlington, VA; WeAT2.4 (2011)

Malak R.J; Tucker L; Paredis C.J.J; "Compositional Modeling of Fluid Power Systems Using Predictive Tradeoff Models," Bath/ASME Symposium on Fluid Power and Motion Control, Bath, UK, September (2010)

Malak R.J. Jr; Paredis C.J.J; "Using Parameterized Pareto Sets to Model Design Concepts," Journal of Mechanical Design, 132; No. 4; 041007, April (2010)

Malak R.J. Jr; Paredis C.J.J; "Using Support Vector Machines to Formalize the Valid Input Domain of Predictive Models for Systems Design Problems," Journal of Mechanical Design, 132: No. 10: 101001, April (2010).

Min, B; Kerzhner, A; and Paredis, C; "Process Integration and Design Optimization for Model-Based Systems Engineering with SysML," Proceedings of ASME IDETC/CIE; Aug 28; DETC2011-48453 (2011)

Moore, R; Paredis, C; and Romero, D; "A Rational Design Approach to Gaussian Process Modeling for Variable Fidelity Models," Proc ASME IDETC/CIE, DETC2011-48227 (2011)

Paradis, C; Kerzhner, A; "Integrating Models and Simulations of Continuous Dynamics into SysML," Journal of Computing and Information in Science and Engineering (2012)

Paredis C.J.J; Bernard Y; Burkhart R.M; Koning H.P; Friedenthal S; Fritzson P; Rouquette N; Schamai W; "An Overview of the SysML-Modelica Transformation Specification," Proceedings of the 20th Anniversary International INCOSE Symposium, Chicago, July 12-15 (2010)

Remmers, R; Cook, D; Gervasi, V; "Custom, Integrated, Pneumatic, Rotary Actuator for an Active Ankle-Foot Orthosis," Solid Freeform Fabrication Symposium Proceedings (2010)

Shah A.A; Paredis C.J.J; Burkhart R; Schaefer D; "Combining Mathematical Programming and SysML for Component Sizing of Hydraulic Systems," Proceedings of the ASME 2010 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference (IDTEC/CIE 2010), paper no. DETC2010-28960, Montreal, Quebec, Canada, August 15-18 (2010)

Turkseven, M; Ueda, J; "Analysis of an MRI Compatible Force Sensor for Sensitivity and Precision," IEEE Sensors Journal (2012)

Turkseven, M; Ueda, J; "Design of an MRI Compatible Haptic Interface," Proceedings of the 2011 IEEE International Conference on Intelligent Robots and Systems, San Francisco, CA; pp.2139 – 2144, 10.1109/IROS.2011.6095170 (2011)

Ueda, J; Turkseven, M; "Development of a Pneumatically Driven MRI-compatible Haptic Device," Proceeding of the 29th Annual Conference of the Robotics Society of Japan, Tokyo, Japan (2011)

*Vikberg, G; Cook, D; "Voronoi Diagrams and Stress-Directed Lattice Structures Applied to Weight Reduction," Proc. of 6th FPNI-PhD Symp. West Lafayette; 323-330 (2010)

*Webster, R, III; Gorlewicz, J; Valdastri, P; "Wireless Insufflation of the Gastrointestinal Tract," IEEE Transactions on Biomedical Engineering (2012)

Xia, J; Houle, K; Mulcahy, C; Durfee, W; "Hydraulic ankle foot orthosis," ASME J Medical Devices (2012)

Thrust 3 – Effectiveness

Bair, S; "A Critical Assessment of the Role of Viscometers in Quantitative Elastohydrodynamics. Tribology Transactions," 55:3:394-399. (2012)

Bair, S; Habchi, V; "On Friction Regimes in Quantitative Elastohydrodynamics," Tribology International (2013)

Bair, S; and Laesecke, A; "High Pressure Viscosity Measurements of 1, 1, 1, 2-Tetrafluoroethan," International Journal of Thermophysics, 32(5):925-941 (2011)

Bair, S; and Laesecke, A; "Normalized Ashurst-Hoover Scaling and a Comprehensive Viscosity Correlation for Compressed Liquids," ASME J. Tribol (2011)

*Casoli, P; Vacca, A; Anthony, A; and Berta, G; "Modellazione della Valvola di Controllo di un Sollevatore Agricolo," Oleodinamica e Pneumatica, Tecniche Nuove, Milano, Italy (2012)

Chung, C; Jiang, S; Udoka, S; Jiang, Z; "Modeling Operator Performance of a Compact Rescue Crawler using a digital human," The Journal of Management Engineering Integration, 5: No.1: 71-79 (2012)

Chung, C; Jiang, S; Udoka, S; Jiang, Z; "Using Digital Human Modeling to Predict Operator Performance of a Compact Rescue Crawler," Proceedings of the 2010 Industrial Engineering Research Conference (2010)

Cook, D; Newbauer, S; Leslie, A; Gervasi, V; Kumpaty, S; "Unit-Cell-Based Custom Thermal Management through Additive Manufacturing," Proceedings of the 23rd Annual International Solid Freeform Fabrication (SFF) Symposium (2012)

Cook, D; Newbauer, S; Pettis, S; Knier, B; Kumpaty, S; "Effective Thermal Conductivities of Unit-Lattice Structures for Multi-Functional Components," Proceedings of the 22nd Annual International Solid Freeform Fabrication Symposium (2011)

*Cristofori, D; and Vacca, A; "A Novel Pressure-Feedback Based Adaptive Control Method to Damp Instabilities in Hydraulic Machines," SAE International Journal of Commercial Vehicles (2012)

*Cristofori, D; and Vacca, A; "The Modeling of Electro-Hydraulic Proportional Valves," ASME Journal of Dynamic Systems, Measurement and Control, 134 (2): 13 (2011)

Cunefare, K; Earnhart, N; and Marek K; "Novel, compact devices for reducing fluid-borne noise," Proceedings of the SAE 2011 Noise and Vibration Conference and Exhibition (2011)

Cunefare, K; Earnhart, N; and Marek K; "Passive Noise Control in Fluid Power," Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV (2011)

Cunefare, K; Earnhart, N; Marek K; Walsh, M; and Edirisinghe, R; "Noise control devices for fluid systems," Noise-Con Proc. 129:877 (2011)

Delpish, R; Jiang, S; Park, E; Udoka, S; "Development of a User-Centered Framework for Rescue Robot Interface Design," Proceedings of the 2010 Industrial Engineering Research Conference (2010)

Durbha, V; Li, P; “A Nonlinear Spring Model of Hydraulic Actuator for Passive Controller Design in Bilateral Teleoperation,” Proceedings of the 2012 American Control Conference (2012)

Durbha, V; Li, P; “Independent Metering of Pneumatic Actuator for Passive Human Power Amplication,” American Control Conference (2010)

Durbha, V; Li, P; “Storage Function for Passivity Analysis of Pneumatic Actuators With Finite Heat Transfer in Human-Interactive Systems,” ASME Dynamic Systems and Control Conference (2012)

Earnhart, N; and Cunefare, K; “Cancelling noise at its source,” Hydraulics & Pneumatics (2011)

Earnhart, N; and Cunefare, K; “Compact Helmholtz resonators for hydraulic systems,” International Journal of Fluid Power (2012)

Earnhart, N; Marek, K; Cunefare, K; “Evaluation of Hydraulic Silencers,” Proceedings of Noise-Con (2010)

Earnhart, N; Marek, K; Cunefare, K; “Modeling and Validation of an In-Line Hydraulic Silencer,” Proceedings of the 6th FPNI - PhD Symposium (2012)

Earnhart, N; Marek, K; Cunefare, K; “The Role of Compliance in Devices for Reduction of Fluid-Borne Noise,” Proceedings of the 7th FPNI PhD Symposium on Fluid Power (2012)

Enes, Aaron; “Towards Shared Control of Hydraulic Excavators,” 6th Fluid Power Net International PhD Symposium West Lafayette, IN, July (2010)

Enes, Aaron; Book, W; “Point to Point Motion of Net Velocity Constrained Manipulators,” 2010 IEEE Conference on Decision and Control, Dec. 15-17 (2010)

Elton, M; “Operator Efficiency Improvements From Novel Human-Machine Interfaces,” 6th Fluid Power Net International 6th Annual PhD Symposium West Lafayette, IN, July (2010)

Elton, M; and Book, W; “An Excavator Simulator for Determining the Principles of Operator Efficiency for Hydraulic Multi-DOF Systems,” Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 18.3 (2011)

Elton, M; and Book, W; “Comparison of Human-Machine Interfaces Designed for Novices Teleoperating Multi-DOF Hydraulic Manipulators,” 20th IEEE International Symposium on Robot and Human Interactive Communication (2011)

Franklin, C.; Jiang, Z; and Jiang, X; “Learning Curve Analysis of a Haptic Controller,” The journal of Management and Engineering Integration, 4(1):63-70 (2011)

Guo, F; Jia, X; Suo, S; Salant, R; Wang, Y; “A Mixed Lubrication Model of a Rotary Lip Seal Using Flow Factors,” Tribology International (2013)

Hughes, K; Jiang, S; “Using Discrete Event Simulation to Model Excavator Operator Performance,” International Journal of Human Factors and Ergonomics in Manufacturing and Service Industries (2010)

Hughes, K; Jiang, X; Jiang, Z; Mountjoy, D; Park, E; “A Preliminary Study of an Integrated Human Performance Model,” Proceedings of the 2010 Industrial Engineering Research Conference (2010)

Hughes, K; Jiang, S; Jiang, Z; Park, E; and Mountjoy, D; “Assessment of Excavator Operator Performance Using an Integrated Human Performance Model,” The journal of Management and Engineering Integration, 4(1): 88-98 (2011)

Humphreys, H.; Book, W.; Huggins, J.; “Biodynamic Feedthrough Compensation and Experimental Results Using a Backhoe” Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 22.3 (2011)

Humphreys, H.; Book, W.; Huggins, J.; “Compensation for Biodynamic Feedthrough in Backhoe Operation by Cab Vibration Control,” Proceedings of the IEEE International Conference on Robotics and Automation, Shanghai, China; (2011)

Humphreys, H.C; Book W.J; "Possible Methods for Biodynamic Feedthrough Compensation in Backhoe Operation," Proc. of the Fluid Power Net International 6th Annual PhD Symposium, West Lafayette, IN, June 15 (2010)

Jenkins, Q; Jiang, S; “Measuring Trust and Application of Eye Tracking in Human Robotic Interaction,” Proceedings of the 2010 Industrial Engineering Research Conference (2010)

Jia, X; Jung, S; Haas, W; Salant, R; “Numerical Simulation and Experimental Study of Shaft Pumping by Plunge Ground Shafts with Rotary Lip Seals,” Tribology International (2012)

Jia, X; Jung, S; Haas, W; Salant, R; “Shaft Pumping by Laser-Structured Shafts with Rotary Lip Seals-Theoretical Calculations and Experiments,” Proc. 16th International Sealing Conference (2010)

*Krauss, R; Book, W; “Transfer Matrix Modeling of Systems with Non-Collocated Feedback,” ASME Journal of Dynamic Systems, Measurement and Controls, 132:No.6:11 Nov (2010)

Krupka, I; Kumar, P; Bair, S; Svoboda, P; Hartl, M; “Mechanical Degradation of the Liquid in an Operating EHL Contact,” Tribology Letters, 41:1:191-197 (2011)

Kumar, P; Bair, S; Krupka, I; “Newtonian Elastohydrodynamic Film Thickness with Linear Piezoviscosity,” Tribology International 43:11:2159- 2165 (2010)

Lee, A; Jiang, S; “Assessing Operator Workload for a Fluid Powered Rescue Crawler,” The Journal of Management and Engineering Integration (2010)

Liu, Y; Jiang, S; Jiang, Z; Park, E; “Predicting Backhoe Excavator Operator Performance Using Digital Human Modeling,” Proceedings of the 2010 Industrial Engineering Research Conference (2010)

Marek, K; Earnhart, N; Cunefare, K; “Model for the design of a hydraulic silencer with a dispersive liner,” Proceedings of Noise-Con (2010)

*Mattos, P, de; Park, E; “Complex Adaptive Systems and Trauma Centers: Decision Making Under Stress,” Proceedings of 2012 Industrial Engineering Research Conference (2012)

*Mattos, P, de; Park, E; Miller, D; “Decision Making In Trauma Centers from the Standpoint of Complex Adaptive Systems,” Management Decision (2012)

*Michael, P; Blazel, B; Reuchel, R; Harville, X; “Hydraulic Fluid Compatibility and Filterability,” Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 35.2, (2011)

Mizumoto, H; Daepp, H; Book, W; Matsuno, F; “Teleoperation system using past image records for legged robot,” 9th IEEE International Symposium on Safety, Security, and Rescue Robotics (2011)

*Newbauer, S; Cook, D; and Pettis, D; “Multifunctional Components Using Engineered Lattice Structures as Materials,” Proceedings of the 2011 COMSOL Conference in Boston (2011)

Osafo-Yeboah, B; Elton, M; Jiang, S; Book, W; “Usability Evaluation of a Coordinated Excavator Controller with Haptic Feedback,” Proceedings of the 2010 Industrial Engineering Research Conference (2010)

Osafo-Yeboah, B; Jiang, S; “Empirical Investigation of Conflict and Interference within Haptic Controlled Human-Excavator Interface,” Advances in Usability Evaluation Part I, CRC Press, 42-51 (2012)

Pelosi, M; Ivantysynova, M; “A Geometric Multigrid Solver for the Piston-Cylinder Interface of Axial Piston Machines. Tribology Transactions,” 55: Issue. 2:163 - 174. (2012)

Salant, R; “Problems and Prospects for the Simulation of Dynamic Elastomeric Seal Wear and Life,” Proc. 17th International Sealing Conference, Stuttgart, Germany (2012)

Salant, R; “Soft Elastohydrodynamic Analysis of Rotary Lip Seals,” Journal of Mechanical Engineering Science (2010)

Salant, R; Yang, B; Thatte, A; “Simulation of Hydraulic Seals,” Journal of Engineering Tribology (2010)

Thatte, A; Salant, R; “Visco-Elastohydrodynamic Model of a Hydraulic Rod Seal during Transient Operation,” Journal of Tribology (2010)

Thatte, A; Salant, R; “Effects of Multi-Scale Viscoelasticity of Polymers on High Pressure, High Frequency Sealing Dynamics,” Tribology International (2012)

Udoka, S; “A Hydraulic Excavator Augmented Reality Simulator for Operator Training,” Proceedings of 2012 International Conference on Industrial Engineering and Operations Management (2012)

Udoka, S; “A Multimodal-Augmented Reality Design Space for Effective Human-Machine Interface Design,” Proceedings of the 2012 Industrial & Systems Engineering Research Conference (2012)

Udoka, S; “Modeling Operator Performance of a Compact Rescue Crawler Using Digital Humans,” The Journal of Management and Engineering Integration (2012)

*Vacca, A; “Modellazione della Valvola di Controllo di un Sollevatore Agricolo (in Italian),” Oleodinamica e Pneumatica, Tecniche Nuove, Milano, Italy (2010)

Wang, L; “Adaptive Robust Control of Variable Displacement Pumps,” 6th Fluid Power Net International 6th Annual PhD Symposium West Lafayette, IN, July (2010)

Wang, L; Wayne, B; Huggins, J; “Hydraulic Circuit for Single-rod Cylinders,” ASME J. Dynamic Systems, Measurement and Controls, 134:No 1:11 (2012)

Wang, L; Book, W; Huggins, J; “Applying Singular Perturbation Theory to Hydraulic Pump Control,” IEEE/ASME Transactions on Mechatronics 17:No.2:251-259 April (2012)

Wang, M; Li, P; “Passivity based adaptive control of a two chamber hydraulic actuator,” American Control Conference (2012)

*Winck, R; Kim, J; Book, W; Park, H; “Command Generation Techniques for a Pin Array using the SVD and the SNMF,” SYROCO 2012, Dubrovnik, Croatia, Sept. 5-7 (2012)

Yang, B; and Salant, R; “EHL Simulation of O-ring and U-cup Hydraulic Seals,” Journal of Engineering Tribology, 225:603-610 (2011)

Yang, B; and Salant, R; “EHL Simulation of O-ring and U-cup Hydraulic Seals,” Proc. Nordtrib 2010, 14th Nordic Symposium on Tribology (2010)

Young, A; Bair, S; “Experimental Investigation of Friction in Entrapped Elastohydrodynamic Contacts,” Tribology International 43:9:1615-1619 (2010)

Testbeds and General

Cheong, K; Li, P; Chase. T; “Optimal Design of Power-Split Transmission for Hydraulic Hybrid Passenger Vehicles,” Proceedings of the 2011 American Control Conference, San Francisco, CA; pp. 3295 – 3300, (2011)

Cheong, K; Li, P; Sedler, S; Chase. T; “Comparison between input coupled and output coupled power-split configurations in hybrid vehicles,” Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 10.3 (2011)

Chin, R; Hsiao-Wecksler, E; Loth, E; “Fluid-Power Harvesting by Under-Foot Bellows During Human Gait,” ASME Journal of Fluids Engineering (2012)

Chipalkatty,R; Daepp, H; Egerstedt, M; Book, W; “Human-in-the-Loop: MPC for Shared Control of a Quadruped Rescue Robot,” IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) (2011)

Daepp, H; “User Interface with Multisensory Feedback for Fluid Powered Rescue Robot,” 6th Fluid Power Net International 6th Annual PhD Symposium West Lafayette, IN, July (2010)

Daepp, H; Book, W; Kim, T; Radecki, P; “An Interactive Simulation for a Fluid-Powered Legged Search and Rescue Robot,” Proceedings of 2010 International Symposium on Flexible Automation, Tokyo, Japan, July 12-14 (2010)

Daepp, H; Book, W; “Modeling and Simulation of a Pneumatically-Actuated Rescue Robot,” Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 3.2 (2011)

Durfee, W.K; Kogler, G.; Morris, E.; Hsiao-Wecksler, E.; “Actuation Timing Strategies for a Portable Powered Ankle-Foot Orthosis,” Proceedings of the ASME Dynamic Systems and Control Conference (2011).

Durfee, W; Xia, J; Hsiao-Wecksler, E; “Tiny Hydraulics for Powered Orthotics,” International Conference of Rehabilitation Robotics (2010)

Hsiao-Wecksler, E; Shorter, K; Li, Y; Kogler, G; Durfee, W; “Portable Pneumatically-Powered Ankle-Foot Orthosis,” ASME Design of Medical Devices Conference (2012)

Li, D; Becker, A; Shorter, K; Bretl, T; and Hsiao-Wecksler, E; “Estimating System State During Human Walking with a Powered Ankle-Foot Orthosis,” IEEE/ASME Transactions on Mechatronics (2011).

Li, P; Mensing, F; “Optimization and Control of a Hydro-Mechanical Transmission based Hydraulic Hybrid Passenger Vehicle,” Proceedings of the 7th International Fluid Power Conference, Aachen (2010)

Li, Y; Hsiao-Wecksler, E; “Gait Mode Recognition and Control for a Portable-Powered Ankle-Foot Orthosis,” 36th Annual Meeting of the American Society of Biomechanics (2012)

Li, Y; Hsiao-Wecksler, E; “Gait Mode Recognition using an Inertial Measurement Unit to Control an Ankle-Foot Orthosis during Stair Ascent and Descent,” ASME Dynamic Systems and Control Conference (2012)

Li, Y; Morris, E; Shorter, K; Hsiao-Wecksler, E; “Energy Efficiency Analysis of A Pneumatically-Powered Ankle-Foot Orthosis,” Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 3.1 (2011)

Li, Y; Shorter, K; Bretl, T; Hsiao-Wecksler; "Modeling and Control of a Portable Powered Ankle Foot Orthosis," 6th Annual FPNI - PhD Symposium (2010)

Li, Y; Shorter, K; Hsiao-Wecksler, E; Bretl, T; "Simulation and Experimental Analysis of a Portable Powered Ankle-Foot Orthosis Control," Dynamic Systems and Control Conference (DSCC) and Bath/ASME Symposium on Fluid Power and Motion Control (2012)

Mensing, F; Li, P; "Sizing and Optimal Operation of a Power Split Hydraulic Hybrid Drive Train," Proceedings of the 52nd National Conference on Fluid Power, Las Vegas, NV; 10.2 (2011)

Michael, P; Wanke, T; "Hydraulic Fluid and System Standards, Chapter 7," Handbook of Hydraulic Fluid Technology, 2nd Edition, (2012)

Mishler, L; Garcia, J; Lumkes, J; "Engaging Pre-College Students in Engineering Using Hands-on Micro-Processor Controlled Portable Fluid Power Demonstrators," ASABE Annual International Meeting, Louisville, KY; 1111500; (2011)

Shorter, K; Hsiao-Wecksler, E; Kogler, G; Loth, E; and Durfee, W; "A Portable Powered Ankle-Foot-Orthosis for rehabilitation," Journal of Rehabilitation Research & Development (2011).

Shorter, K; Li, Y; Bretl, T; Hsiao-Wecksler, E; "Modeling, control, and analysis of a robotic assist device," Mechatronics 22:8:1067-1077 (2012)

Shorter, K; Li, Y; Morris, E; Kogler, G; Hsiao-Wecksler, E; "Experimental Evaluation of a Portable Powered Ankle-Foot Orthosis," 33rd Annual International IEEE EMBS Conference, Boston, MA; pp. 624 – 627; 10.1109/IEMBS.2011.6090138 (2011)

*Tilton, A; Hsiao-Wecksler, E; Mehta, P; "Filtering with Rhythms: Application to Estimation of Gait Cycle," American Control Conference (2012)

Zhang, C; Saadat, M; Li, P; Simon, T; "Heat Transfer in a Long, Thin Tube Section of an Air Compressor: An Empirical Correlation from CFD and a Thermodynamic Modeling," ASME IMECE (2012)

Zhang, C; Simon, T; Li, P; "Storage Power and Efficiency Analysis of Air Compressors Based on CFD," ASME IMECE (2012)

Year 8 Annual Report Publications

Thrust 1 – Efficiency

Björling, M.; Habchi, W.; Bair, S.; Larsson, R.; Marklund, P. "Friction Reduction in Elastohydrodynamic Contacts by Thin-Layer Thermal Insulation" Tribol Lett 53:477-486 (2014)

Björling, M.; Habchi, W.; Bair, S.; Larsson, R.; Marklund, P. "Towards the True Prediction of EHL Friction" Tribology International Volume 66, Pages 19-26, October (2013)

Busquets, E. and Ivantysynova, M. "Temperature Prediction of Displacement Controlled Multi-actuator Machines" International Journal of Fluid Power 14 No. 1 pp. 25-36 (2013)

*Busquets, E. and Ivantysynova, M. "Thermal-hydraulic Behavior Prediction of a Valve Controlled Wheel Loader" Proceedings of the 22nd International Conference on Hydraulics and Pneumatics. Prague, Czech Republic, pp. 23-31 Oct. 24-25, (2013)

*Daher, N. and Ivantysynova, M. "System Synthesis and Controller Design of a Novel Pump Controlled Steer-By-Wire System Employing Modern Control Techniques" ASME/Bath Symposium on Fluid Power and Motion Control (2013)

*Daher, N. and Ivantysynova, M. "Pump Controlled Steer-by-Wire System" SAE Commercial Vehicle Engineering Congress (ComVEC) (2013)

*Daher, N.; Wang, N.; Ivantysynova, M. "Novel Energy-Saving Steer-by-Wire System for Articulated Steering Vehicles: A Compact Wheel Loader Case Study" Proceedings of the 13th Scandinavian International Conference on Fluid Power (2013)

Devendran, R. and Vacca, A. "Design Potentials of External Gear Machines with Asymmetric Tooth Profile" ASME/Bath Symposium on Fluid Power and Motion Control, FPMC (2013)

Devendran, R. and Vacca, A. "Optimal Design of Gear Pumps for Exhaust Gas After treatment Applications (Elsevier)" Simulation Modelling Practice and Theory, vol. 38, pp. 1-19 (2013)

Dhar, S. and Vacca, A. "A Fluid Structure Interaction-EHD Model of the Lubricating Gaps in External Gear Machines: Formulation and Validation" Tribology International (2013)

Dhar, S.; Vacca, A.; Lettini, A. "A Novel Fluid Structure Thermal Interaction Model for the Analysis of the Lateral Lubricating Gap Flow in External Gear Machines" ASME/Bath Symposium on Fluid Power and Motion Control, FPMC (2013)

Dhar, S.; Vacca, A.; Lettini. A. "Force Balance Analysis of Elastohydrodynamic Effects using a Fluid Structure Interaction Model of External Gear Machines" The 8th Int. Conference on Fluid Power Transmission and Control (ICFP 2013)

Dutta, Rahul; Wang, F.; Bohlmann, B.; Stelson, K. "Analysis of Short-Term Energy Storage for Midsize Hydrostatic Wind Turbine" Transactions of A.S.M.E., Journal of Dynamic Systems, Measurement and Control, Vol. 136, No. 1 (2014)

Habchi, W.; Bair, S.; Vergne, P. "On Friction Regimes in Quantitative Elastohydrodynamics" 41306 Tribology International Volume 58, Pages 107-117 February (2013)

Hippalgaonkar, R. and Ivantysynova, M. "A Series-Parallel Hydraulic Hybrid Mini-Excavator with Displacement Controlled Actuators" 13th Scandinavian International Conference on Fluid Power, Linköping, Sweden, June 3-5, (2013) Ivantysynova, M.; Pelosi, M. "The Impact of Axial Piston Machines Mechanical Parts Constraint Conditions on the Thermo-Elastohydrodynamic Lubrication Analysis of the Fluid Film Interfaces" Int. J. of Fluid Power, Vol. 14, No. 3, pp. 35-51, November (2013)

Johnston, M. and Ewoldt, R. "Precision Rheometry: Surface Tension Effects on Low-torque Measurements in Rotational Rheometers" Journal of Rheology, 57(6), 1515-1532 (2013)

Khalid, H. and Michael, P. "An Investigation of Hydraulic Motor Efficiency through Stribeck Analysis Tribology and Lubrication Technology (TLT)" 41640,70:1, 20-23 (2014)

Merrill, K.; Breidi, F.; Lumkes, J. "Simulation Based Design and Optimization of Digital Pump/Motors" ASME/Bath Symposium on Fluid Power and Motion Control, October (2013)

*Ramdan, M.; Stelson, K. “Optimized Single-Stage Power-Split Hydraulic Hybrid City Bus,” ASME/BATH 2013 Symposium on Fluid Power and Motion Control, 6-9 October 2013, Sarasota, FL. (FPMC 2013)

Saadat, M.; Shirazi, F.; Li, P. "Nonlinear Controller Design with Bandwidth Consideration for a Compressed Air Energy Storage System" Dynamic Systems and Control Conference (2013)

Saadat, M.; Yan, B.; Li, P. "Optimal Control Experimentation of Compression Trajectories for a Liquid Piston Air Compressor" ASME Heat Transfer Summer Conference (2013)

Schenk, A.; Zecchi, M.; Ivantysynova, M. "Accurate Prediction of Axial Piston Machines Performance Through a Thermo-Elasto-Hydrodynamic Simulation Model" ASME/Bath Symposium on Fluid Power and Motion Control (2013)

Shirazi, F.; Saadat, M.; Yan B.; Li, P.; Simon, T. "Iterative Optimal Control of a Near Isothermal Liquid Piston Air Compressor in a Compressed Air Energy Storage System" American Control Conference (2013)

Skelton, D.; Xiong, S.; Breidi, F.; Lumkes, J. "Improving actuation speed and controllability" SAE Off-Highway Engineering Magazine (2013)

Skow, E.; Cunefare, K.; Erturk, A. "Transduction as energy conversion; harvesting of acoustic energy in hydraulic systems" Proceedings of the Joint 21st meeting of the International Congress of Acoustics and 165th Meeting of the Acoustical Society of America (2013)

Wang, F. and Stelson, K. “Model Predictive Control for Power Optimization in a Hydrostatic Wind Turbine,” The 13th Scandinavian International Conference on Fluid Power, SICFP2013, 3-5 June2013, Linköping, Sweden, pp. 155-160. (2013).

Wang, F.; Trietch, B.; Stelson, K. "Mid-sized Wind Turbine with Hydro-mechanical Transmission Demonstrates Improved Energy Production" Proceedings of the 8th International Conference on Fluid Power Transmission and Control, (ICFP) (2013)

Whitten, M. and Stelson, K. “Determining Water Content at Saturation for Three Common Wind Turbine Gearbox Oils: Mobilgear SHC XMP 320, AMSOIL EP Gear Lube ISO-320 and Castrol Optigear A320,” ASME/BATH 2013 Symposium on Fluid Power and Motion Control, 6-9 October 2013, Sarasota, FL. (FPMC 2013)

Zhang, C.; Simon, T.; Li, P. “Optimization of the Axial Porosity Distribution of Porous Inserts in a Liquid-Piston Gas Compressor Using a One-Dimensional Formulation” Proceedings of the ASME International Mechanical Engineering Congress and Exposition (IMECE) (2013)

Zhang, C.; Wieberdink, J.; Yan, B.; Simon, T.; Shirazi, F.; Li, P. “Numerical Investigation of Metal-Foam Filled Liquid Piston Compressor Using a Two-Energy Equation Formulation Based on Experimentally Validated Models” Proceedings of the ASME International Mechanical Engineering Congress and Exposition (IMECE) (2013)

Zhang, C.; Yan, B.; Wieberdink, J.; Li, P.; VandeVen, J.; Simon, T.; Loth, E. “Thermal Analysis of a Compressor for Application to Compressed Air Energy Storage” Proceedings of the ASME International Workshop on Heat Transfer Advances for Energy Conservation and Pollution Control (IWHT) (2013)

Thrust 2 – Compactness

Barth, E.; Hofacker, M.; Kumar, N. "A Free-Liquid-Piston Engine Compressor for Compact Robot Power" ASME Mechanical Engineering, Dynamic Systems and Control Magazine, Special Edition, p. s10-s12, June (2013)

Comber, D.; Barth, E.; Webster III, R. "Design and Control of a Magnetic Resonance Compatible Precision Pneumatic Active Cannula Robot" ASME Journal of Medical Devices, Mar; 8(1):011003-1-011003-7 (2014)

Comber, D.; Slightam, J.; Gervasi, V.; Webster III, R.; Barth, E. "Design and Precision Control of an MR-Compatible Flexible Fluidic Actuator" 41554 Proc ASME/BATH 2013 Symp Fluid Power & Motion Control. Oct 7 (2013)

Comber, D.; Webster III, R.; Neimat, J.; Barth, E. "Open-Loop Tip Accuracy of an MRI-Compatible Active Cannula Robot" 41448 Proc Hamlyn Symp Medical Robotics. Jun 23 (2013)

Cramer, D. and Barth, E. "Pneumatic Strain Energy Accumulators for Exhaust Gas Recycling" Bath/ASME Symposium on Fluid Power and Motion Control (FPMC 2013) 41553 Paper# FPMC2013-4488, Sarasota, FL Oct 6-9, (2013)

Hofacker, M.; Kumar, N.; Barth, E. "Dynamic Simulation and Experimental Validation of a Single Stage Thermocompressor for a Pneumatic Ankle-Foot Orthosis" Proceedings of the ASME/Bath 2013 Symposium on Fluid Power & motion Control, FPMC2013 Sarasota, FL Oct 6-9, (2013)

Kumar, N.; Hofacker, M.; Barth, E. "Design of a Thermocompressor for a Pneumatically Actuated Ankle-Foot Orthosis" ASME Dynamic Systems and Control Conference, Oct. 21-23, Palo Alto, CA, (2013)

Kumar, N.; Hofacker, M.; Barth, E. "Design and Control of a Free-Liquid-Piston Engine Compressor for Compact Robot Power" 41426 Vanderbilt Undergraduate Research Journal, Vol. 9, Summer (2013)

Lacey, L.; Buharin, V.; Turkseven, M.; Shinohara, M.; Ueda, J. "Control of Voluntary and Involuntary Nerve Impulses for Hemiparesis Rehabilitation and MRI Study" ASME Dynamic Systems and Control Conference,(DSCC13), In CD-ROM (2013)

Li, K.; Zhang, C.; Sun, Z. "Transient Control of a Hydraulic Free Piston Engine" Proceedings of the ASME Dynamic Systems and Control Conference (2013)

Slightam, J. and Gervasi, V. "Additively Manufactured Flexible Fluidic Actuators For Precision Control in Surgical Applications" 24th Annual Solid Freeform Fabrication Symposium (2013)

Strohmaier, K., and VandeVen, J. "Constrained Multi-Objective Optimization of a Hydraulic Flywheel Accumulator" ASME/BATH 2013 Symposium on Fluid Power & Motion Control, Sarasota, FL, FPMC2013-4425, Oct. 6-9, (2013)

Tucker, J.; Barth, E. "Design, Fabrication, and Evaluation of a Distributed Piston Strain-Energy Accumulator" International Journal of Fluid Power, Vol. 14, No. 1, pp. 47-56, March (2013)

Ueda, J.; Comber, D.; Slightham, J.; Turkseven, M.; Gervasi, V.; Webster III, R.; , Barth, E. "MRI-Compatible Fluid-Powered Medical Devices" ASME Mechanical Engineering Magazine, p. s13-s16, June (2013)

Willhite, J.; Yong, C.; Barth, E. "The High Inertance Free Piston Engine Compressor Part 1: Dynamic Modeling" ASME Journal of Dynamic Systems, Measurement and Control. 135(4), 041003 (12 pages), Apr 29, (2013)

Willhite, J.; Yong, C.; Barth, E. "The High Inertance Free Piston Engine Compressor Part 2: Design and Experimental Evaluation" ASME Journal of Dynamic Systems, Measurement and Control. 135(4), 041003 (9 pages), Apr 25, (2013)

Xia, J. and Durfee, W. "Analysis of Small-scale Hydraulic Actuation Systems" ASME J Mechanical Design, November (2013)

Thrust 3 – Effectiveness

*Bagley, K. and Park, E. "Development of a Graphical User Interface as Data Collection Tool for Cognitive Performance in a Navigation Task" Proceedings of the HCI International, July (2013)

*Bagley, K.; Park, E.; Miller, D. "Assessing Performance Variability in a Military Population Emphasizing Individual Differences" Proceedings of Industrial Engineering Research Conference (2013)

Bair, S.; Krupka, I.; Sperka, P.; Hartl, M. "Quantitative Elastohydrodynamic Film Thickness of Mechanically Degraded Oil" Tribology International Volume 64, Pages 33-38, August (2013)

Davis, D.; Franca, P.; Delpish, R.; Jiang, S. "Usability testing of rescue robot interface using eye tracking" Proceedings of the 2003 Industrial and Systems Engineering Research Conference, May 18-22, (2013)

*deMattos, P.; Park, E.; Miller, D. "Decision Making In Trauma Centers from the Standpoint of Complex Adaptive Systems Management" Decision

Guo, F.; Jia, X.; Huang, L.; Salant, R.; Wang, Y. "The Effect of Aging During Storage on the Performance of a Radial Lip Seal" Polymer Degradation and Stability, Vol. 98, pp. 2193-2200, (2013)

Huang, Y. and Salant, R. "Simulation of the Effects of a Plunge-Ground Rod on Hydraulic Rod Seal Behavior" Tribology Transactions, Vol. 56, pp. 986-996, (2013)

Humphreys, H.; Book, W.; Feigh, K. "Development of Controller-Based Compensation for Biodynamic Feedthrough in a Backhoe" Journal of Systems and Control Engineering (2013)

Humphreys, H.; Book, W.; Huggans, J. "Hydraulically Actuated Patient Transfer Device with Passivity Based Control" Proc. of the ASME/BATH Symposium on Fluid Power and Motion Control (2013)

Jia, X.; Guo, F.; Huang, L.; Salant, R.; Wang, Y. "Parameter Analysis of the Radial Lip Seal by Orthogonal Array Method" Tribology International Vol. 64, pp. 96-102, (2013)

*Opperwall, T. and Vacca, A. "A Combined FEM/BEM Model and Experimental Investigation into the Effects of Fluid-borne Noise Sources on the Air-borne Noise Generated by Hydraulic Pumps and Motors" Proceedings of the Institution of Mechanical Engineers, Part C, Journal of Mechanical Engineering Science (2013)

*Opperwall, T. and Vacca, A. "Performing and Interpreting Experiments Towards Understanding Noise Generation in Displacement Machines" The 13th Scandinavian International Conference on Fluid Power, SICFP (2013)

Osafo-Yeboah, B.; Frota, E.; Jiang, S.; Ntuen, C. "Quantitative Modeling of Human Interaction with Haptic-controlled Excavators" Proceedings of the 2003 Industrial and Systems Engineering Research Conference, May 18-22, (2013)

Osafo-Yeboah, B.; Jiang, S.; Delpish, R.; Jiang, Z.; Ntuen, C. "Empirical Study to Investigate the Range of Force Feedback Necessary for Best Operator Performance in a Haptic Controlled Excavator Interface" International Journal of Industrial Ergonomics, 43(3), pp.197-202 (2013)

*Park, E. and Bagley, K. "Development of Graphic Unser Interface as data Collection Tool for Cognitive Performance" Proceedings of 2014 International Conference on Industrial Engineering and Operations Management (2014)

*Ritelli, G. and Vacca, A. "Energy Saving Potentials of a Novel Electro-Hydraulic Method to Reduce Oscillations in Fluid Power Machines: The Case of a Hydraulic Crane" SAE Int. J. Commer. Veh., Vol.6(2), (2013)

*Ritelli, G. and Vacca, A. "Energetic and dynamic impact of counterbalance valves in fluid power machines" Energy Conversion and Management 2013. Vol.76: p. 701-711 (2013)

Salant, R. "Friction in Seals" 41487 Encyclopedia of Tribology. (J. Wang & Y-W Chung, Eds.), Springer, New York (2013)

Salant, R. "Reciprocating Seal Analysis" Encyclopedia of Tribology(J. Wang & Y-W Chung, Eds.), Springer, New York (2013)

Salant, R. "Rotary Lip Seal Analysis" Encyclopedia of Tribology(J. Wang & Y-W Chung, Eds.), Springer, New York, (2013)

Skow, E.; Cunefare, K.; Erturk, A. "Design and Performance Enhancement of Hydraulic-pressure Energy Harvesting Systems" Part of Proceedings of SPIE Vol. 8688 Active and Passive Smart Structures and Integrated Systems (2013)

*Zhou, J. and Vacca, A. "A Methodology to Model Oil Flow Through Orifices Considering Dynamic Air Release" The 8th Int. Conference on Fluid Power Transmission and Control, ICFP (2013)

*Zhou, J.; Vacca, A.; Manhartsgruber, B. "A Novel Approach for the Prediction of Dynamic Features of Air Release and Adsorption in Hydraulic Oils" ASME Journal of Fluid Engineering 135(9), 091305 (8 pages), Jul 11 (2013)

Testbeds and General

*Bell, C.; Obstein, K.; Valdastri, P. "Image Partitioning and Illumination in Image-based Pose Detection for Teleoperated Flexible Endoscopes" Artificial Intelligence in Medicine, Vol. 59, N. 3, pp. 185-196 (2013)

*Gorlewicz, J.; Battaglia, S.; Smith, B.; Ciuti, G.; Gerding, J.; Menciassi, A.; Obstein, K.; Valdastri, P.; Webster III, R. "Wireless Insufflation of the Gastrointestinal Tract" IEEE Trans Biomed Eng., 60(5):1225-33, May (2013)

*Obstein, K.; Battaglia, S.; Smith, B.; Gerding, J.; Valdastri, P. "Novel Approach for Colonic Insufflation Via an Untethered Capsule (with video)" Gastrointestinal Endoscopy, Vol. 77, N. 3, pp. 516-517 (2013)

Boes, M.K.; Islam, M.; Li, Y.; Hsiao-Wecksler, E. "Functional Efficiency of a Portable Powered Ankle-Foot Orthosis" IEEE 13th International Conference on Rehabilitation Robotics, ICORR (2013)

*Di Natali, C.; Beccani, M.; Valdastri, P. "Real-Time Pose Detection for Magnetic Medical Devices" IEEE Transactions on Magnetics IEEE Transactions on Magnetics, Vol. 49, N. 7, pp. 3524-3527 (2013)

Du, Z.; Cheong, K.; Li, P.; Chase, T. "Fuel Economy Comparisons of Series, Parallel and HMT Hydraulic Hybrid Architectures" American Control Conference (2013)

Li, Y. and Hsiao-Wecksler, E. "Gait Mode Recognition and Control for a Portable-Powered Ankle-Foot Orthosis" IEEE 13th International Conference on Rehabilitation Robotics, ICORR (2013)

*Obstein, K. and Valdastri, P. "Advanced Endoscopic Technologies for Colorectal Cancer Screening" World J Gastroenterol; 19(4): 431-439 (2013)

Petrucci, M.; MacKinnon, C.; Hsiao-Wecksler, E. "Mechanical Modulation of Anticipatory Postural Adjustments of Gait Using a Portable Powered Ankle-Foot Orthosis" IEEE 13th International Conference on Rehabilitation Robotics, ICORR (2013)

Shorter, K.A.; Xia, J.; Hsiao-Wecksler, E.; Durfee, W.; Kogler, G. "Technologies for Powered Ankle Foot Orthotic Systems: Possibilities and Challenges" IEEE/ASME Transactions on Mechatronics, 18(1): 377-347, (2013)

Opdenbosch, P. "Intelligent Controls for Electro-Hydraulic Poppet Valves" Control Engineering Practice, accepted, Feb. (2013)

Year 9 Annual Report Publications

Thrust 1: Efficiency

*Agarwal, P. and Vacca A., “A Numerical Model for the Simulation of Flow in Radial Piston Machines”, Proceedings of International Fluid Power Exhibition, International Fluid Power Expo, Las Vegas, NV (March 2014)

*Agarwal, P., Vacca, A., Wang, K., Kim, K., Kim, T., “An Analysis of Lubricating Gap Flow in Radial Piston Machines”, SAE International Journal of Commercial Vehicles, 7(2): 524-534 (October 2014)

*Altare, G. and Vacca, A., “A Design Solution for Efficient and Compact Electro-Hydraulic Actuators”, Proceedings of the Second International Conference on Dynamics and Vibroacoustics of Machines, Samara, Russia (September 2014)

*Altare, G.; Vacca, A.; Richter, C., "A Novel Pump Design for an Efficient and Compact Electro-Hydraulic Actuator", Proceedings of the 2014 IEEE Aerospace Conference, Big Sky, Montana (March 2014)

Bair, S., “The temperature and pressure dependence of the dynamic properties of branched perfluoropolyethers", Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, Volume 228, Issue 4, pp. 424-434 (2014)

Barth, E. and Pedchenko, A., "Elastic Hydraulic Accumulator/Reservoir System", U.S. patent #8,434,524

Bramer, J.; Puzzuoli, A.; Michael, P.; Wanke, T. , "Hydraulic Fluid Efficiency Effects in External Gear Pumps", Proceedings of the 53rd National Conference on Fluid Power, National Fluid Power Association, Paper NCFP I14-13.3, Las Vegas, NV (2014)

*Breidi, F.; Helmus, T.; Holland, M.; Lumkes, J., "The Impact of Peak-and-Hold and Reverse Current Driving Strategies on the Dynamic Performance of Commercial Cartridge Valves", Proceedings of the ASME/Bath Symposium on Fluid Power and Motion Control, Bath, UK (2014)

Busquets, E. and Ivantysynova, M., "A Robust Multi-Input Multi-Output Control Strategy for the Secondary Controlled Hydraulic Hybrid Swing of a Compact Excavator with Variable Accumulator Pressure", Proceedings of the ASME/BATH Symposium on Fluid Power & Motion Control, Bath, UK (2014)

Busquets, E. and Ivantysynova, M., "An Adaptive Robust Control for Displacement-controlled End-effectors", Proceedings of the 8th FPNI PhD Symposium, Lappeenranta, Finland (September 2014)

Busquets, E. and Ivantysynova, M., "The World's First Displacement Controlled Excavator Prototype with Pump Switching - A Study of the Architecture and Control", 9th JFPS International Symposium on Fluid Power (October 2014) **Best Paper Award**

Chacon, R. and Ivantysynova, M., "An Investigation of the Impact of Micro Surface Shaping on Cylinder Block/Valve Plate Interface Performance", Proceedings of the 8th FPNI PhD Symposium, Lappeenranta, Finland (2014)

*Cook, D., "Heat and Efficiency Considerations in Fluid-Powered Co-Robotics Applications", Proceedings of the International Fluid-Power Exposition (IFPE) Technical Conference, Las Vegas, NV (March 2014)

Cummins, J.; Maurice, C.; Song, Y.; Sanchez, F.; Barth, E.; Adams, D., "Elastomeric Evolution: A New Look at Carbon Nanotube Reinforced Elastomers", Proceedings of the 40th European Rotorcraft Forum (September 2014)

*Daher, N. and Ivantysynova, M., "An Indirect Adaptive Velocity Controller for a Novel Steer-by-Wire System", ASME Journal of Dynamic Systems, Measurement, and Control (2014)

*Daher, N. and Ivantysynova, M., "Energy Analysis of an Original Steering Technology that Saves Fuel and Boosts Efficiency", Energy Conversion and Management (July 2014)

*Daher, N. and Ivantysynova, M., “A Steer-by-Wire System that Enables Remote and Autonomous Operation”, SAE Commercial Vehicle Engineering Congress, Rosemount, IL (2014)

*Daher, N. and Ivantysynova, M., “A Virtual Yaw Rate Sensor for Articulated Vehicles Featuring Novel Electro-Hydraulic Steer-by-Wire Technology”, Control Engineering Practice (June 2014)

Devendran, R. and Vacca, A., “A novel design concept for variable delivery flow external gear pumps and motors”, International Journal of Fluid Power, 15:3, pp. 121-137 (2014)

Devendran, R., Vacca, A., "Experimental Characterization of External Gear Machines with Asymmetric Teeth Profile", Proceedings of IFPE 2014, Int. Fluid Power Expo, Las Vegas, NV (March 2014)

Dhar, S. and Vacca, A., "A novel FSI–thermal coupled TEHD model and experimental validation through indirect film thickness measurements for the lubricating interface in external gear machines", Tribology International 82, pp. 162-175 (October 2014)

Dhar, S., Vacca, A., Lettini, A., "An Experimental Investigation of the Lateral Lubricating Gaps in External Gear Machines with Axially Balanced Lateral Bushes", Proceedings of the International Fluid Power Conference (9 IFK), Aachen, Germany (March 2014)

Johnston, M.T., W.P. King, R.H. Ewoldt, "Shear stress characteristics of microtextured surfaces in gap-controlled hydrodynamic lubrication", Tribology International, 82, 123-132 (2015)

*Krause, M. and Michael, M., "Relative Humidity Sensors and the Solubility of Water in Lubricants", Environmentally Considerate Lubricants, STP 1575, In-Sik Rhee, Ed., pp. 131-146, ASTM International, West Conshohocken, PA (2014)

Lee, S. and Li, P., "Trajectory Tracking Control Using a Hydraulic Transformer", Proceedings of ISFA 2014 International Symposium on Flexible Automation (July 2014)

Li K.; Zhang C.; Sun, Z., "Precise Piston Trajectory Control for a Free Piston Engine", Control Engineering Practice. vol. 34 pp. 30-38 (January 2015)

Miller, M.; Khalid, H.; Michael, P.; Guevremont, J.; Garelick, K.; Pollard, G.; Whitworth, A.; Devlin, M., “An Investigation of Hydraulic Motor Efficiency and Boundary Lubrication Additive Effects”, Proceedings of the 9th International Fluid Power Conference, Aachen, Germany, Vol. 1, 266-277 (March 2014)

Miller, M.; Khalid, H.; Michael, P.; Guevremont, J.; Garelick, K.; Pollard, G.; Whitworth, A.; Devlin, M.. “An Investigation of Hydraulic Motor Efficiency and Tribological Surface Properties”, Tribology Transactions, 57: 622-630 (2014)

Mizell, D. and Ivantysynova, M., "Material Combinations for the Piston-Cylinder Interface of Axial Piston Machines: A Simulation Study", Proceedings of the 8th FPNI PhD Symposium, Lappeenranta, Finland (June 2014)

*Naseem, D. and Ivantysynova, M., "New Steering Concept for Wheel Loaders", Proceedings of the International Fluid Power Conference (9 IFK), Aachen, Germany (March 2014)

*Padovani, D. and Ivantysynova, M., "Energy Efficient Hydraulic Rotary Drive: Analysis and Comparison of Two Different Displacement Controlled Solutions", Proceedings of the 8th FPNI PhD Symposium, Lappeenranta, Finland (2014)

Pena, O.R., Leamy, M.J., "A Self-Contained Architecture for Energy Recovery in Hydraulic Elevators", Proceedings of the ASME 2014 International Mechanical Engineering Congress & Exposition, Montreal, Canada (November 2014)

Qin, C.; Loth, E.; Li, P.; Simon, T.; Van de Ven, J., "Spray-cooling concept for Wind-Based Compressed Air Energy Storage", Journal of Renewable and Sustainable Energy, Vol.6 043125 (2014)

Saadat, M. and Li, P., "Modeling and Control of an Open Accumulator Compressed Air Energy Storage (CAES) System for Wind Turbines", Applied Energy [http://dx.doi.org/10.1016/j.apenergy.2014.09.085] (2015)

Saadat, M.; Shirazi, F.; Li, P., "Revenue Maximization of Electricity Generation for a Wind Turbine Integrated with a Compressed Air Energy Storage System", Proceedings of 2014 American Control Conference (2014)

Schenk, A. and Ivantysynova, M., “A transient fluid structure interaction model for lubrication between the slipper and swashplate in axial piston machines”, Proceedings of the 9th International Fluid Power Conference (2014)

Schenk, A. and Ivantysynova, M., “A transient thermoelastohydrodynamic lubrication model for the slipper / swashplate in axial piston machines”, ASME Journal of Tribology (January 2015)

Shirazi F.; Gagnon P.; Li, P.; Van de Ven, J., "Design, modeling and control of a lab- scale compressed air energy storage (CAES) testbed for wind turbines with simulated input and demand power variability", Proceedings of the ASME Dynamic Systems and Control Conference (2014)

Skelton, D.; Xiong, S.; Lumkes, J.; Breidi, F., "High Performance Actuation Systems Enabled by Energy Coupling Mechanisms", SAE Commercial Vehicle Engineering Congress, Rosemont, Illinois (October 2014)

Skelton, D.; Xiong, S.; Lumkes; J., "Design of High Performance Actuation System for High Speed Valves", Proceedings of the 9th International Fluid Power Conference, Aachen, Germany (March 2014)

Skow, E.; Cunefare, K.; Erturk, A., "Power performance improvements for high pressure ripple energy harvesting: Smart Materials and Structures, vol. 23, p. 104011 (2014)

Skow, E.; Koontz, Z.; Han, C.; Cunefare, K.; Erturk, A., "Pressure ripple energy harvester enabling autonomous sensing", Proceedings of IFPE 2014, International Fluid Power Expo, Las Vegas, NV (March 2014)

Sprengel, M. and Ivantysynova, M., "Hardware-in-the-Loop Testing of a Novel Blended Hydraulic Hybrid Transmission", Proceedings of the 8th FPNI PhD Symposium, Lappeenranta, Finland (2014) **Backe Medal for Best Paper**

Sprengel, M. and Ivantysynova, M., "Investigation and Energetic Analysis of a Novel Blended Hydraulic Hybrid Power Split Transmission", Proceedings of the 9th International Fluid Power Conference (9IFK) (March 2014)

Sprengel, M. and Ivantysynova, M., "Recent Developments in a Novel Blended Hydraulic Hybrid Transmission", 2014 SAE Commercial Vehicle Engineering Congress, Rosemount, IL (September 2014)

Thiagarajan, D.; Dhar, S.; Vacca, A., “A Novel Fluid Structure Interaction-EHD Model and Optimization Procedure for an Asymmetrical Axially Balanced External Gear Machine”, Tribology Transactions, Vol. 58(2), pp. 274-287 (2015)

Thiagarajan, D.; Vacca, A., "A Numerical Procedure to Design the Optimal Axial Balance of Pressure Compensated Gear Machines", 8th FPNI Ph.D. Symposium on Fluid Power (2014)

Wang, F.; Bissen, M.; Ward, W.; Stelson, K., “Modeling and Design of a Hybrid Bicycle with Hydraulic Transmission,” The Ninth JFPS International Symposium on Fluid Power, Matsue, Japan (October 2014)

Wang, F. and Stelson, K., "Midsize wind turbines with hydraulic transmissions", Proceedings of the 53rd National Conference on Fluid Power, Las Vegas, NV (2014)

Wang, F., Stelson, K., "A Novel Pressure Controlled Hydro-mechanical Transmission", Proceedings of the ASME/BATH Symposium on Fluid Power & Motion Control, Bath, UK (September 2014)

Wilhelm, S., and Van de Ven, J., "Adjustable Linkage Pump: Efficiency Modeling and Experimental Validation", Journal of Mechanisms and Robotics, v. 7, n. 3. (2015)

Wilhelm, S., and Van de Ven, J., "Design of a Variable Displacement Triplex Pump", National Conference on Fluid Power, International Fluid Power Exposition, Las Vegas, NV (March 2014)

Wilhelm, S., and Van de Ven, J., "Efficiency Testing of an Adjustable Linkage Triplex Pump", ASME/BATH 2014 Symposium on Fluid Power & Motion Control, Bath, UK, FPMC2014-7856. (September 2014)

Winkelmann, A. and Barth, E., "System Dynamic Model and Design of Stirling Pump", Proceedings of the ASME/Bath Symposium on Fluid Power and Motion Control, Bath, UK, (2014)

Wondergem, A. and Ivantysynova, M., "The Impact of the Surface Shape of the Piston on Power Losses", Proceedings of the 8th FPNI PhD Symposium, Lappeenranta, Finland (June 2014)

Xiong, S. and Lumkes, J., "Coupled Physics Modelling for Bi-Directional Check Valve System", International Journal of Fluid Power, 15:2, 55-67 (2014)

Zhang, C.; Li, K.; Sun, Z., "Modeling of Piston Trajectory-based HCCI Combustion", Applied Energy [http://dx.doi.org 10.1016/j.apenergy.2014.11.007] (2015)

Zhang, C.; Li, K.; Sun, Z., "Modeling of Piston Trajectory-based HCCI Combustion", Proceedings of the 2014 ASME Dynamic Systems and Control Conference (October 2014)

Zhang, C.; Shirazi F.; Yan, B.; Simon T., "Design of an Interrupted-Plate Heat Exchanger Used in a Liquid-Piston Compression Chamber for Compressed Air Energy Storage", ASME Summer Heat Transfer (June 2014)

Zhang, C.; Yan, B. ; Wieberdink, J. , Li, P.; Van de Ven, J.; Loth, E.; Simon, T., "Thermal analysis of a compressor for application to compressed air energy storage", Applied Thermal Engineering, V. 73,:2, pp. 1402-1411 (2014)

Zhou, J.; Vacca, A.; Casoli, P., “A Novel Approach for Predicting the Operation of External Gear Pumps under Cavitating Conditions”, Simulation Modeling Practice and Theory (Elsevier), Vol. 45, pp. 35-49 (2014)

Zhou, J.; Vacca, A.; Casoli, P.; Lettini, A., "Investigation of the impact of Oil Aeration on Outlet Flow Oscillations in External Gear Pumps", Proceedings of IFPE 2014, International Fluid Power Expo, Las Vegas, NV (March 2014)

Thrust 2: Compactness

Cummins, J.; Pedchenko, A.; Barth, E.; Adams, D., “Advanced Strain Energy Accumulator: Materials, Modeling and Manufacturing”, Proceedings of the ASME/Bath Symposium on Fluid Power and Motion Control, Bath, UK (2014)

Lacey, L.; Maliki, A.; Bhattacharjee, D.; Veldhorst, J.; Ueda, J., "Design of fMRI-Compatible Hemiparesis Rehabilitation Device", Proceedings of the 2014 ASME Medical Device Conference (April 2014)

Lacey, L.; Maliki, A.; Bhattacharjee, D.; Veldhorst, J.; Ueda, J., "Design of MRI-Compatible Hemiparesis Rehabilitation Device", ASME Journal of Medical Devices, 8(2) [10.1115/1.4027028] (April 2014)

Strohmaier, K., Cronk, P., Knutson, A., and Van de Ven, J., 2014, "Experimental Studies of Viscous Loss in a Hydraulic Flywheel Accumulator", Proceedings of the National Conference on Fluid Power, International Fluid Power Exposition, Las Vegas, NV, 0369-000017, (March 2014)

Thrust 3: Effectiveness

Bair, S. and Qureshi, F., "Time-Temperature-Pressure Superposition in Polymer Thickened Liquid Lubricants", ASME Journal of Tribology 136(2), 021505 (February 2014)

Bair, S. and Vergne, P., "Classical EHL versus Quantitative EHL: A Perspective Part I: Real viscosity-pressure dependence and the viscosity-pressure coefficient for predicting film thickness", Tribology Letters, Volume 54, Issue 1, pp. 1-12 (April 2014)

Bair, S., "A Critical Evaluation of Film-Thickness-Derived Pressure-Viscosity Coefficients", Lubrication Science [DOI: 10.1002/ls.1284] (2014)

Bair, S., "The pressure and temperature dependence of volume and viscosity of four Diesel fuels", Fuel 135 pp. 112-119 (2014)

Bair, S.; Yamaguchi, T.; Brouwer, L.; Schwarze, H.; Vergne, P.; Poll, G., "Oscillatory and steady shear viscosity: The Cox-Merz rule, superposition, and application to EHL friction", Tribology International Volume 79, pp. 126-131 (November 2014)

Bair, S., "Density Scaling of the Thermal Conductivity of a Jet Oil", Tribology Transactions, Volume 57, Issue 4 (April 2014)

Cunefare, K.; Skow, E.; Erturk, A., "Design and modeling of hydraulic pressure energy harvesters for low dynamic pressure environments", Proceedings of ASME 2014 International Mechanical Engineering Congress and Exposition, Montreal, Canada, paper IMECE2014-38684 (November 2014)

Daepp, H. and Book, W., "Model Predictive Control for compliant pneumatic systems", Proceedings of the 2014 ASME Dynamic Systems and Control Conference (October 2014)

Daepp, H. and Book, W., "Predictive friction compensation for control of pneumatic actuators", Proceedings of the 8th FPNI PhD Symposium, Lappeenranta, Finland (June 2014)

Daepp, H. and Book, W., "Value of a high fidelity actuator model for dynamic simulation of a pneumatic rescue robot", 19th International Federation of Automatic Control (IFAC) World Congress (2014)

Davis, D.; Jimerson, B.; Stajsic, D.; Jiang, Z., "Trunk Kinematics of Pulling at or Below Sub-waist Height", Proceedings of the 2014 Industrial and Systems Engineering Conference (2014)

Desai, Y.; Davis, D.; Jiang, S.; Ward, A., "The Effect of Auditory Cues on Haptic-Controlled Excavator Operator Performance", Proceedings of the 2014 Industrial and Systems Engineering Conference (2014)

Huang, Y. and Salant, R., "Numerical Modelling of a Hydraulic Rod Seal with a Micro-Patterned Rod", Proceedings of the 18th International Sealing Conference, Stuttgart, pp.611-623 (October 2014)

Humphreys, H. and Book, W., "Advanced Hydraulically Actuated Patient Transfer Assist Device", Proceedings of the 8th FPNI PhD Symposium, Lappeenranta, Finland (June 2014)

Humphreys, H.; Book, W.; Huggins, J.; Jimerson, B., "Caretaker-Machine Collaborative Manipulation with an Advanced Hydraulically Actuated Patient Transfer Assist Device", Proceedings of the 2014 ASME Dynamic Systems and Control Conference (October 2014)

*Kim, T.; Kalbfleisch, P.; Ivantysynova, M., "The Effect of Cross Porting on Derived Displacement Volume", International Journal of Fluid Power (June 2014)

Li, P. and Wang, M., "Natural Storage Function for Passivity Based Trajectory Control of Hydraulic Actuators", IEEE/ASME Transactions on Mechatronics [10.1109/TMECH.2013.2266916] (June 2014)

Ritelli, G. and Vacca, A., "Experimental-Auto-Tuning Method for Active Vibration Damping Controller. The Case Study of a Hydraulic Crane", Proceedings of the International Fluid Power Conference (9 IFK), Aachen, Germany (March 2014)

Winck, R.; Elton, M.; Book, J., "A practical interface for coordinated position control of an excavator arm", Automation in Construction, pp. 46-58 (2015)

Test Beds and General

Beccani, M.; Di Natali, C.; Sliker, L.; Schoen, J.; Rentschler, M.; Valdastri, P., “Wireless Tissue Palpation for Intraoperative Detection of Lumps in Soft Tissue”, IEEE Transactions on Biomedical Engineering, Vol. 61, N. 2, pp. 353-361 (2014) **This paper was featured by IEEE Spectrum, IEEE TBME Highlights, and was on the cover of the February issue of IEEE Transactions on Biomedical Engineering**

Breidi, F.; Helmus, T.; Lumkes, J., "Development of Portable Pneumatic Educational Tool for STEM Education", Proceedings of IFPE 2014, International Fluid Power Expo, Las Vegas, NV (March 2014)

Chase, T.; Cheong, K.; Du, Z.; Li, P., "Design and Experimental Validation of a Virtual Vehicle Control Concept for Testing Hybrid Vehicles Using a Hydrostatic Dynamometer", Proceedings of the 2014 ASME Dynamic Systems and Control Conference (October 2014)

Cheong, K.; Du, Z.; Li, P.; Chase, T., "Hierarchical Control Strategy for Hybrid Hydro-Mechanical Powertrain", Proceedings of 2014 American Control Conference (2014)

Du, Z.; Cheong, K.; Li, P.; Chase, T., "Energy Management Strategy for a Power-Split Hydraulic Hybrid Vehicle Based on Lagrange Multiplier and Its Modifications", IEEE Transactions on Vehicular Technology (January 2015)

Garcia, J., Kuleshov, Y., and Lumkes, J., "Using fluid power workshops to increase STEM interest in K-12 students", Proceedings of the 2014 American Society for Engineering Education Annual Conference and Exposition, (June 2014)

Neubauer, B.; Nath, J.; Durfee, W., "Design of a portable hydraulic ankle-foot orthosis", Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society (2014)

Petrucci, M.; MacKinnon, C.; Hsiao-Wecksler, E. "A Step Towards Reducing Freezing of Gait in Parkinson’s Disease: Using a Portable Powered Orthosis", Proceedings of the 6th World Congress of Biomechanics, Boston, MA, (July 2014)

Xia, J. and Durfee, W., "Experimentally validated models of O-ring seals for tiny hydraulic cylinders", Proceedings of the ASME/Bath Symposium on Fluid Power and Motion Control, Bath, England (2014)

Year 10 Annual Report Publications

Thrust 1: Efficiency

Breidi, Farid; Helmus, Tyler; Lumkes, John. "The impact of peak-and-hold and reverse current solenoid driving strategies on the dynamic performance of commercial cartridge valves in a digital pump/motor." International Journal of Fluid Power 17:1 pp. 37-47 (2016). DOI: 10.1080/14399776.2015.1120138

Cook, Douglas. "Peak Force Measurements for a Combustion-Driven, Direct-Conversion, Actuation System for Powered Orthoses." ASME Journal of Medical Devices 9:2 (2015). DOI: 10.1115/1.4030149.

Cummins, Joshua J., Barth, Eric J. and Adams, Douglas E. "Modeling of a Pneumatic Strain Energy Accumulator for Variable System Configurations with Quantified Projections of Energy Efficiency Increases." Proceedings of the 2015 Bath/ASME Symposium on Fluid Power and Motion Control (October 2015)

Frosina, E., Senatore, A., Buono, D., Stelson, K. A., Wang, F., Mohanty, B. and Gust, M. J. "Vane Pump Power Split Transmission: Three Dimensional Computational Fluid Dynamics Modeling", Proceedings of the 2015 Bath/ASME Symposium on Fluid Power and Motion Control (October 2015)

Garcia, JM., Johnson, J. and Michael, P., "Toward the Development of a Pump Energy Rating System based upon Performance Indexes", Proceedings of the Fluid Power Innovation Research Conference, Proceedings of the Fluid Power Innovation Research Conference, Chicago, IL (2015)

Lee, Sangyoon and Li, Perry. "Passive Control of a Hydraulic Human Power Amplifier Using a Hydraulic Transformer", Proceedings of the ASME 2015 Dynamic Systems and Control Conference. October 28-30 (2015)

Lee, Sangyoon, Li, Perry. "Passivity Based Backstepping Control for Trajectory Tracking Using a Hydraulic Transformer", Proceedings of the ASME/BATH 2015 Symposium on Fluid Power and Motion Control. Chicago, IL, October 12-14 (2015): pp. V001T01A064. DOI:10.1115/FPMC2015-9618

Mettakadapa, S., S. Bair, S. Aoki, M. Kobessho, L. Carter, H. Kamimura, and P. Michael. "A Fluid Property Model for Piston Pump Case Drain and Pressure Compensator Flow Losses." Proceedings of the ASME/BATH 2015 Symposium on Fluid Power and Motion Control. Chicago, IL Oct. 12-14 (2015): pp. V001T01A009. doi:10.1115/FPMC2015-9515

Michael, P., Mettakadapa, S. and Shahahmadi, S., "An Adsorption Model for Hydraulic Motor Lubrication", ASME Journal of Tribology 138:1 (2015). DOI:10.1115/1.4031139

Mohanty, B., Wang, F. and Stelson, K. A., "Design of a Vane Pump Power Split Transmission for a Highway Vehicle", 14th Scandinavian International Conference on Fluid Power SICFP2015 (2015)

Mohanty, B., Wang, F. and Stelson, K.A. "Performance Study of Vane Pump Power Split Transmission for a Highway Vehicle." ASME/BATH 2015 Symposium on Fluid Power and Motion Control. Chicago, IL Oct. 12-14 (2015): pp. V001T01A028 DOI:10.1115/FPMC2015-9545

Pellegri, M. and Vacca, A. "A CFD-Radial Motion Coupled Model for the Evaluation of the Features of Journal Bearings in External Gear Machines." ASME/BATH 2015 Symposium on Fluid Power and Motion Control. Chicago, IL Oct. 12-14 (2015): pp. V001T01A025 DOI:10.1115/FPMC2015-9540

Pena, O., Leamy, M. "An Efficient Architecture for Energy Recovery in Hydraulic Elevators." International Journal of Fluid Power 16:2: (2015): pp.83-98. http://dx.doi.org/10.1080/14399776.2015.1055991

Pena, O., Leamy, M. "Optimal Control of a New Hydraulic Elevator Architecture." Proceedings of the 2015 Fluid Power Innovation & Research Conference (FPIRC15), Chicago, IL, Oct. 14-16 (2015)

Rao, L., Schuh, J., Ewoldt, R. and Allison, JT. "On Using Adaptive Surrogate Modeling in Design For Efficient Fluid Power." ASME 2015 International Design Engineering Technical Conferences, DETC2015-46832, Boston, MA, USA, (2015). DOI: 10.1115/DETC2015-46832

Wang, F. and Stelson, K. A. "A Hydraulic Hybrid Wheel Loader with a Novel Power Split Hydraulic Transmission." 14th Scandinavian International Conference on Fluid Power SICFP2015 (2015)

Wondergem, A. and Ivantysynova, M. "The Impact of Micro-Surface Shaping on the Piston/Cylinder Interface of Swash Plate Type Machines." Proceedings of the ASME/Bath 2015 Symposium on Fluid Power and Motion Control, Chicago, Illinois, October 12–14 (2015): pp. V001T01A060 DOI:10.1115/FPMC2015-9610

Xiao, Y., Guan, C., Li, P. Y. and Wang, F. "Optimal Design of a Compound Hybrid System Consists of Torque Coupling and Energy Regeneration for Hydraulic Hybrid Excavator." 2015 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM), Busan, Korea, July 7-11 (2015): pp.1525 – 1530.

Yan, B., Wieberndink, J., Shirazi, F., Li, P.Y., Simon, T. W., Van de Ven, J. D. "Experimental Study of Heat Transfer Enhancement in a Liquid Piston Compressor/Expander Using Porous Media Inserts." Applied Energy Vol.154, September (2015): pp. 40-50. http://dx.doi.org/10.1016/j.apenergy.2015.04.106

Zhang, C., Li, P. Y., Van de Ven, J. D. and Simon, T.W. "Design Analysis of a Liquid-Piston Compression Chamber with Application to Compressed Air Energy Storage." ASME-AIT-UIT 2015 Conference on Thermal Energy Systems: Production, Storage, Utilization and the Environment Napoli, Italy, May 17-20 (2015)

Zhang, C., Li, K. and Sun, Z. "Modeling of Piston Trajectory-based HCCI Combustion Enable by a Free Piston Engine." Applied Energy vol.139 (2015): pp. 313-326. DOI:10.1016/j.apenergy.2014.11.007

Zhang, C., Li, K. and Sun, Z. "A Control-oriented Model for Piston Trajectory-based HCCI Combustion." Proceedings of American Control Conference Chicago, IL (2015) DOI:10.1109/ACC.2015.7172077

Thrust 2: Compactness

Altare, G., Vacca, A, "A Design Solution for Efficient and Compact Electro-Hydraulic Actuators." Proceedings of the 2nd Intereneational Conference on Dynamics and Vibroacoustics of Machines (DVM2014) Samara, Russia, September 15-17, 2014. Procedia Engineering 106 (2015): pp.6-16

Deppen, T.O., A.G. Alleyne, J.J. Meer and K.A. Stelson. "Comparative Study of Energy Management Strategies for Hydraulic Hybrids", Journal of Dynamic Systems, Measurement and Control, vol. 137, no. 4, (April 2015)

Hemstad, E., Fikru, N. and Chase, T. "CCEFP Update: MEMS technology helping to create micro-pneumatic valves." http://www.pneumatictips.com, (2015)

Johnson, D., Kittelson, D. and Durfee, W. "Testing and modeling of a miniature air compressor for a prototype free-piston engine." Proceedings of the ASME/BATH 2015 Symposium on Fluid Power & Motion Control Chicago, IL October 12-14, (2015): pp. V001T01A061 DOI:10.1115/FPMC2015-9611

Kovalenko, I., Lai, J., Williams, J., Maliki, A. and Ueda, J. "Design and Testing of a Pneumatic Hemiparesis Rehabilitation Device for a Neurofacilitation Exercise." Journal of Medical Devices V.9(3) September (2015). DOI: 10.1115/1.4030548

Li, P. Y. and Saadat, M. "An Approach to Reduce the Flow Requirement for a Liquid Piston Air Compressor/Expander in a Compressed Air Energy Storage (CAES) System." 2nd Offshore Energy and Storage Symposium (OSES), Edinburgh, U.K., July (2015).

Saadat, M. and Li, P. Y., "Combined Optimal Design and Control of a Near-isothermal Liquid Piston Air Compressor/Expander for a Compressed Air Energy Storage (CAES) System for Wind Turbines." Proceedings of the ASME 2015 DSCC Conferrence DSCC2015, Columbus, OH., October 28-30, (2015)

Singh, G., Farooq, D., Xiao, C., Oo, Y., Tawfick, S.H., Ferreira, P., Slavens, B., Krishnan, G., and Hsiao-Wecksler, E.T. "Project 2F.1: Soft Pneumatic Actuator for Arm Orthosis." Proceedings of the 2015 Fluid Power Innovation and Research Conference (FPIRC), Chicago, IL. October 14-16, (2015).

Strohmaier, K.G., Cronk, P.M., Van de Ven, J.D. "Design optimization of a hydraulic flywheel accumulator for a hydraulic hybrid vehicle." International Journal of Fluid Power vol.16(3) (2015): pp.149-162. DOI: 10.1080/14399776.2015.1103102 http://dx.doi.org/10.1080/14399776.2015.1103102

Turkseven, M., Kovalenko, I., Kim, E., and Ueda, J. "Analysis of a Tele-Operated MRI-Compatible Vane Actuator for Neuromuscular Facilitation in Hemiparetic Limbs." 2015 ASME Dynamic Systems and Control Conference (DSCC2015), Columbus, OH, October 28-30, (2015): pp. V002T27A012 DOI:10.1115/DSCC2015-9992

Ueda, J., Lacey, L., Turkseven, M., Shinohara, M., Kovalenko, I., Kim, E., Sulejmani, F. "Robotic Neuromuscular Facilitation for Regaining Neural Activation in Hemiparetic Limbs." Proceedings of ASME 2015 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, IDETC/CIE, Boston, Massachusetts, August 2-5 (2015):pp. V05AT08A050 DOI:10.1115/DETC2015-48085

Winkelmann, A., Barth, E. J. "Design, Modeling, and Experimental Validation of a Stirling Pressurizer with a Controlled Displacer Piston." Mechatronics, IEEE/ASME Transactions on, Mechatronics, IEEE/ASME Transactions on November 11, (2015): Vol.PP(99). DOI: 10.1109/TMECH.2015.2499706

Winkelmann, A., Barth, E.J. "Stirling Power Unit: Impact of a Controlled Displacer Piston on Efficiency and Power Output." ASME/BATH 2015 Symposium on Fluid Power and Motion Control
Chicago, Illinois, USA, October 12–14, (2015): pp. V001T01A059 DOI:10.1115/FPMC2015-9609

Thrust 3: Effectiveness

Bair, S., Habchi, W., Sperka, P., and Hartl, M. "Quantitative elastohydrodynamic film forming for a gear oil with complex shear-thinning." Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology (2015). DOI: 10.1177/1350650115600185

Bair, Scott, "Choosing Pressure-Viscosity Relations." High Temperatures--High Pressures Vol.44(6) (2015): pp.415-428.

Bair, Scott. "Comment on New Experimental Data and Reference Models for the Viscosity and Density of Squalane." Journal of Chemical & Engineering Data vol.60(4) (2015):pp.1211-1212.
DOI: 10.1021/je501147a

Bianchi, R., Ritelli G.F., Vacca A. and Ruggeri, M. "A Frequency-Based Methodology for the Reduction of Payload Oscillations in Hydraulic Load Handling Machines." ASME/BATH 2015 Symposium on Fluid Power and Motion Control Chicago, Illinois, October 12–14 (2015): pp. V001T01A004 DOI:10.1115/FPMC2015-9510

*Opperwall, T. and Vacca, A. “Modeling Noise Sources and Propagation in Displacement Machines and Hydraulic Lines.” JFPS International Journal of Fluid Power System, Vol. 8(1) (2015): pp. 30-37. http://doi.org/10.5739/jfpsij.8.30

*Pan J., Cheng Y., Vacca A., Yang J. “Effect of Temperature on Grease Flow Properties in Pipes.” Tribology Transactions November (2015). DOI: 10.1080/10402004.2015.1093205

Skow, E., Koontz, Z., Cunefare, K. and Erturk, A. “Hydraulic pressure energy harvester enhanced by Helmholtz resonator”, Proceedings of SPIE, Active and Passive Smart Structures and Integrated Systems 2015, April (2015). DOI:10.1117/12.2084343

Tang, Q.; Chen, J.; Vacca A. “Tribological Behaviors of Carbon Fiber Reinforced PEEK Sliding on Ion Nitrided 2Cr13 Steel Lubricated with Tap Water.” Tribology Transactions Vol. 58(4) (2015): pp: 691-697 DOI:10.1080/10402004.2014.990593

Testbeds and General

*Heinrich, M., Mattson, C., Ramuta, M., Stock, J., Liang, J., Morris, M., Tippett, S., Hsiao-Wecksler, E. and Henderson, J. “Pneumatic Elbow Simulator of Spasticity and Rigidity for Training of Healthcare Clinicians.” Proceedings of the 2015 Fluid Power Innovation and Research Conference (FPIRC) Chicago, IL., October (2015)

*Singh, G., Farooq, D., Xiao, C., Oo, Y., Tawfick, S.H., Ferreira, P., Slavens, B., Krishnan, G. and Hsiao-Wecksler, E.T. “Project 2F.1: Soft Pneumatic Actuator for Arm Orthosis.” Proceedings of the 2015 Fluid Power Innovation and Research Conference (FPIRC) Chicago, IL. October (2015)

Zhang, C. and Sun, Z. “A New Approach to Reduce Engine-out Emissions Enabled by Trajectory-based Combustion Control.” ASME 2015 Dynamic Systems and Control Conference Columbus, Ohio, October 28-30 (2015): pp.V001T11A002 DOI: 10.1115/DSCC2015-9838

This page is intentionally left blank

APPENDIX III

Year 10 Highlights

This page is intentionally left blank

Research Highlights – Systems

Energy Efficient Hydraulic Hybrid Excavator

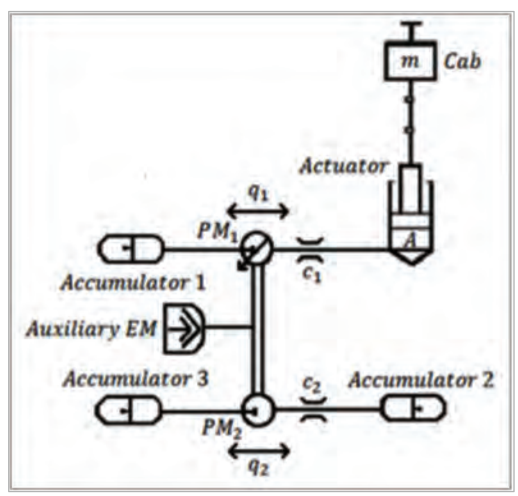
In 2011, CCEFP researchers at Purdue filed a patent for a hydraulic hybrid system for an excavator. The novel hydraulic hybrid system, called displacement control, combines hydraulic hybrid technology with energy efficient displacement controlled actuation. Hydraulic accumulators are used to store and 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 displacement controlled (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 OEM. Caterpillar launched its first production hydraulic hybrid excavator in 2013. The excavator provides up to 33% fuel savings over the non-hybrid version. These two excavators are pictures below.

CCEFP Test Bed 1: Hydraulic Hybrid Excavator

Novel Energy Recovery Architecture for Use in Hydraulic Elevators

Hydraulic elevators suffer from high inefficiencies due to fluid throttling and costly mechanical to electric energy conversion, both of which are currently required for proper control of an elevator. Together with the continuous improvement of the traction elevator, this has caused a loss of market share for the hydraulic elevator. The elimination of fluid throttling and electromechanical energy conversion improve system efficiency compared to the state-of-the-art. We have conceived a novel hydraulic system using a hydraulic transformer that requires minimal electromechanical energy conversion and eliminates throttling. Simulation results of the novel system show promising efficiency improvements when compared to existing systems. Algorithms for effectively controlling the architecture have been developed.



Schematic of Energy Recapture System for Hydraulic Elevators

Pneumatic Ankle Foot Orthosis

Walking impairment presents major personal, social and economic burdens on stroke victims. One method for improving the walking among post-stroke persons involves the use of abd ankle-foot orthosis (AFOs). Researchers have reported mixed results when evaluating the clinical and biomechanical advantages of patient-specific, physician-prescribed, custom AFOs in post-stroke persons.

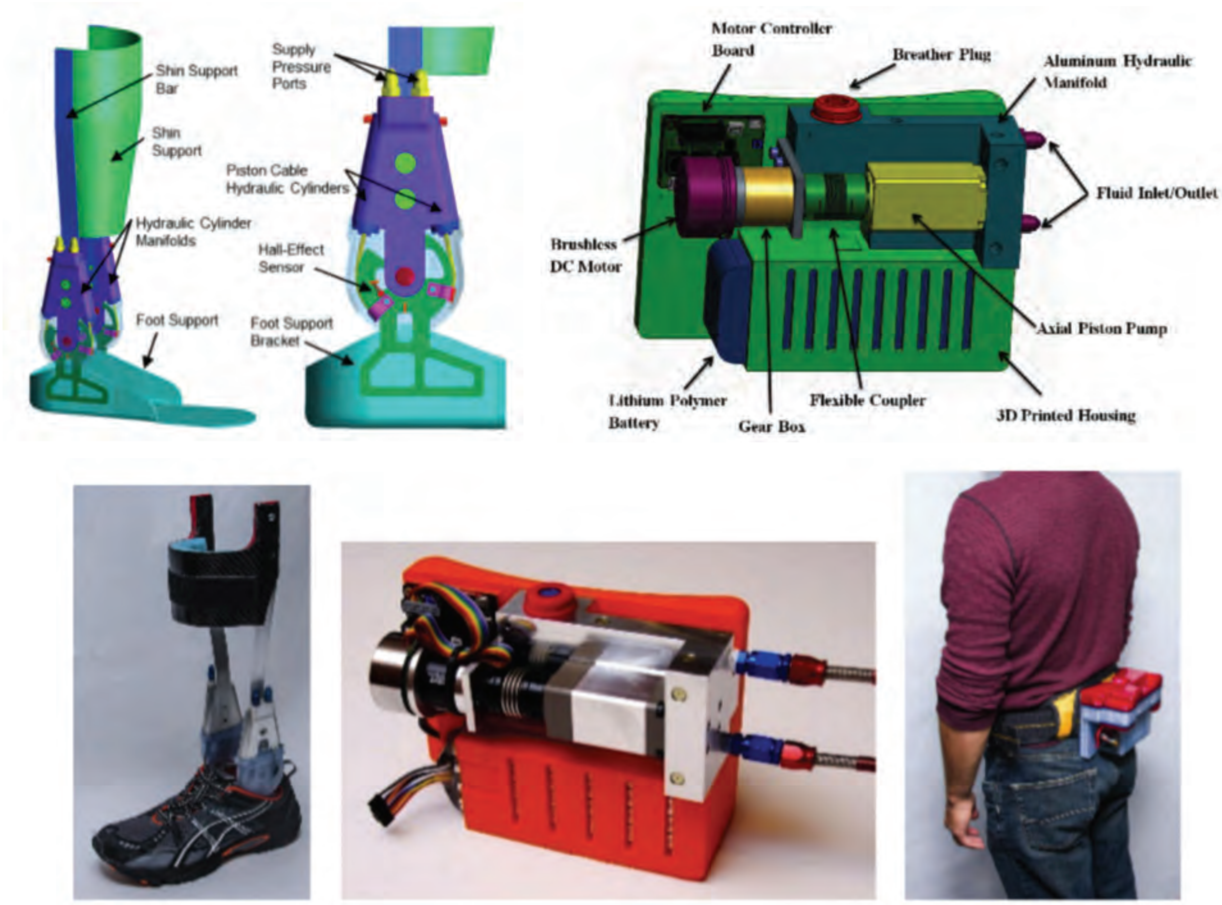
Current, commercially-available AFOs are passive or semi-active devices that provide joint stability and motion control, with the primary goal of holding the foot in a neutral position during the swing phase of gait to correct for foot drop. We are exploring whether the pneumatic Portable Powered Ankle-Foot Orthosis (PPAFO) can be used as a successful gait assistance device.

Pneumatic ankle-foot orthosis in clinical trial

In collaboration with researchers at the Rehabilitation Institute of Chicago, testing has begun to explore the advantages of the PPAFO compared to other assistive devices (e.g., tibial stimulators and commercially-available passive AFOs) in post-stroke subjects. The devices are being compared by asking each participant to complete a set of clinically-accepted walking tasks with both the PPAFO and their personal device. During each walking task, the subject's oxygen consumption is being measured as well using standard outcome measures of the task.

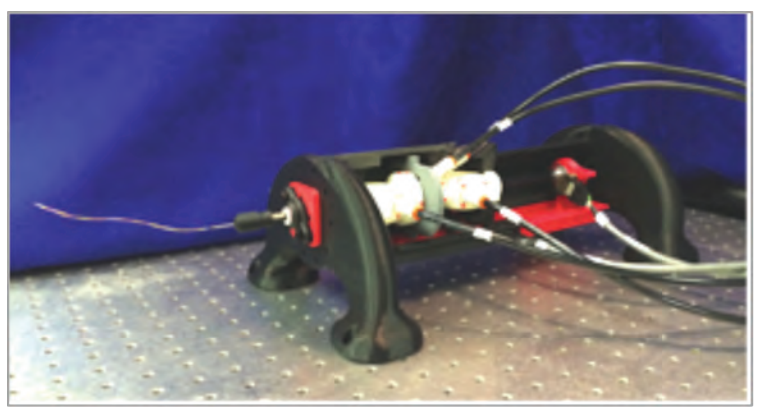
Hydraulic Ankle Foot Orthosis

The CCEFP hydraulic ankle foot orthosis (HAFO) demonstrates the capabilities and advantages of tiny hydraulics for untethered powered human assist machines. A key part of the work was system and component level modeling to predict the efficiency and weight of small hydraulic systems. The models, including simple models of O-ring seals, were validated by experimental data and showed that first, hydraulic exoskeletons must operate at high pressure (>1000 psi) to take advantage of their inherent power and force density and second, that actuator bore sizes of less than about 4 mm cause a rapid drop in system efficiency. The models also enabled system-level thinking of tiny hydraulic designs where every component in the power transmission path (battery, electric motor, hydraulic pump, conduit, cylinder, linear-to-rotary transmission, ankle motion) is a transformer whose transmission ratio influences system efficiency and component weight. These concepts have been realized in the HAFO where the power supply is worn at the waist leaving small hydraulic actuators at the ankle to minimize the weight carried on the foot. The HAFO runs at 2,000 psi, provides 90 Nm at 100 degrees/second, weighs less than 1 kg at the ankle and fits under a pair of loose-fitting pants.



HAFO layout (top) and prototype (bottom)

<u>*MRI Guided Surgery Using Precision Pneumatics*</u>



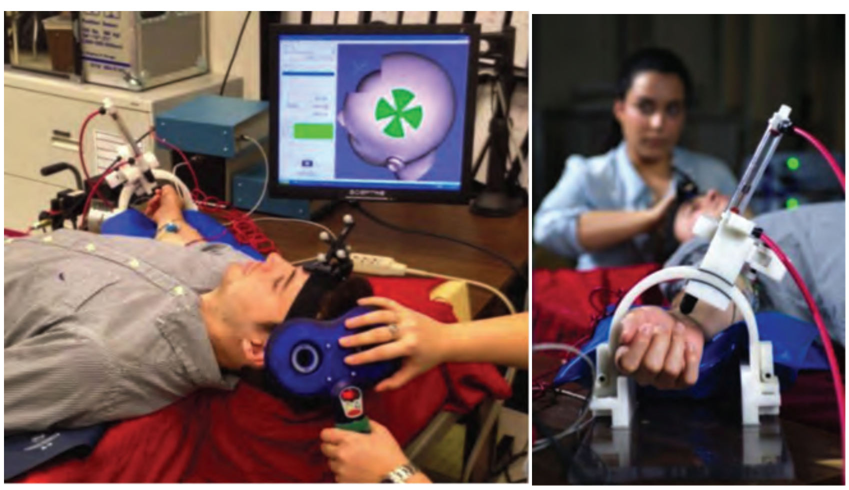
Photograph of prototype with helix-shaped concentric tube needle. One half of device housing is not shown to expose inner working parts.

Fluid power actuators (hydraulic and pneumatic) are well suited for electromagnetically sensitive environments such as magnetic resonance imaging (MRI) machines because they enable intraoperative MRI guidance of robotically steerable needles. A technical barrier to using fluid power in MRI-guided surgical systems is the absence of commercial, off-the-shelf fluid power actuators that are sterilizable and intrinsically safe. To fill this technology gap, researchers at Vanderbilt University and Milwaukee School of Engineering designed and built a pneumatic stepper actuator. Designed using corrugated diaphragm theory; one helix-shaped bellows and one toroid-shaped bellows provide pure rotation and translation. The actuator module functions as a two degree-of-freedom needle driver; that is, the two bellows directly translate and rotate the base of one tube of a steerable needle. Several modules can be cascaded together for steerable needles comprised of multiple, concentric tubes. For needle tip translations and rotations, mechanical stops limit the bellows' movements to maximum unplanned step sizes of 0.5 mm and 0.5 degrees, which are acceptably safe in the event of a systems failure. Additively manufactured, the prototype device is compact and hermetically sealed for sterilizability. The linear bellows produced peak forces of 7.4 lb_f and -6.0 lb_f for needle insertion and retraction, respectively. The rotary bellows produced peak torques of ±0.60 lb_f-in. A precision, sub-step controller allows translations and rotations less than full step increments, such that mean steady-state errors of 0.013 mm and 0.29 degrees were achieved with the prototype shown below.

Pneumatic Control of Nerve Impulses for Stroke Rehabilitation using fMRI

This project was designed to understand the neuromechanical mechanisms associated with repetitive facilitation exercise (RFE) for stroke survivors to gain functional recovery of their hemiparetic limbs. RFE, a new effective method for stroke patients proposed by Dr. Kawahira of Japan, consists of mechanical stimulation to a dysfunctional muscle by a gentle tap at the muscle inducing a stretch reflex response at the brain. This exercise facilitates the reorganization of neural pathways by overlapping the stretch reflex response with a voluntary motor command signal by the patient, leading to muscle response. Although the outcomes of RFE treatment obtained so far are promising, the hypothesized mechanism under RFE still awaits verification with neurological data. Functional magnetic resonance imaging (fMRI) technology can be used on the brain regions for clarifying the effects of RFE therapy and the underlying mechanism

The first prototype of RFE rehabilitation device that replicates the RFE procedure was built and tested with trans cranial magnetic stimulation (TMS), simulating the weak motor command signal of stroke patients. This device has a pneumatically actuated medical hammer and it is made up with fMRI-compatible material. Mechanical stimulation given by the medical hammer evokes the stretch reflex response at the tendon of interest. Subject received mechanical stimulation and TMS with various time intervals between the two to observe the temporal dynamics of RFE. Human subject data shows that there is a critical time window between two signals that evokes muscle response, showing that treatment this contribute to regaining neural functionality by RFE.



Stroke Rehabilitation Using fMRI Experimental Setup

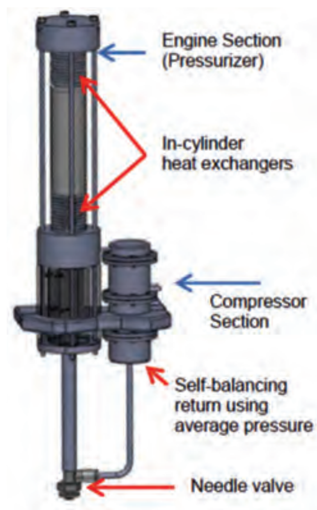
Hydrostatic Transmissions for Wind Power

In a utility scale wind turbine, there is an eighty to one hundred times increase in rotational speed between the turbine and the generator. This required speed increase is currently achieved with a mechanical gearbox. The gearbox experiences high loads during wind gusts and the resulting stresses are transferred from the gearbox to the generator. As a consequence, two of the highest maintenance costs in a wind turbine are for gearbox and generator bearing replacement. At CCEFP we are replacing the mechanical gearbox with a hydrostatic transmission (HST). Since the power path in an HST is hydraulic, the inherent compliance in the fluid and provides a damping effect resulting in a large stress reduction in the gearbox and generator during wind gusts. The HST, a continuously variable transmission, also allows the generator to run at constant speed regardless of wind speed. This reduces the need for power electronics, lowering cost, improving efficiency and further reliability. An associated project with an industry partner investigated the use of HSTs in offshore wind turbines. High reliability and low maintenance are especially important in offshore wind turbines.

Research Highlights – Enabling Technologies (Power)

Controlled Stirling Fluid Power Unit

The lack of suitable energy sources is extremely limiting for powered portable devices such as exoskeletons, powered prosthetics and orthotics, human-assist devices, and mobile robots. Using batteries as the source of energy and motors as actuators results in systems that are heavy, incapable of force and power densities adequate for human-scale applications, and exhibit inadequate operational durations. The controlled Stirling fluid power unit is a potential fluid power solution to this problem. This power unit is a Stirling engine that pumps hydraulic fluid or compresses air, depending on the application. The power unit uses hydrocarbon fuel as its energy source. It is compact and silent, with no internal combustion. A highly efficiency Stirling cycle is achieved by controlling the motion of a displacer piston inside the engine resulting in a sealed engine section that produces large pressure swings that can be used to pump hydraulic fluid or compress air. Current testing of the prototype and validated analytical models show that the unit can reach a hydraulic output pressure of 70 bar with power output ranging from 50 to 200 W. The target energy density is four times that of batteries and the target power density when coupled with a highly power dense fluid power actuator is five times than that of DC motors. This technological leap will enable a much-needed solution to the current inadequacy of power units for untethered applications.



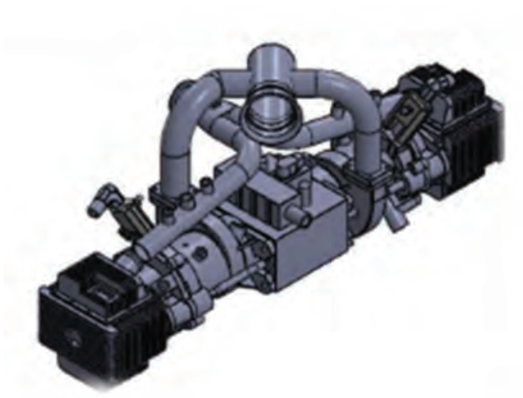
Controlled Stirling power unit prototype

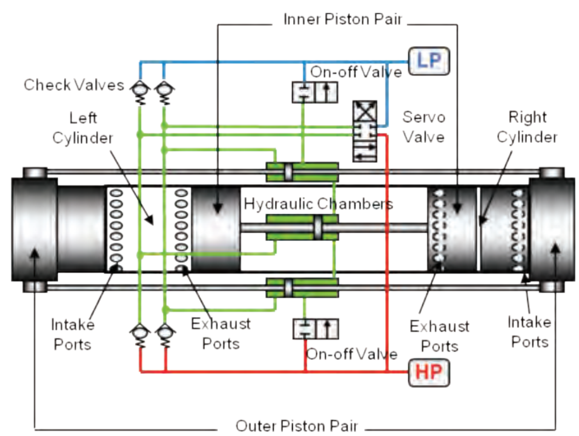
Free Piston Engine Pump

Currently, fluid power is generated for both on-road and off-road mobile applications using an internal combustion engine (ICE) coupled to a rotational hydraulic pump. The main drawbacks of this configuration are low system efficiency and complex design of both the ICE and the hydraulic pumping system. The free piston engine (FPE) is an alternative that offers the ultimate flexibility for variable compression ratio control by eliminating the crankshaft. The merit of this setup lies in its simple design with few moving parts, resulting in a compact engine with low maintenance cost and reduced frictional losses. As shown in the images below, linear hydraulic pumps are integrated into the engine block to produce hydraulic flow. This design eliminates the need for mechanical linkages between components, drastically increasing the modularity of the system.

The major technical barrier for the FPE is the large cycle-to-cycle variation, especially during transient operation. Therefore a robust and precise piston motion controller was designed to ensure stable engine operation. The controller acts as a "virtual crankshaft" guiding the piston to follow a reference trajectory via the hydraulic actuator (servo valve) by utilizing energy from the storage element. The advantage of the active motion controller lies in its ability to precisely track and shape the piston trajectory. The reference trajectory of the virtual crankshaft can be altered digitally, in real-time, to achieve a wide range of piston motions, thus obtaining maximum engine efficiency for various operating points. The virtual crankshaft also enables the engine to have a variable compression ratio, allowing multi-fuel operation and permiting HCCI combustion.

Experimental results have demonstrated the feasibility and promise of the technology. The virtual crankshaft accurately tracks desired piston motion. Experiments on engines using HCCI combustion at Sandia National Lab have demonstrated 56% thermal efficiency with virtually no NOx emissions. Typical peak efficiency is 32% for an SI engine and 42% for a diesel engine.

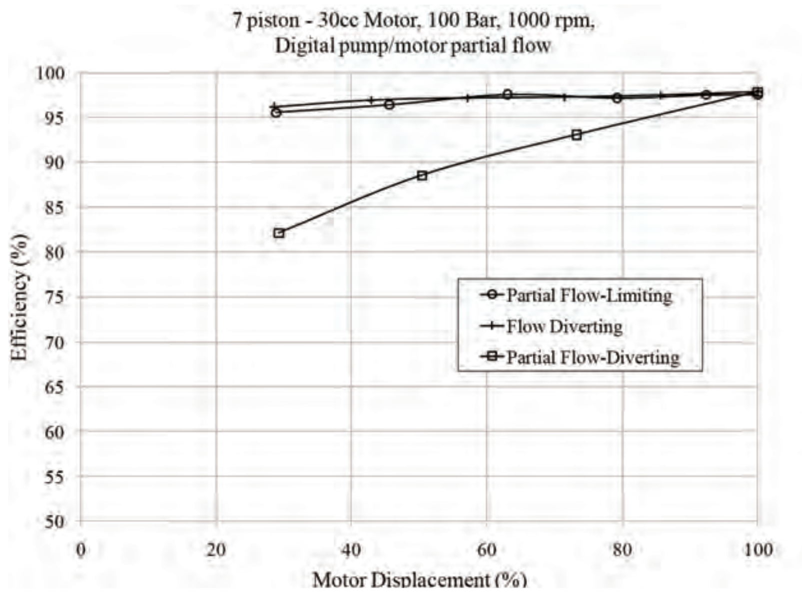




Free Piston Engine-Driven Hydraulic Pump. *Schematic of the Free Piston Engine Hydraulic Pump.*

Variable Displacement Digital Pump/Motor

The goal of this project is to overcome a major system efficiency limitation in the fluid power industry by providing a high bandwidth and efficient four-quadrant pump/motor. This is accomplished by providing an accurate simulation model to predict the effects of using actively controlled on/off valves to replace the valve plate timing in hydraulic pump/motors, and using the latest designs of high speed valves. As can be seen in the figure below, the variable displacement pump/motor maintains high operating efficiencies at lower displacements. It is also capable of high bandwidth four-quadrant operation. Improving pump/motor efficiency, particularly at lower displacements with four-quadrant capability, will strengthen existing markets and enable new markets by improving efficiency and effectiveness. A prototype has been constructed and tested, validating the concept.



Pump valve loss and piston leakage, motoring efficiency

Miniature Free Piston Engine Compressor

CCEFP researchers have developed a miniature free-piston engine compressor for the fluid power orthosis. This device can be used on small mobile applications, opening new markets for the fluid power industry. Developing a small engine compressor is not as straightforward as developing a larger engine because designing tiny valves, sensors, actuators is challenging and the behavior of ignition is different. Fabricating miniature components with tight tolerances is also not easy and some of the basic assumptions used in designing larger engines are not valid at this scale.

The miniature free piston engine compressor has a tiny homogeneous charge compression ignition (HCCI) engine compressor that creates compressed air at 80 psi for small powered devices such as an active ankle foot orthosis or a powered construction tool. The prototype device is the world's smallest air compressor. Developing the tiny engine requires comprehensive mathematical models of the ignition, fluid flow and mechanical motion of the parts and clever manufacturing methods. Recent results have led to the first ever models of small engines that power model aircraft, useful benchmarking devices for the new CCEFP engine. Performance measurements on the tiny engine-compressor prototypes are being used to improve and calibrate the mathematical models. Extensive work is going into accurate models of the combustion and scavenging processes, as they are the key to high operating efficiency. Plans include improving the tiny engine compressor efficiency and to use di-methyl ether (DME) fuel, a low emission, non-toxic alternative that has excellent combustion and emission characteristics.

World's smallest free-piston engine for human-scale mobile fluid power applications.

Variable Linkage Pump

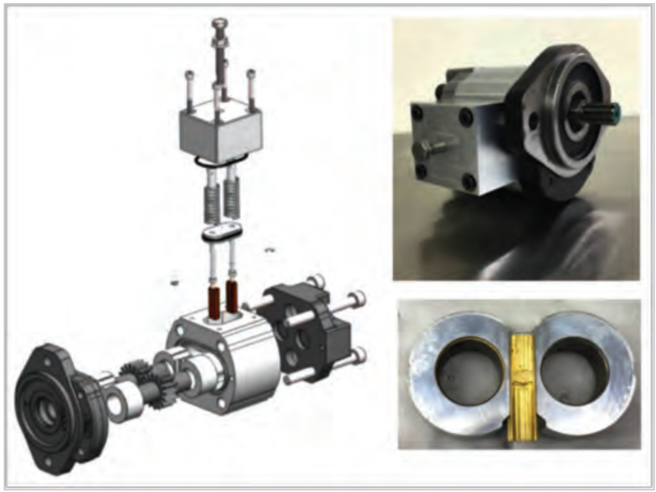
In an affiliated research project on compressed air energy storage, a novel variable displacement pump driven by an adjustable linkage was invented. Through an NSF PFI:AIR Technology Translation project, the team is translating the adjustable linkage pump to fill the need for a hydraulic pump with high efficiency at low volumetric displacement. The project has resulted in a functional prototype of a multi-cylinder variable displacement linkage pump. This adjustable linkage pump has the following novel features: 1) it uses low friction pin joints, 2) it can reach true zero displacement, 3) the piston reaches the same top dead center position regardless of the displacement, and 4) it can pump corrosive fluids. These features improve efficiency and allow the pump to be used in a wide range of applications and environments, including applications where current variable displacement hydraulic pumps are unsuitable. This project addresses the following technology gaps as it translates from research to commercial application: construction of a dynamic model of the pump, construction of a framework for multi-domain multi-objective optimization of machines with mechanisms and applying the method to optimize the pump for water pumping applications, designing a multi-cylinder prototype for water pumping with low flow ripple, and testing the prototype in an industrial application.

Adjustable Linkage Pump CAD Model

Adjustable Linkage Pump Prototype

Variable Displacement External Gear Machine

A novel concept for a variable delivery flow unit based on the classic external gear machine design has been formulated. After some proof of concept experiments performed in 2013, a fully operational prototype was realized and tested in 2014. The figure below shows some details of the prototype. The new machine possesses the well-known advantages of traditional external gear machines such as low cost, compact units, good reliability and reasonable efficiency. The proposed design also allows for variable delivery flow, while maintaining an energy efficiency level comparable to other variable displacement machines. Although unit designs for higher flow variation have been formulated, the prototype used for the experiments has a displacement variation of 35%. This new concept for low cost variable displacement units has the potential to substitute current fixed displacement units in many applications such as charge pumps in hydrostatic transmissions, or hydraulic fan drives, with significant reduction of fuel consumption.

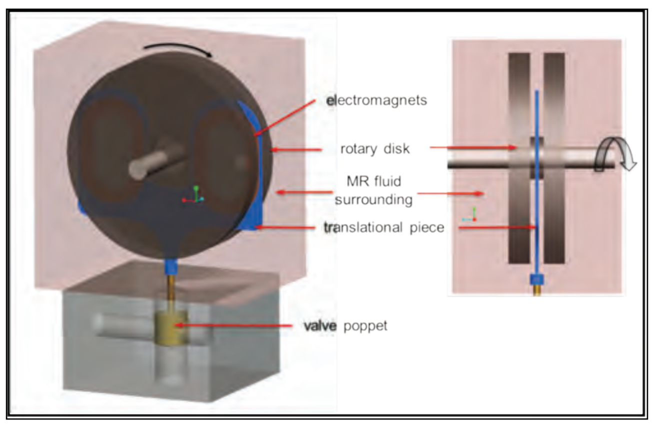


Exploded view of the proposed variable displacement external gear machine as well as the prototype produced as an outcome of project 1F.1

Research Highlights – Enabling Technologies (Sensing and Control)

High Performance MR Valve Actuation

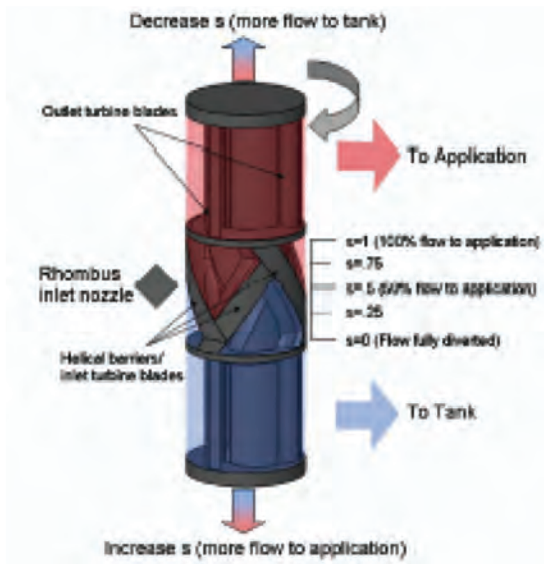
A novel high-speed valve actuation system capable of proportional and bidirectional operation has been developed and tested. It can be used to actuate poppet or spool type valves and does not require a pilot pressure source. Multiple actuators and valves can be compactly stacked on a single rotating shaft. The proof-of-concept actuator uses magnetorheological (MR) fluid as the coupler between the rotary and translational pieces. It experimentally achieved a 1.5mm stroke in 4.5ms (equivalent to the design target of 100L/min @5bar) and scales favorably, achieving a 7mm stroke in 10ms, enabling the actuator to be used in large flow rate valves. The simulation model accurately predicted the measured response, and the validated model is being used to optimize the design. With an improved coil design the valve will have a faster response while using less power per switch.



High Speed Valve with Energy Coupler Actuator (ECA) using MR fluid

Self-Powered Rotary PWM Valve

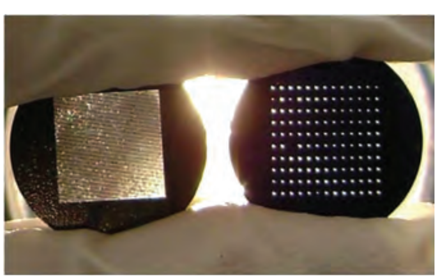
A major energy loss in current fluid power systems is from the metering control valves that dissipate energy through partially opened valve orifices. Replacing them with throttle-less methods will increase energy efficiency significantly. Pulse width modulation (PWM) of on/off valves that are either fully open or fully closed is a potential approach for throttle-less control. This approach is analogous to switched mode converters in power electronics. A primary challenge to realizing PWM control of fluid power systems is the lack of high-speed on/off valves. These on/off valves must have large orifices (to allow large flow to pass through at low pressure drops), have fast transitions (to reduce the time when the valve is partially open), and must operate at high PWM frequencies (to reduce ripple and to achieve high control bandwidth). Typically, a control valve consists of a linear translating element such as a spool or poppet that opens and shuts an orifice. Actuating such a valve at high frequency requires rapidly acceleration and deceleration, which in turn requires large actuators and power input proportional to the third power of the frequency. To overcome this challenge, a self-spinning rotary on/off valve has been developed at the CCEFP. The valve is turned on and off as the spool rotates and the PWM duty ratio is adjusted by translating the spool axially. Since the spool is continuously rotating, rapid acceleration and deceleration is not required, and the power input is proportional to the second power of frequency allowing much faster operation. The CCEFP rotary valve uses fluid momentum as a power source so that no external rotary actuator is needed. To date, a 3-way version of the rotary on/off valve was integrated with a (40 lpm) fixed displacement pump to achieve variable displacement function. The unit has been prototyped and demonstrated. PWM frequency up to 90Hz, closed loop duty ratio modulation with 0-100%, and transition time of less than 0.1sec has been achieved.

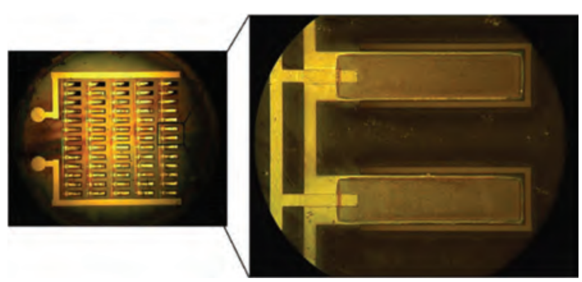


Self-powered pulse width modulated valve

<u>*MEMS Proportional Pneumatic Valve*</u>

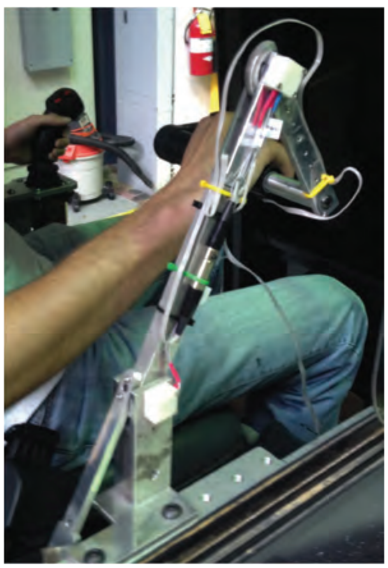
The MEMS proportional valve project successfully fabricated MEMS scale port plates and MEMS scale valve actuator arrays that comprise the two essential elements of MEMS valves. Two port plates are shown below. The port plate on the left contains 6900 orifices with a diameter of 29 microns. The port plate in the right contains 130 orifices with a diameter of 86 microns. The right port plate withstood the full design pressure of 7 bar without fracture. Novel etching procedures were required due to the large ratio of plate thickness to orifice diameter. A piezoelectric actuator array is also shown at right below. A similar array was made with cantilevered actuators having dimensions of 2000 x 700 x 17 microns. Tip deflections of over 20 microns were measured. The actuators were fabricated using "PZT" for the piezoelectric layers since PZT has the best-known piezoelectric properties of any material. The work was in collaboration with the Nanofabrication Lab at Penn State University to fabricate the PZT layers, as this is the only domestic facility available to fabricate PZT at the MEMS scale. Now that fabrication procedures have been base-lined, the two components will be "tuned" and combined to make complete prototype valves.


Port plates


Piezoelectric actuator array

Improved User Interface for an Excavator

Excavators, backhoes and similar earthmoving equipment have been controlled for decades by joysticks with each joystick motion controlling one axis of motion. The current standard electronic joystick has two motions or degrees of freedom hence two functions are controlled with each joystick. However, the swing, arm, stick and bucket motions are not intuitively coupled to the joystick motions. “Natural” motions can be achieved with a single device that has been shown to remove 85% more soil than the two-joystick interface when operated for short periods in tests on an excavator simulator. Unfortunately the arrangement tested initially was tiring to the operator because the weight of his arm did not have support during operation. Additionally, releasing the grip causes the device to drop under its own weight. Consequently, a search for new configurations was launched with both natural correspondence and ergonomic arm support. A “kinematically similar” design as shown below, with motion in the vertical plane and with swing controlled by a separate joystick proved to move 50% more soil than two joysticks but failing to have ergonomic support. By changing the motion to a horizontal plane the learning time was not significantly affected and the operator’s arm is now well supported. Tests concluded that on longer duration runs the operator did not fatigue and still moved 35% more soil than two joysticks.



A kinematically similar interface controls the vertical motion of an excavator arm. The cab swing rotation is still controlled by a joystick.

By changing the arm control to a horizontal motion the operator’s arm is supported reducing fatigue. Minimal reduction of the “natural” correspondence of motions was observed.

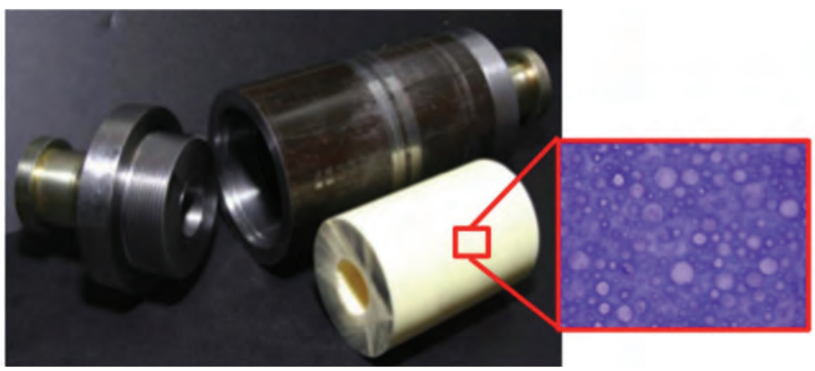
Energy harvesting for self-powered sensors

The Hydraulic Pressure-Ripple Energy Harvester (HPEH) project set new benchmarks for power generation performance, power density, and demonstration of viability. The project has greatly benefited from contributions from REU students, who have designed and tested every one of the nine prototype devices, representing six distinct generations of designs. Advancement in the energy harvesting circuit with inductance matched to the piezoelectric energy conversion element within an HPEH yielded a prototype with peak power output of 3.3 mW. Another prototype was developed for compact, low-power sensing applications, and achieved its required target output of 67 μW. The first HPEH-powered, wireless temperature sensor was demonstrated. A single-crystal piezoelectric variant HPEH prototype yielded twice the power density compared to variants using co-fired multi-layer piezoelectric elements. Prototypes were developed with a flexible design enabling the use of combinations of commercially available piezoelectric elements, permitting ease of configuration of the device for different target power demands. The project has been successful in pushing research and development such that HPEH powered devices could be viable across a broad range of power demands, available energy densities, form factors, static pressures, and target applications.

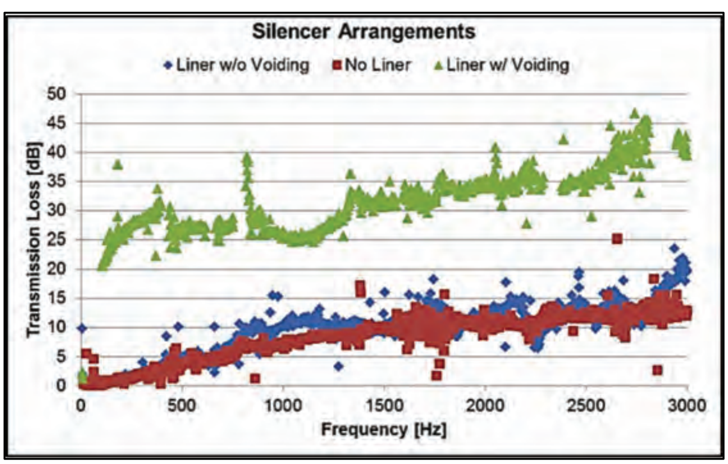
Six generations of High Pressure Energy Harvester prototypes

<u>*Compact Hydraulic In-line Silencer*</u>

Hydraulic systems can be noisy, limiting their where noise is a critical factor, such as passenger vehicles. Currently available noise control devices can be bulky, and require more maintenance than is desirable. A novel hydraulic noise control device has been developed that employs an engineered compliant material lining. The device his fewer parts than current products, so it will be less costly to manufacture, and, its lining is maintenance-free. The device has been shown to provide 30 dB of sound transmission loss. The material has uses beyond the silencer, and is being considered for compliance control in other devices.



Compact In-Line Hydraulic Silencer

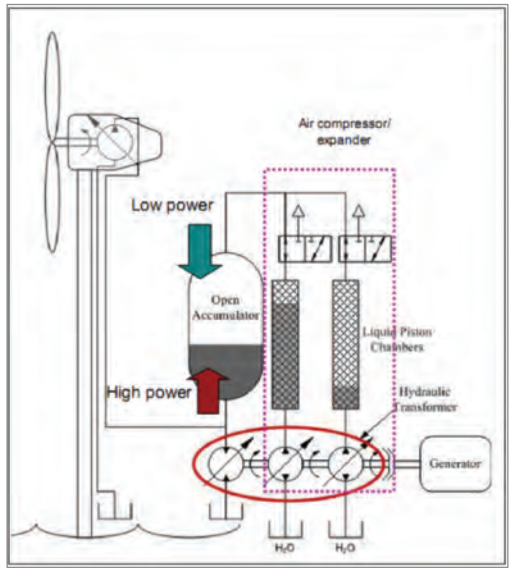


Research Highlights – Enabling Technologies (Energy Storage)

Compressed Air Open Accumulator

Because wind is intermittent and unpredictable, the ability to store wind power can significantly increase its usefulness. However, storing large amounts of energy (in the order of several MW-hours) economically, efficiently and with the capability of high conversion rates (at several MWs) is a challenge. To answer this challenge, CCEFP researchers are developing a fluid power-based approach to wind energy storage with a four-year, $2 million research grant from the National Science Foundation (NSF) Engineering Frontiers for Research and Innovation (EFRI) program. The approach is based on the open accumulator energy storage concept previously developed within the CCEFP.

In the open accumulator, excess wind energy is stored as high-pressure compressed air. When power demand exceeds available wind power, compressed air is released to generate electricity. Power output from the wind turbine becomes more predictable, and energy that would otherwise be wasted is captured. Because energy storage occurs prior to the generation of electricity, many electrical components can be downsized. By enhancing heat transfer inside the air compressor/ expander, a near isothermal process is achieved attaining high efficiency. The open accumulator concept uses the high power density of hydraulics (liquid fluid power) and the high energy density of pneumatics (gas fluid power) in a single architecture. This architecture 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.

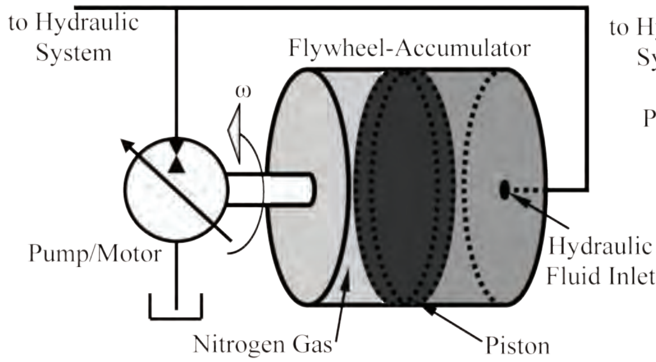


Open accumulator energy storage concept enables energy storage at the turbine.

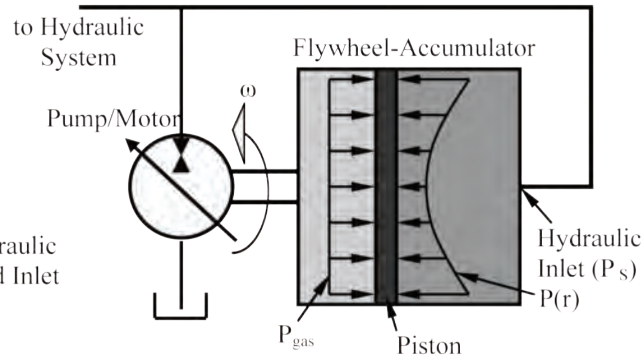
Flywheel Accumulator for Compact Energy Storage

The hydraulic flywheel accumulator is a novel device that stores energy in both the hydro-pneumatic and rotating kinetic energy domains. The energy density of the hydraulic flywheel accumulator is theoretically more than an order of magnitude higher than conventional accumulators. This is due to the high energy density of rotating kinetic energy storage, which reaches 325 kJ/kg for high performance flywheels. The ability to store energy in two modes decouples the system pressure from of the state of charge, allowing the system pressure to be actively controlled. The changing volume of hydraulic fluid in the device results in a variable flywheel inertia that creates the coupling between the energy domains.

The hydraulic flywheel accumulator (HFA) has been granted a full utility patent. It is a cylindrical piston-style accumulator rotating about its central axis and coupled to a pump/motor. Hydraulic fluid enters and exits the HFA at the center of one end of the cylinder. The opposing side of the piston is occupied by nitrogen gas at a the pre-charged pressure.



Pneumatic strain Diagram of the hydraulic flywheel accumulator. The pump/motor is coupled to the flywheel-accumulator directly or through a geared connection. The hydraulic inlet is at the center of the opposite end.

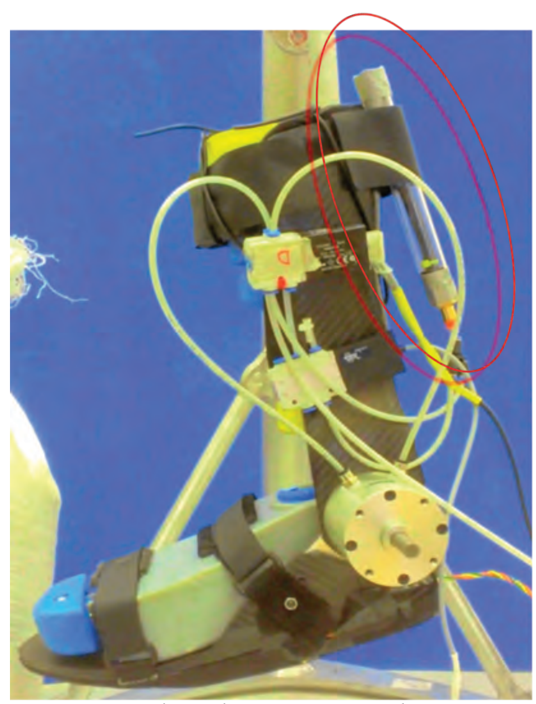


Pressure distributions of the gas and hydraulic fluid in the device. Due to the centripetal acceleration and density of the hydraulic fluid, a parabolic pressure distribution is formed.

Energy can be added or removed from the HFA in two ways, either through an applied torque or by adding or removing hydraulic fluid. When hydraulic fluid is added, the piston compresses the gas, increasing the pneumatic energy storage, and the moment of inertia increases. In the absence of an applied torque, the increase in inertia creates a decrease in the angular velocity due to conservation of angular momentum. If the quantity of hydraulic fluid in the HFA remains constant as a torque is applied, the angular velocity increases, causing a decrease in the hydraulic system pressure. This unique coupling allows the hydraulic system pressure to be directly controlled by modulating the method of energy storage.

Pneumatic Strain Energy Accumulator

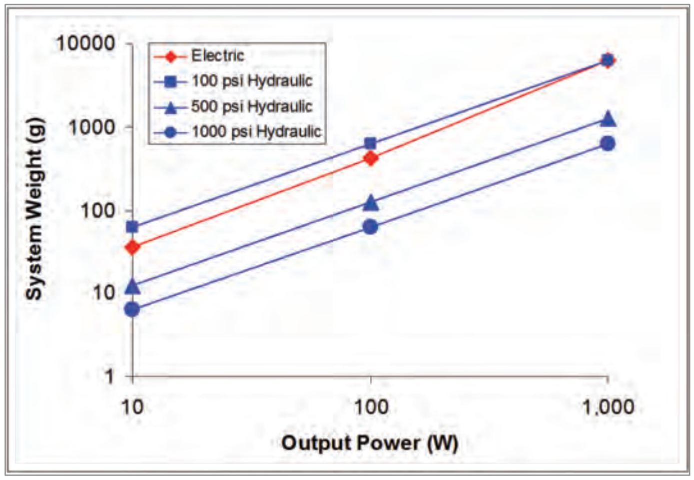
The Strain Energy Accumulator was demonstrated on Test Bed 6, the Ankle Foot Orthosis (AFO), as a way to recover exhaust gas in its pneumatic system. In these preliminary trials, the use of the pneumatic strain energy accumulator resulted in an energy savings of over 25% relative to operating the pneumatic actuation of the AFO in the conventional manner. This is an important milestone since the orthosis is representative of a typical pneumatic actuator task. The typical method of pneumatic actuation is only 23% to 30% efficient since a large amount of the energy is exhausted when the actuator changes direction. The pneumatic strain energy accumulator is able to store a portion of this exhaust gas and then reuse it to assist the powered return motion of the actuator. A recent report from Oak Ridge National Lab ("Estimating the Impact (Energy, Emissions and Economics) of the U.S. Fluid Power Industry" published December 2012) states that the recovery of exhaust gas from pneumatic systems could increase their efficiency by 14% to 23%. The demonstration on the AFO increased efficiency by 25%. Given that about 0.5% of the energy consumed in the United States is for industrial pneumatics, an application of this technology for pneumatic devices on assembly lines could save $1.4B to $2.5B per year.



Pneumatic strain energy accumulator implemented on ankle-foot orthosis

Research Highlights – Fundamental

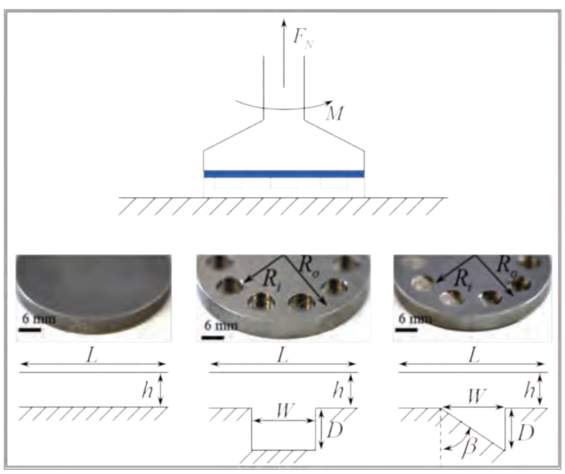
Principles of Miniature Hydraulics



For the same reason that large-scale hydraulics makes sense in mobile excavators, miniature hydraulics makes sense in wearable human assist machines, including powered orthotics. Hydraulic actuators at all scales have exceptional force to weight and power to weight ratios, so if you want to design a lightweight powered device, choose hydraulics. As hydraulic system become smaller, their efficiency drops because of the losses from pushing oil at high speed through small passages. A goal of this CCEFP project was to use basic mathematical models to develop guidelines for engineers designing tiny hydraulic systems. One conclusion of a system level analysis is that to maximize the weight advantage of tiny hydraulics, one must use high pressure. This is shown in the plot above, which demonstrates that a 100 W hydraulic system running at 1,000 psi will be about 10 times lighter than the equivalent 100 W electric motor system. Another conclusion is that to maintain reasonable efficiency for systems in the range of 100 W, one should not use a cylinder bore size of less than 4 mm. A third conclusion is that for maximum efficiency in a tiny hydraulic cylinder, replace the traditional elastomer seal with a small gap seal. Application of these and other principles enables the development of novel technology using miniature hydraulics.

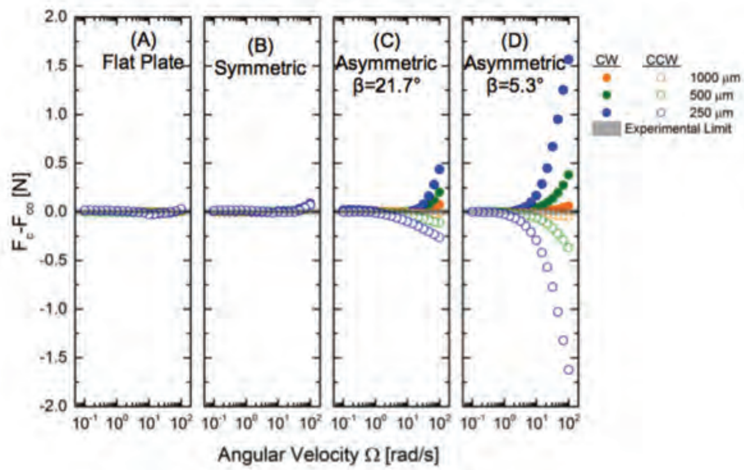
Measurement of normal forces due to asymmetric surface textures

We have shown that broken symmetry produces measurable normal forces with surface textures. A flat plate, a symmetric texture, and two asymmetric textures where experimentally tested to determine the texture profile dependence on the friction reduction. The figure below shows the experimental set up and the surfaces tested.



Experimental setup showing the three types of textures tested. FN is the measured normal force, and M is the measured torque. The top plate rotates in both directions in order to determine direction of relative motion effects.

The measured normal forces, after corrections for inertia and surface tension, are given in the figure below. The symmetric texture produced forces that were barely above the experimental limit, and the forces produced are direction independent. However, the normal forces produced by the asymmetric textures are well above the experimental limit, and the sign of the forces depended on the direction of relative motion. When the top plate was moving in the step contraction direction, the forces were positive, and when the top plate was moving in the step expansion direction, the forces were negative. The figure also shows that the magnitude of the forces produced by the textures depends on the value of α. This is because an end mill was used to manufacture the textures. The use of the end mill caused a right angle to be formed at the location of maximum depth, resulting in a sloped surface from the location of maximum depth up to the non-textured region. Therefore, as α approaches 45° the asymmetric textures become symmetric due to the right angle formed by the end mill. Since it was already shown that symmetric textures produce forces that are barely above the experimental limit, this suggests that there is an optimal α value for producing normal forces with textures that are manufactured using an end mill.



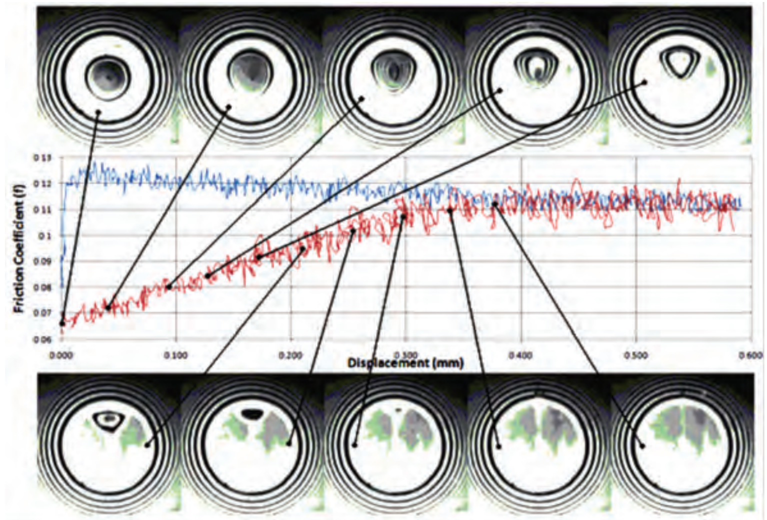
Experimental normal forces measured using high viscosity standard S600. The forces have been corrected for inertia and surface tension effects. Non-parallelism was minimized in the experimental set up. (A) is the flat plate. (B) is the symmetric texture. (C) is the asymmetric texture with α=68.3°. (D) is the asymmetric texture with α=84.7°. CW denotes clockwise spin which creates a step contraction for the asymmetric textures. CCW denotes counter clockwise spin which creates a step expansion for the asymmetric textures.

Rheology of High Pressure Fluid Films

Certain hydraulic motors are sized larger than is necessary for steady operation because of the need to overcome start-up friction. Larger motor size results in greater costs and decreased efficiency. The work of researchers at the CCEFP is increasing understanding of friction in high-pressure contacts, improving modeling capabilities, and pointing toward practical applications that could lead to reducing equipment and fuel costs while increasing efficiency.

Among their findings, participants in the research team have observed that dimples filled with highly pressurized oil, known as elastohydrodynamic lubrication entrapments, appear in the contacts between components made of hardened steel following a sudden halt to rolling or sliding motion or after an impact. These entrapments may support a significant portion of the contact load and could, therefore, reduce the startup friction by providing less resistance to sliding for a portion of the contact area.

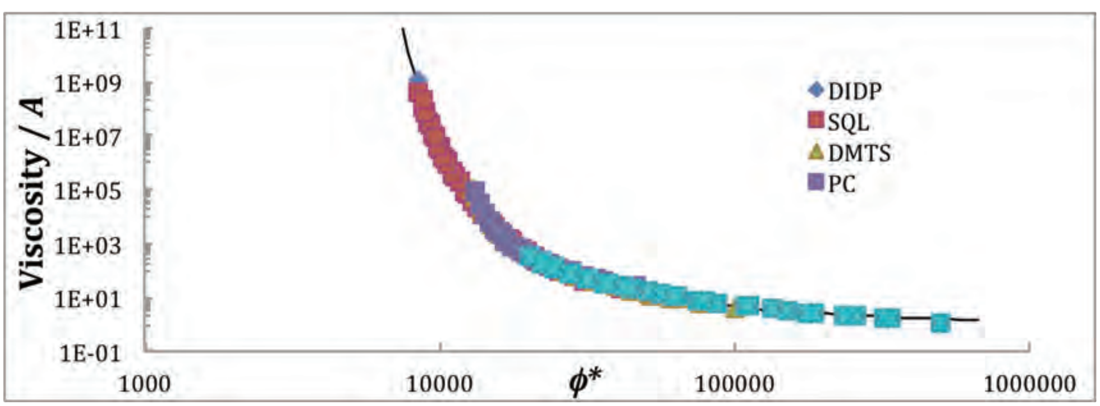
In testing their hypotheses, a specialized rig was constructed to slide a sapphire plate against a hardened steel ball. In some tests, an entrapment was formed between the ball and plate. The friction at the start of sliding was measured and the tests with an entrapment were compared to those without.



One comparison of the effect of an entrapment on sliding friction: The upper (blue) curve corresponds to the friction measured without an entrapment whereas the lower (red) curve is the friction measured with an entrapment. Ten micrographs of the contact showing the shape and position of the entrapment surround the plot. Lines in the figure show the position on the friction plot corresponding to each micrograph.

This demonstrates that entrapments can substantially reduce start-up friction (about 50% shown above) and give new insights into how they may be used to improve the performance of hydraulic motors.

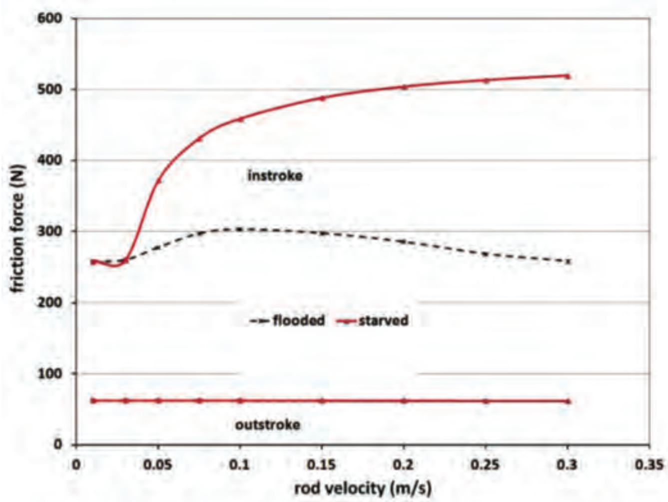
In cooperation with colleagues from eight laboratories in five countries, this team has been able to accurately calculate friction of a high-pressure, sliding contact in the thermal regime from the measurable properties of the liquid. This required a correlation of the transport properties of the liquid, viscosity, and thermal properties with respect to temperature and pressure. The team also established a framework for thermodynamic scaling of transport properties of liquidswhich combines the temperature and pressure dependence into a single parameter. This framework is being used in friction calculations. A new normalization of the scaling parameter for viscosity provides a single equation to describe behavior over a broad range of temperature and pressure that previously required two different forms of the free volume relation, (Batchinsky and Doolittle). The new equation should be superior for extrapolation to extremes of temperature and pressure.



This figure plots the viscosity of five very different liquids; dimethyl pentane, a fuel; propylene carbonate, a solvent; decamethyl tetrasiloxane, a silicone oil; squalane, a hydrocarbon oil; and diisodecyl phthalate, a diester oil for temperatures to 150°C and pressures to 1.2 GPa (175,000 psi). A single relation, plotted as the curve, describes the viscosity of all materials at all conditions with a standard deviation of relative viscosity of 16%.

Effect of Rod Surface Finish and Starved Conditions on Seal Behavior

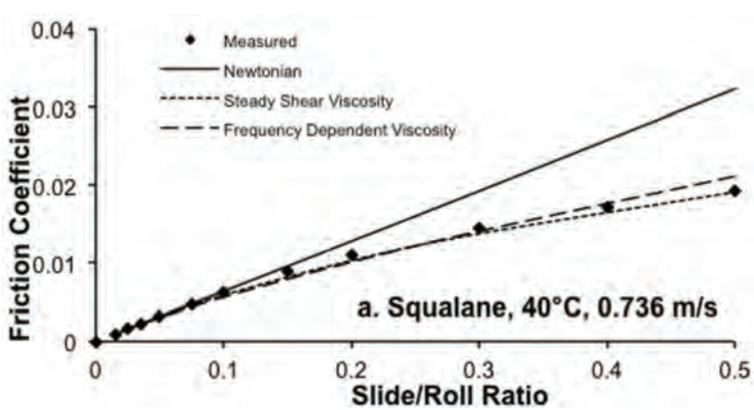
The elastomeric rod seal, which seals the gap between the protruding rod and the housing of a linear hydraulic actuator, is one of the most critical elements in a hydraulic system because it must prevent the leakage of hydraulic fluid into the environment. Numerical models of the rod seal have been developed at the CCEFP. The models are capable of predicting key seal performance characteristics, especially seal leakage and friction for a proposed design. These models simulate the physical processes governing the operation of the seal. They analyze the behavior of the hydraulic fluid in the interface between the seal and the rod, the contact between asperities on the seal and the rod, and deformation of the seal. Previous models consider the interface between the seal and rod to be flooded with lubricant. However, in the majority of applications there is insufficient lubricant, and starvation occurs. Therefore, our most recent models take account of such starvation. Results from these models show that starvation leads to significantly higher friction forces.



Comparison of starved and flooded lubrication conditions in a rod seal

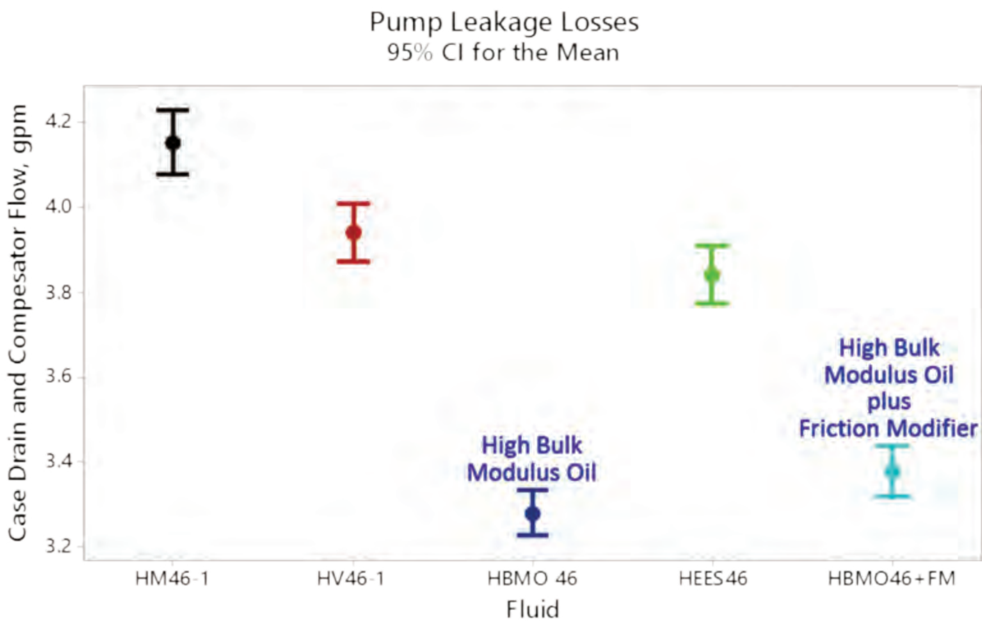
Understanding Fluid Film Behavior in Pumps

The friction in highly loaded lubricated contacts is determined mainly by the pressure and shear dependences of viscosity. Progress in reducing friction through the selection of these properties has been slowed by the difficulty in measuring the properties for correlation with chemical structure. The analogy between shearing frequency and shearing rate (Cox-Merz) is well established for polymers. The measurement of the steady shear dependence for low viscosity liquids has been an exceeding challenging task requiring very high pressures to avoid thermal softening from viscous heating. Using high frequency, small-strain techniques would provide a simple, easy method to explore friction reduction through intelligent property selection. This research has made the first successful use of the Cox-Merz rule in predicting friction. A plot of the predicted and empirical results is shown below.



High Bulk Modulus Oil Research Collaboration

A prototype high-bulk modulus hydraulic fluid was developed, characterized and evaluated in collaboration including Paul Michael at MSOE, Dr. Hideto Kamimura of Idemitsu Lubricants America and Dr. Scott Bair or Georgia Tech. Testing in a dynamometer revealed a 20% reduction in pump case and pressure compensator control valve leakage flows. A model for relating pump flow losses to fluid properties was developed through an extension of earlier work by Jeong. The results reveal that case drain and control valve flow rates are affected by the bulk modulus, density, and viscosity properties of fluids. Low speed efficiency of the high-bulk modulus oil in hydraulic motors was improved through the addition of a friction modifier. The friction modifier was selected based upon bench-top test parameters developed by the CCEFP researchers.

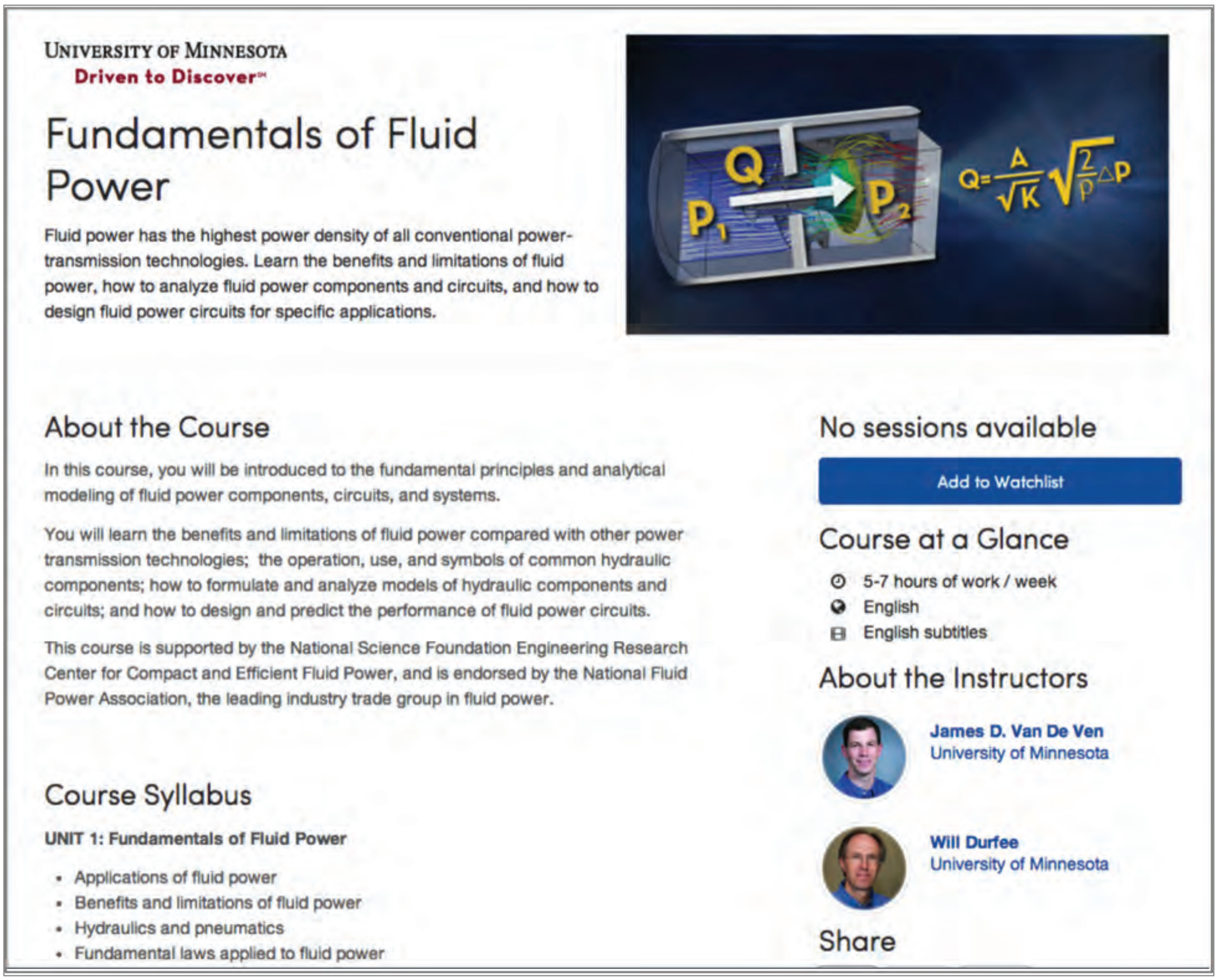


The HBMO and HBMO plus Friction Modifier reduced pump and PV control valve leakage flows under a wide range of conditions.

Education Highlights

Fluid Power Fundamentals MOOC Offered Through Coursera

Professors James Van de Ven and William Durfee at the University of Minnesota created a Massive Online Open Course (MOOC) titled "Fundamentals of Fluid Power." The course was competitively selected by the University of Minnesota to be offered on Coursera. This course introduces students to the fundamental principles of fluid power systems, circuits, and components. Students learn: 1) the benefits and limitations of fluid power compared with other power transmission technologies, 2) the function of common hydraulic components, 3) how to formulate and analyze models of hydraulic components and circuits, and 4) how to design hydraulic circuits for specific system requirements. The course is delivered through short, focused video presentations that include lectures, laboratory demonstrations, large system demonstrations, and interviews with industry experts. The target audience for the course includes entry-level engineers, senior-level undergraduate students, and entry-level graduate students. The six-week course was first offered during the fall of 2014.



UMN Fundamentals of Fluid Power MOOC Home Page

Fluid Power Chainless Challenge

The Parker Hannifin Chainless Challenge is a design competition for undergraduate college students. The focus is to design and build a human powered vehicle (typically bicycles or recumbent or upright tricycles) in which the conventional chain drive is replaced with a hydraulic transmission. Elements of the competition 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 this project 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 Chainless Challenge provides undergraduate engineering design students with a hands-on experience in fluid power design and development. It also increases the number of mechanical engineers graduating from Center schools with training and experience in fluid power (20-25 students from Center schools per year). The Chainless Challenge is a two-semester commitment. In fall semester, the students work on the project in their capstone design projects course. Teams of five to six undergraduate students learn about fluid power, develop design specifications for their bike, complete the design, and fabricate and install their design on the bike. In spring semester, the students test and optimize the bike's operation in preparation for the national competition in April.

Students in the slalom portion of the 2014 Chainless Challenge road race event

There are typically a dozen teams in the competition. In 2011-12, Illinois, Illinois Tech, Minnesota and Purdue represented CCEFP. Minnesota took second place overall. In the 2012-13 competition, teams from Illinois, Minnesota and Purdue participated. Illinois took first place overall. In the 2013-14 competition, teams represented CCEFP from Illinois, Minnesota and Purdue. Purdue and Minnesota took second and third place, respectively.

NSF Adopts CCEFP's Innovative Approach to Recruitment of Underrepresented Students in Engineering through the National GEM Consortium

A formal partnership with the National GEM Consortium and a proposed program structure, designed and piloted by CCEFP, is expected to be adopted and implemented within the NSF ERC system, to increase the ability of ERCs to recruit and retain underrepresented students in graduate engineering programs. The GEM-ERC Fellows Program overcomes barriers to ERC student recruitment of underrepresented students in engineering. The National GEM Consortium is a prestigious organization committed to the training and development of underrepresented students in science and engineering. GEM has a legacy of serving as the liaison between academia and industry, pairing the two entities with to education and hire advanced degreed students. It is a natural and complimentary partnership to NSF Engineering Research Centers.

CCEFP Award for Best Technical/Application Video

Hydraulics & Pneumatics magazine hosted its first Best of Industry Awards at the 2014 International Fluid Power Expo (IFPE) Show. These awards were created to help recognize those in the industry that have done a great job evolving to help provide engineers with the critical information. CCEFP's video, *Bringing Talent to the Fluid Power Industry* was runner-up in the Best Technical / Application video. The CCEFP has created a series of videos to describe what the Center is and the impact it's had on technology and the fluid power workforce.

CCEFP Hosts Fluid Power Challenges - An Engineering Design Competition for 8th Graders

Over 375 8th grade students participated in four outreach events hosted by CCEFP institutions. The NFPA Fluid Power Challenge encourages students to learn about fluid power technology and gain hands-on experience while building a fluid power mechanism with real world applicability. The program is designed to introduce the students, and their teachers, to the world of engineering and fluid power careers. Outcomes of this activity are students who are exposed to fluid power technology, who are encouraged to continue math and science courses in school, and consider engineering as a career field. Additionally, teachers are given support and resources for science and technology curriculum using fluid power as a way to demonstrate everyday engineering applications.

Fluid Power Challenge Competition

Twin Cities Public Television Fluid Power Program

The CCEFP has partnered with the National Fluid Power Association (NFPA) to create two half-hour videos, one to educate the general public on fluid power and the other to inform engineering graduates of the career opportunities in fluid power. The videos feature CCEFP faculty, students and industry members. The main themes of the video for the general public are that fluid power is all around us even though we may not realize it, that fluid power has intrinsic capabilities that are unmatched by any other technology, and that fluid power has the potential for solving many of society's pressing problems. The career opportunity video features graduate students and engineers in fluid power communicating the excitement and importance of their work.

Additional financial support for the careers video was provided by fluid power organizations from other countries. Twin Cities Public Television produced the video for broadcast in April 2008. CCEFP and NFPA hold the copyright on the video and are free to distribute it in DVD form for educational purposes. The Center and its partners in this project are developing a plan to widely distribute the video for high impact.

Science Museum of Minnesota Interactive Fluid Power Exhibit

The CCEFP exhibit program educates adults and families about the basics of fluid power and introduces them to some of the research carried out in the Center's programs. Prototypes and exhibits are developed and extensively field-tested at the Science Museum of Minnesota, an organization affiliated with the CCEFP. These will serve as models for dissemination to other science museums around the world. Two exhibits are shown below. The upper photo is a detail from Hydraulics Lab, which challenges visitors to create hydraulic circuits to ring a large bell and operate a carousel powered by a Pelton wheel. The lower photo shows a detail from an exhibit created in collaboration with a team of senior mechanical engineering students at the University of Minnesota. The exhibit shows how wind energy can be stored through compressing air into an open accumulator.

Photo credits: Science Museum of Minnesota

Technology Transfer Highlights

CCEFP researchers built the first displacement controlled hydraulic hybrid excavator

A novel hydraulic hybrid system 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. System simulations have shown, that the combination of both novel technologies in one system architecture allows 50% engine downsizing and up to 20% additional fuel savings over the non-hybrid displacement controlled excavator. The hybrid system was implemented in the CCEFP excavator test bed, the 5-ton Bobcat displacement controlled mini-excavator. In 2013, independent testing by Caterpillar on the CCEFP developed non-hybrid displacement controlled excavator demonstrated 40% fuel savings and 69% machine efficiency improvements in ton soil moved per kg fuel burned. In 2014, Caterpillar commercialized a hydraulic hybrid excavator, the model 336E H. In contrast to competing electric hybrid excavators, the 336E H has been a clear commercial success having captured 15% of the excavator market in its class.

CCEFP Test Bed 1: Hydraulic Excavator

CCEFP Researchers Help Parker Hannifin Bring Novel Hydraulic Hybrid Technology to Market

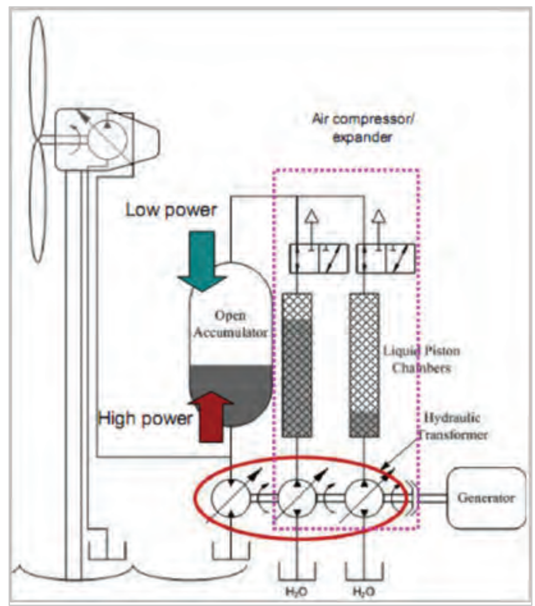
Researchers with the National Science Foundation Engineering Research Center for Compact and Efficient Fluid Power (CCEFP) developed a novel and efficient hybrid system for commercial vehicles. Parker Hannifin Corporation funded the research that led to a commercialized new hybrid system. While most hybrid systems today are hybrid electric, the research developed a *hybrid hydraulic* system featuring a hydro-mechanical transmission (HMT). The system is initially being targeted at medium duty package delivery vehicles, such as those used by UPS. In this type of vehicle, the hybrid HMT provides more than 50% percent better fuel economy than current package delivery vehicles.

Hybrid Hydraulic UPS Package Delivery Vehicle

The majority of hybrid vehicles sold today are in the passenger vehicle market. However, the largest potential benefit for a hybrid system is in the commercial vehicle market due to their higher weight, lower fuel economy and high usage (e.g., often higher miles/year and more stop and go driving). Hybrid electric systems have been available for light and medium duty commercial vehicles for many years, but market acceptance has been slow. The challenge has been that the savings created by the hybrid electric system (from using less fuel primarily) combined with the system cost provide a payback period that is too long for most companies. The hybrid HMT holds the promise of reducing the payback period to one that is attractive to commercial vehicle end users. Parker Hannifin created a new division, Hybrid Drive Systems (HDS), located in Columbus, Ohio to design and manufacture hydraulic hybrid systems. The technology was created in the US, is being built in the US and creates a new market segment for hydraulics all of which lead to good paying jobs in the US. HDS is the first division in Parker's 90-plus year history that was created through organic growth and not through acquisition. The significant fuel consumption savings from the hybrid HMT coupled with broad market acceptance will reduce greenhouse gas emissions and help lower US dependence on foreign oil.

Open Accumulator Developed for Off-shore Wind Power Energy Storage

The open accumulator has already been described in the research highlight section above. The research has generated significant commercial interest. The system is capable of high energy density, storing 24 MW-hr. of energy in a 500 m^3 volume. As of February 2016, two companies have licensed the technology and are working with CCEFP researchers to commercialize the technology.

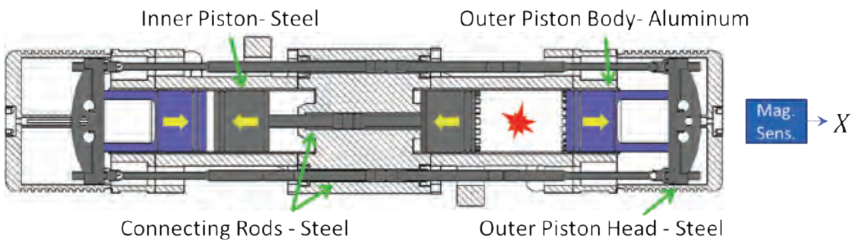


Open accumulator energy storage concept enables energy storage at the turbine.

Commercialization of CCEFP Research on Novel Magnetic Based Position Measurement System

Ferromagnetic objects have inherent magnetic fields around them. CCEFP researchers have shown that the magnetic field variation around a ferromagnetic object can be modeled using purely the geometry of the object under consideration. Exploiting this model of the inherent magnetic field, the position of the object can be measured quite accurately without direct conduct by using a small inexpensive magnetic sensor. Further, the use of one additional redundant magnetic sensor can eliminate the need to calibrate the position measurement system. The technology has been demonstrated through a series of experimental results that the developed measurement system is applicable to accurate position measurement of small and large ferromagnetic objects, including cars on highways, oscillating pistons in IC engines, pneumatic cylinders, hydraulic cylinders, as well as moving parts in many machines.

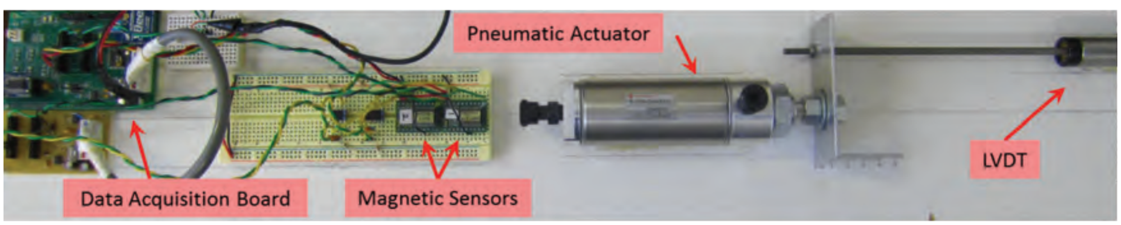
A primary motivation behind this discovery was the CCEFP Free Piston Engine Pump (FPEP) project shown in the figure below. One of the critical barriers to overcome was the need to quickly and accurately measure the position of the outer piston in a potentially harsh operating environment. The non-contacting magnetic sensor solved this difficult problem. Note that the FPEP was equipped with a redundant linear variable differential transformer (LVDT) which was used only as a reference sensor.



Use of the inherent magnetic field in a Free Piston Engine Pump for piston position estimation

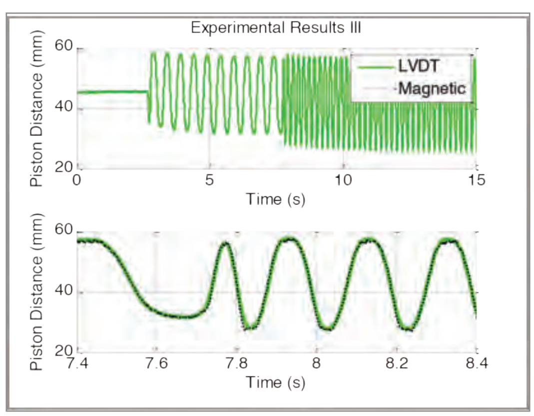
By modeling the inherent magnetic field of the outer piston and measuring the field using magnetic sensors, piston position can be estimated. The figure below shows the result from an experiment with the FPEP. It can be seen that the developed technology is capable of accurately estimating piston position even under fast transients.

In cases that the piston does not have an inherent magnetic field (for example pistons made of aluminum), the same technology can be applied by adding a magnet to the piston head. This has been shown through experiments with a pneumatic actuator made of aluminum shown in the figure below. In these experiments a LVDT was again used as a reference.



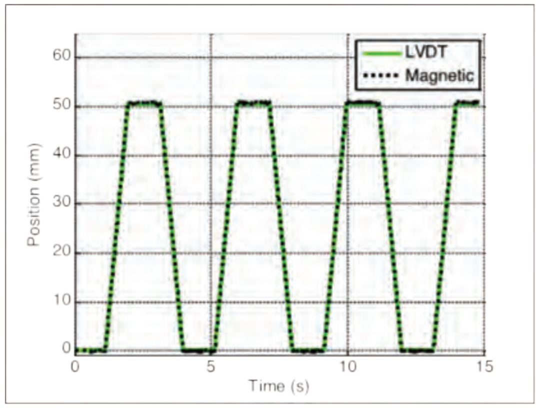
Test setup for piston position measurement in nonmagnetic pneumatic cylinder

Using the developed technology, along with a small embedded magnet on the internal piston head, it can be shown that piston position can once again be accurately measured. The figure below shows a sample result from the experiments with the pneumatic actuator.



Results from applying the technology to measure piston position in the FPEP

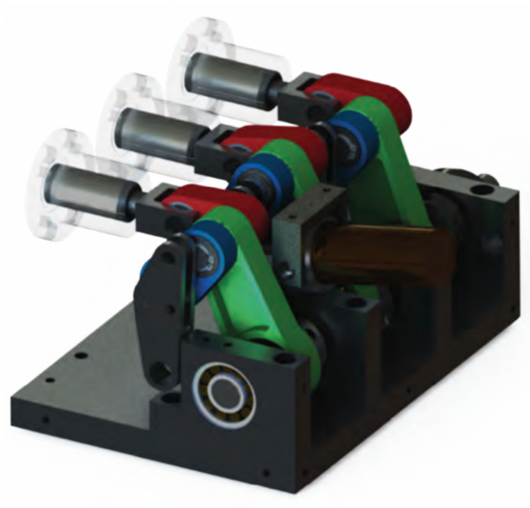
Patents have been filed and members of the CCEFP research team started a company, Innotronics LLC, to license and commercialize this technology. To date the startup has been obtained two funding awards from the inventing university, a NSF PFI:AIR-TT award and a sponsored research contract from an industry member to demonstrate the technology on their system.



Piston position measurement in a pneumatic actuator

Commercialization of an Adjustable Linkage Pump

In a CCEFP-affiliated research project on compressed air energy storage, a novel variable displacement pump driven by an adjustable linkage was invented. Through an NSF PFI:AIR Technology Translation grant, the team is currently translating the adjustable linkage pump to fill the need for a hydraulic pump with high efficiency at low volumetric displacement. The team has produced a functional prototype of a multi-cylinder variable displacement linkage pump. The pump has the following novel features: 1) it uses low friction pin joints, 2) it can reach true zero displacement, 3) the piston reaches the same top dead center position regardless of the displacement, and 4) it can pump corrosive fluids. These features improve efficiency and allow the pump to be used in a wide range of applications and environments, when compared to market leading variable displacement hydraulic pumps.



Adjustable Linkage Pump CAD Model

Adjustable Linkage Pump Prototype

Infrastructure Highlights

CCEFP Centers of Excellence Vision

The sustainability plan for CCEFP requires supporting laboratory expertise. The CCEFP envisions a network of complementary labs within the partner universities. Three of these labs are already well established, the Fluid Power Institute at Milwaukee School of Engineering (MSOE), The Maha Fluid Power Lab at Purdue University, and the Manufacturing Lab at Georgia Tech. To strengthen the network two additional labs will be further developed.

The Thomas E. Murphy Engine Lab at the University of Minnesota will be expanded into a comprehensive powertrain research facility. The research will emphasize heavy-duty, off-road and wind power applications including engine, transmission and chassis dynamometers. This will support research in a variety of research areas including free piston engine pumps and hydraulic hybrid powertrains. A unique combustion research capability of the lab will be the rapid compression and expansion machine.

Laboratory for Systems Integrity and Reliability (LASIR) at Vanderbilt University is a 20,000 square-foot high-bay facility that will enable researchers to test advanced sensor systems that can detect the earliest signs of failure in a variety of structures in the built environment, including aircraft, automobiles and wind turbines. The lab will expand its capabilities to include human scale fluid power including energy saving industrial pneumatics, untethered, soft and assistive robotics.

APPENDIX IV

Year 10 ERC Web Tables

This page is intentionally left blank

Table 1: Quantifiable Outputs							
Outputs	**Early Cumulative Total [1]**	**Feb-01-2011 - Jan-31-2012**	**Feb-01-2012 - Jan-31-2013**	**Feb-01-2013 - Jan-31-2014**	**Feb-01-2014 - Jan-31-2015**	**Feb-01-2015 - Jan-31-2016**	**All Years**
Publications Resulting From Core Funding							
In Peer-Reviewed Technical Journals	61	12	22	24	17	10	146
In Peer-Reviewed Conference Proceedings	186	52	32	23	37	23	353
In Trade Journals	26	2	0	3	1	0	32
With Multiple Authors:	259	51	54	50	55	33	502
Co-authored With ERC Students	184	51	40	35	35	18	363
Co-authored With Industry	9	2	2	0	4	2	19
With Authors From Multiple Engineering Disciplines	19	6	7	4	9	6	51
With Authors From Both Engineering and Non-Engineering Fields	20	6	2	7	5	5	45
With Authors From Multiple Institutions	28	9	0	8	8	7	60
Publications Resulting From Associated Projects in the Strategic Plan							
In Peer-Reviewed Technical Journals	36	5	7	8	14	7	77
In Peer-Reviewed Conference Proceedings	67	10	13	17	22	7	136
Publications Resulting From Sponsored Projects							
In Peer Reviewed Technical Journals	6	0	0	2	0	0	8
In Peer-Reviewed Conference Proceedings	24	0	0	3	1	0	28
Participating Organizations							
Industrial Practitioner Members	280	48	41	46	0	0	415
Innovation Partners	0	1	1	1	0	0	3
Funders of Sponsored Projects	0	0	0	1	1	2	4
Funders of Associated Projects	34	8	8	10	10	8	78
Contributing Organizations	7	9	6	4	12	12	50
ERC Technology Transfer							
Inventions Disclosed (by researchers or tech transfer office)	31	12	3	6	4	2	58
Total Patent Applications Filed	20	4	6	6	5	3	44
Provisional Patent Applications Filed [1]	N/A	N/A	3	5	4	2	14
Full Patent Applications Filed [1]	N/A	N/A	3	1	1	1	6
Patent Awarded	2	2	1	1	1	0	7
Licenses Issued	2	0	2	1	0	1	6
Spin-off Companies Started	1	0	1	1	1	1	5
Estimated Number of Spin-off Company Employees	0	0	1	1	2	3	7
Building Codes Impacts	0	0	0	0	0	0	0
Technology Standards Impacts	8	1	1	1	0	0	11
New Surgical and Other Medical Procedures Adopted	0	0	0	0	0	0	0
Degrees to ERC Students							
Bachelor's Degrees Granted	94	10	10	7	12	2	135
Master's Degrees Granted	70	10	10	7	12	12	121
Doctoral Degrees Granted	22	6	12	11	12	6	69
Job Sector of ERC Graduates							
Undergraduates Hired by:							
Industry:	N/A	4	0	1	2	0	7
ERC Member Firms	N/A	0	0	1	0	0	1
Other U.S. Firms	N/A	4	0	0	2	0	6
Other Foreign Firms	N/A	0	0	0	0	0	0
Government	N/A	0	0	0	1	0	1
Academic Institutions	N/A	4	3	0	0	0	7
Other	N/A	0	1	0	0	0	1
Undecided/Still Looking/Unknown	N/A	2	6	6	9	2	25
Undergraduate ERC Graduates Total	0	10	10	7	12	2	41
Master's Graduates Hired by:							
Industry:	N/A	8	1	0	1	0	10
ERC Member Firms	N/A	2	1	0	0	0	3
Other U.S. Firms	N/A	6	0	0	1	0	7
Other Foreign Firms	N/A	0	0	0	0	0	0
Government	N/A	0	0	0	2	0	2
Academic Institutions	N/A	2	0	0	0	0	2
Other	N/A	0	2	2	1	0	5
Undecided/Still Looking/Unknown	N/A	0	7	5	8	12	32
Master's ERC Graduates Total	0	10	10	7	12	12	51
Ph.D.s Hired by:							
Industry:	N/A	2	0	1	10	0	13
ERC Member Firms	N/A	1	0	1	0	0	2
Other U.S. Firms	N/A	1	0	0	10	0	11
Other Foreign Firms	N/A	0	0	0	0	0	0
Government	N/A	0	0	1	0	0	1
Academic Institutions	N/A	3	0	0	0	0	3
Other	N/A	0	4	1	0	0	5
Undecided/Still Looking/Unknown	N/A	1	8	8	2	6	25
Ph.D. ERC Graduates Total	0	6	12	11	12	6	47
ERC Influence on Curriculum							
New Courses Based on ERC Research That Have Been Approved by the Curriculum Committee and Are Currently Offered [2]	14	2	0	4	2	2	24
Currently Offered, ongoing Courses With ERC Content	39	19	28	29	31	31	N/A
New Textbooks Based on ERC Research	4	0	0	0	0	0	4
New Textbook Chapter Based on ERC Research	1	0	0	0	1	0	2
Free-Standing Course Modules or Instructional CDs	0	3	5	2	7	1	18
New Full-Degree Programs Based on ERC Research	0	0	0	0	0	0	0
New Degree Minors or Minor Emphases Based on ERC Research	3	0	0	0	0	0	3
New Certificate Programs Based on ERC Research	0	0	0	0	0	0	0
Total Full-Degree Programs Based on ERC Research	0	0	0	0	0	0	0
Number of Students Enrolled	0	1710	1700	0	0	0	3410
Number of Students Graduated	0	0	0	0	0	0	0
Total Certificate Programs Based on ERC Research	0	0	0	0	0	0	0
Number of Students Enrolled	0	0	0	0	0	0	0
Number of Students Graduated	0	0	0	0	0	0	0
Active Information Dissemination/Educational Outreach							
Workshops, Short Courses, and Webinars [3]	49	83	85	62	22	72	373
Number of Participants That Attended Events	221	2322	5189	500	1000	598	9830

Table 1: Quantifiable Outputs							
Outputs	**Early Cumulative Total [1]**	**Feb-01-2011 - Jan-31-2012**	**Feb-01-2012 - Jan-31-2013**	**Feb-01-2013 - Jan-31-2014**	**Feb-01-2014 - Jan-31-2015**	**Feb-01-2015 - Jan-31-2016**	**All Years**
Innovation-focused Workshops, Short courses, Webinars, and Seminars	5	39	14	1	0	0	59
Number of Participants That Attended Events	25	1172	1120	25	0	0	2342
Seminars, Colloquia, Invited Talks, Etc.	127	18	7	10	89	19	270
ERC Sponsored Educational Outreach Events for K-12 Students	42	15	19	25	12	16	129
Number of Students That Attended Events	7616	10926	11000	40513	34023	1956	106034
Number of Teachers That Attended Events	56	100	500	5141	4317	249	10363
ERC Sponsored Educational Outreach Events for Community Colleges	17	9	4	1	0	1	32
Number of Community College Students That Attended Events	369	5000	250	10	0	0	5629
Number of Community College Faculty That Attended Events	33	50	4	0	0	5	92
ERC Sponsored Educational Outreach Events for Non-ERC Undergraduate Students	0	N/A	N/A	15	0	5	20
Number of Non-ERC Undergraduate Students That Attended Events	0	N/A	N/A	25	0	50	75
Number of Undergraduate Faculty That Attended Events	0	N/A	N/A	0	0	0	0
Personnel Exchanges							
Student Internships in Industry	41	12	9	5	9	17	93
Faculty Working at Member Firm	2	1	0	0	0	0	3
Member Firm Personnel Working at ERC	10	0	0	1	0	0	11

[1] Data for the breakdown of "Total Patent Applications Filed" into "Provisional Applications Filed" and "Full Patent Applications Filed" were not collected prior to 2013.

[2] New courses currently offered and approved by the curriculum committee are only counted in the first year that they are offered so there is no multiple counting of these courses.

[3] For years prior to 2009, the values include "Workshops and short courses to industry" and "Workshops and short courses to non-industry groups".

Table 1a: 2015 Average Metrics Benchmarked Against All Active ERCs and the Center's Tech Sector					
Metric	Average All Active ERCs FY 2015	Average Advanced Manufacturing Sector FY 2015	Average Class of 2006 FY 2015	Minnesota Twin Cities- CCEFP Total	Minnesota Twin Cities- CCEFP Total
	(17 ERCs)	(5 ERCs)	(5 ERCs)	FY 2015	FY 2016
Organizations Within Non-Industry Sectors	**22**	**16**	**20**	**6**	**6**
Organizations Within Industry Sectors	**23**	**27**	**28**	**17**	**16**
Small	45%	48%	56%	59%	25%
Medium	8%	7%	8%	0%	0%
Large	47%	44%	37%	41%	75%
Industrial/Practitioner Member Firms	**23**	**25**	**27**	**0**	**0**
Innovation Partners	**7**	**6**	**4**	**0**	**0**
Funders of Sponsored Projects	**1**	**1**	**0**	**1**	**2**
Funders of Associated Projects	**12**	**9**	**13**	**10**	**8**
Contributing Organizations	**3**	**3**	**3**	**12**	**12**
Total Number of Organizations	**45**	**43**	**49**	**23**	**22**
Total Membership Fees Received	**$278,681**	**$411,100**	**$328,402**	**$0**	**$0**
Direct Sources of Support [1]	**$5,591,135**	**$5,015,848**	**$3,831,427**	**$4,031,304**	**$3,571,701**
NSF	64%	69%	60%	67%	57%
Other Federal	0%	1%	0%	0%	2%
State Government	2%	0%	0%	0%	0%
Local Government	0%	0%	0%	0%	0%
Foreign Government	0%	0%	0%	0%	0%
Quasi-Government Research	0%	0%	0%	0%	0%
Industry (U.S. and Foreign)	9%	12%	14%	4%	5%
University (U.S. and Foreign)	16%	12%	18%	6%	10%
Other	8%	7%	8%	23%	25%
Associated Project Support	**$4,688,884**	**$6,917,482**	**$8,575,415**	**$2,425,839**	**$2,568,334**
ERC Personnel and Educational Participants	**6,740**	**10,007**	**8,695**	**38,576**	**2,488**
Leadership Team [2]	16	13	13	9	9
Faculty [3]	44	34	41	37	55
Graduate Students	91	85	78	92	77
Undergraduate Students	60	73	66	50	100
REU Students	18	17	23	25	22
Community College RET	0	0	0	2	0
K-12 Teachers (RET and non-RET)	14	24	10	21	15
K-12 Students (Young Scholars)	13	10	7	0	0
Faculty/Teachers That Attended ERC Sponsored Educational Outreach Events for K-12 Students [4]	392	1,000	890	4,317	249
Students That Attended ERC Sponsored Educational Outreach Events for K-12 Students [4]	6,028	8,710	7,566	34,023	1,956
Faculty That Attended ERC Sponsored Educational Outreach Events for Community Colleges [4]	14	14	0	0	5
Students That Attended ERC Sponsored Educational Outreach Events for Community Colleges [4]	49	26	0	0	0
% Women [5]	31%	34%	31%	20%	16%
% Underrepresented Racial Minorities [6]	12%	7%	9%	9%	5%
% Hispanic [6]	11%	11%	13%	4%	4%
Publications	**Average**	**Average**	**Average**	**Total**	**Total**
In Peer-Reviewed Technical Journals	39	31	50	17	10
In Peer-Reviewed Conference Proceedings	25	7	19	37	23
Multiple Authors: Co-Authored With ERC Students	48	29	48	35	18
Multiple Authors: Co-Authored With Industry	7	3	8	4	2
Intellectual Property	**Average**	**Average**	**Average**	**Total**	**Total**
Invention Disclosures	7	3	3	4	2
Patent Applications (Provisional and Full)	7	6	3	5	3
Patents Awarded	3	2	2	1	0
Licenses (patents, software)	1	0	0	0	1
Education and Outreach Outputs	**Average**	**Average**	**Average**	**Total**	**Total**
New Courses Developed	2	1	1	2	2
Currently Offered, Ongoing Courses With ERC Content	22	17	30	31	31
New Full Degree Programs	0	0	0	0	0
New Degree Minors or Minor Emphases	0	0	0	0	0
New Certificate Programs Based on ERC Research	0	0	0	0	0

[1] - Includes new support (unrestricted cash, restricted cash, and in-kind donations) from Table 9 only. Multi-year support and residual funds carried over from previous years are not included in benchmarking figures.

[2] - Includes Directors, Thrust Leaders, Education Program Leaders, Research Thrust Management & Strategic Planning, Administrative Director, and Industrial Liasion Officer.

[3] - Includes Directors, Education Program Leaders, Thrust Leaders, Senior Faculty, Junior Faculty, and Visiting Faculty.

[4] - Includes participant values from Table 1 Quantifiable Outputs.

[5] - Calculated out of total number of personnel.

[6] - Calculated out of total number of U.S. Citizens or Permanent Residents.

Table 2 Summary: Budgets by Research Thrust and Project Type					
Thrust	**Current Year Budget**				**Estimated Next Year Budget**
	Center Controlled Projects	**Sponsored Projects**	**Associated Projects**	**Projects Total**	
1: Efficiency	$401,338	$0	$1,663,977	$2,065,315	$738,388
2: Compactness	$418,060	$0	$0	$418,060	$0
3: Effectiveness	$269,734	$0	$408,782	$678,516	$194,220
5. Manufacturing	$0	$0	$135,944	$135,944	$135,944
Test Beds	$356,188	$0	$359,631	$715,819	$205,713

Table 2: Estimated Budgets by Research Thrust [1]						
Thrust	**Project Name**	**Organizational Sponsor**	**Project Leader**	**Investigators**	**Current Year Budget**	**Estimated Next Year Budget**
1: Efficiency Thrust Leader: Monika M. Ivantysynova (Purdue University)	1B.1: Next Steps towards Virtual Prototyping of Pumps and Motors (Center Controlled Project)	NSF ERC Program	Monika M. Ivantysynova (Purdue University)		$20,068	$738,388
	1E.3: Actively Controlled Digital Pump Motor (Center Controlled Project - translational research)	NSF ERC Program	John H. Lumkes (Purdue University)		$63,545	
	1E.6: High Performance Valve Actuation Systems (Center Controlled Project - translational research)	NSF ERC Program	John H. Lumkes (Purdue University)		$63,545	
	1F.1: Variable Displacement External Gear Machine (Center Controlled Project)	NSF ERC Program	Andrea Vacca (Purdue University)		$63,545	
	1G.1: Energy Efficient Fluids (Center Controlled Project - translational research)	NSF ERC Program	Paul W. Michael (Milwaukee School of Engineering-Fluid Power Institute)		$63,545	
	1G.3: Rheological Design for Efficient Fluid Power (Center Controlled Project - translational research)	NSF ERC Program	Randy H. Ewoldt (University of Illinois at Urbana-Champaign-Department of Mechanical Science and Engineering)		$63,545	
	1J.2: A Novel Pressure-controlled Hydro-Mechanical Transmission (Center Controlled Project - translational research)	NSF ERC Program	Kim A. Stelson (University of Minnesota-Mechanical Engineering)		$63,545	
	Adjustable Linkage Pump (Associated Project - translational research - NSF)	Cat Pumps	James D. Van de Ven (University of Minnesota-Mechanical Engineering)		$27,404	
	Advanced Hydraulic Systems for Next Generation of Skid Steer Loaders (Associated Project - translational research)	Confidential Organization (optional use for associated or sponsored projects only)	Monika M. Ivantysynova (Purdue University)		$71,309	
	Aeration and Fluid Efficiency 060 (Associated Project - translational research)	Confidential Organization (optional use for associated or sponsored projects only)	Paul W. Michael (Milwaukee School of Engineering-Fluid Power Institute)		$80,000	
	Building a Hardware-in-the-loop Simulation Testbed and a Living Laboratory for Evaluating Connected Vehicle-Highway Systems (Associated Project - translational research)	Confidential Organization (optional use for associated or sponsored projects only)	Zongxuan Sun (University of Minnesota)		$147,562	
	CAREER: Control of Mechatronic Automotive Propulsion Systems (Associated Project - NSF)		Zongxuan Sun (University of Minnesota)		$57,799	
	Detailed modeling of Gerotor units (Associated Project)	Thomas Magnete GmbH	Andrea Vacca (Purdue University)		$38,526	
	Development of a Gasoline Engine Driven Ultra High Pressure Hydraulic Pump (Associated Project)	Dae Jin Hydraulics - TECPOS	Andrea Vacca (Purdue University)		$27,083	
	EFRI-RESTOR: Novel Compressed Air Approach for Off-Shore Wind Energy Storage (Associated Project - NSF)		Perry Y. Li (University of Minnesota)		$283,440	

Table 2: Estimated Budgets by Research Thrust [1]						
Thrust	Project Name	Organizational Sponsor	Project Leader	Investigators	Current Year Budget	Estimated Next Year Budget
	Energy Efficienct Fluid Field Trial 061 (Associated Project - translational research)	Confidential Organization (optional use for associated or sponsored projects only)	Paul W. Michael (Milwaukee School of Engineering-Fluid Power Institute)		$66,133	
	Energy Efficient Fluids (Associated Project - translational research)	Confidential Organization (optional use for associated or sponsored projects only)	Paul W. Michael (Milwaukee School of Engineering-Fluid Power Institute)		$120,967	
	Energy saving hydraulic system architecture for next generation of combines utilizing displacement control (Associated Project - translational research)	Confidential Organization (optional use for associated or sponsored projects only)	Monika M. Ivantysynova (Purdue University)		$177,733	
	Evaluation And Design Improvements For A Hydraulic Pump (Associated Project - translational research)	Confidential Organization (optional use for associated or sponsored projects only)	Monika M. Ivantysynova (Purdue University)		$47,009	
	Evaluation of performance of counterbalance valves (Associated Project)	Oerlikon Fairfield	Andrea Vacca (Purdue University)		$14,400	
	Modeling of external gear pumps operating with power law fluids and experimental validation (Associated Project)	Proctor and Gamble	Andrea Vacca (Purdue University)		$108,412	
	Modelling and analysis of swash plate axial piston pump (Associated Project - translational research)	Confidential Organization (optional use for associated or sponsored projects only)	Monika M. Ivantysynova (Purdue University)		$51,243	
	MRI: Development of a Controlled-Trajectory Rapid Compression and Expansion Machine (Associated Project - translational research - NSF)		Zongxuan Sun (University of Minnesota)		$271,684	
	New Geometries for External Gear Machines towards the reduction of Noise Emissions (Associated Project)	Casappa S.p.A.	Andrea Vacca (Purdue University)		$13,810	
	Numerical Modeling of GEROTORs unit (Associated Project)	Thomas Magnete GmbH	Andrea Vacca (Purdue University)		$12,463	
	Optimal design of a fuel injection pump (Associated Project - translational research)	Robert Bosch SpA	Andrea Vacca (Purdue University)		$47,000	
Translational Research Projects Within Thrust					**$1,425,769**	
Subtotal (all projects) for Thrust					**$2,065,315**	**$738,388**
Total Number of Undergraduate Students in Thrust					**0**	
Total Number of Graduate Students (M.S. and Ph.D.) in Thrust					**17**	
Total Number of Postdocs in Thrust					**0**	
Total Number of Personnel in Thrust					**33**	
2: Compactness Thrust Leader: Eric J. Barth (Vanderbilt University)	2B.3: Free Piston Engine Hydraulic Pump (Center Controlled Project - translational research)	NSF ERC Program	Zongxuan Sun (University of Minnesota)		$63,545	$0
	2B.4: Controlled Stirling Thermocompressors (Center Controlled Project - translational research)	NSF ERC Program	Eric J. Barth (Vanderbilt University)		$63,545	
	2C.2: Advanced Strain Energy Accumulator (Center Controlled Project - translational research)	NSF ERC Program	Eric J. Barth (Vanderbilt University)		$63,545	
	2F.1 Soft Pneumatic Actuator for Arm Orthosis (Center Controlled Project - translational research)	NSF ERC Program	Elizabeth T. Hsiao-Wecksler (University of Illinois at Urbana-Champaign-Department of Mechanical Science & Engineering)		$63,545	
	2F: MEMS Proportional Pneumatic Valve (Center Controlled Project - translational research)	NSF ERC Program	Thomas R. Chase (University of Minnesota)		$63,545	
	2G: Fluid Powered Surgery and Rehabilitation via Compact, Integrated Systems (Center Controlled Project - translational research)	NSF ERC Program	Robert J. Webster (Vanderbilt University)		$100,335	
Translational Research Projects Within Thrust					**$418,060**	
Subtotal (all projects) for Thrust					**$418,060**	**$0**
Total Number of Undergraduate Students in Thrust					**2**	
Total Number of Graduate Students (M.S. and Ph.D.) in Thrust					**10**	
Total Number of Postdocs in Thrust					**0**	
Total Number of Personnel in Thrust					**24**	

Table 2: Estimated Budgets by Research Thrust [1]

Thrust	Project Name	Organizational Sponsor	Project Leader	Investigators	Current Year Budget	Estimated Next Year Budget
	3A.1: Operator Interface Design Principles for Hydraulics (Center Controlled Project - translational research)	NSF ERC Program	Wayne J. Book (Georgia Institute of Technology)		$63,545	
	3A.3: Human Performance Modeling and User Centered Design (Center Controlled Project)	NSF ERC Program	Steven X. Jiang (North Carolina Agriculture and Technical State University-Industrial and Systems Engineering)		$25,084	
	3D Excavator (Center Controlled Project - translational research)	NSF ERC Program	Kim A. Stelson (University of Minnesota-Mechanical Engineering)	Jane Davidson (University of Minnesota)	$97,493	
	3D.2: New Directions in Elastohydrodynamic Lubrication to Solve Fluid Power Problems (Center Controlled Project)	NSF ERC Program	Scott S. Bair (Georgia Institute of Technology-School of Mechanical Engineering)		$63,545	
	3E.1: Pressure Ripple Energy Harvester (Center Controlled Project)	NSF ERC Program	Kenneth A. Cunefare (Georgia Institute of Technology)		$20,067	
3: Effectiveness Thrust Leader: Wayne J. Book (Georgia Institute of Technology)	Electrohydraulic Braking System (Associated Project)	CNH America, Inc.	Andrea Vacca (Purdue University)		$100,600	$194,220
	High Pressure Compliant Material Development (Associated Project - translational research)	Danfoss	Kenneth A. Cunefare (Georgia Institute of Technology)		$45,745	
	New Generation Of Green, Highly Efficient Agricultural Machines Powered By High Pressure Water Hydraulic Technology (Associated Project)	Confidential Organization (optional use for associated or sponsored projects only)	Andrea Vacca (Purdue University)		$127,660	
	Noise measurements and valve plate design to reduce noise and maintain low control effort for tandem pumps. (Associated Project - translational research)	Confidential Organization (optional use for associated or sponsored projects only)	Monika M. Ivantysynova (Purdue University)		$40,644	
	Phase 3: Low Cost Compressed Natural Gas (Associated Project - translational research)	Confidential Organization (optional use for associated or sponsored projects only)	Perry Y. Li (University of Minnesota)		$38,133	
	Viscosity Measurements of Polymer Solutions at Elevated Temperatures and Pressure (Associated Project)	Confidential Organization (optional use for associated or sponsored projects only)	Scott S. Bair (Georgia Institute of Technology-School of Mechanical Engineering)		$56,000	
Translational Research Projects Within Thrust					**$285,560**	
Subtotal (all projects) for Thrust					**$678,516**	**$194,220**
Total Number of Undergraduate Students in Thrust					**1**	
Total Number of Graduate Students (M.S. and Ph.D.) in Thrust					**5**	
Total Number of Postdocs in Thrust					**0**	
Total Number of Personnel in Thrust					**20**	
5. Manufacturing Thrust Leader: Kim A. Stelson (University of Minnesota-Mechanical Engineering)	Fluid Power Advanced Manufacturing Technology Consortium (Associated Project)		Kim A. Stelson (University of Minnesota-Mechanical Engineering)		$135,944	$135,944
Translational Research Projects Within Thrust					**$0**	
Subtotal (all projects) for Thrust					**$135,944**	**$135,944**
Total Number of Undergraduate Students in Thrust					**0**	
Total Number of Graduate Students (M.S. and Ph.D.) in Thrust					**0**	
Total Number of Postdocs in Thrust					**0**	
Total Number of Personnel in Thrust					**1**	
	Test Bed 1: Heavy Mobile Equipment- Excavator (Center Controlled Project - translational research)	NSF ERC Program	Monika M. Ivantysynova (Purdue University)		$80,268	
	Test Bed 4: Patient Transfer Device - Hydraulics at Human Scale (Center Controlled Project)	NSF ERC Program	Wayne J. Book (Georgia Institute of Technology)		$80,268	
	Test Bed 6: Human Assist Devices (Fluid Powered Ankle-Foot-Orthoses) (Center Controlled Project - translational research)	NSF ERC Program	Elizabeth T. Hsiao-Wecksler (University of Illinois at Urbana-Champaign-Department of Mechanical Science & Engineering)		$115,384	
	Testbed 3: Highway Vehicles -- Hydraulic Hybrid Passenger Vehicle (Center Controlled Project)	NSF ERC Program	Perry Y. Li (University of Minnesota)		$80,268	
Test Beds Thrust Leader: Kim A. Stelson (University of Minnesota-Mechanical Engineering)	Controllable Hydraulic Ankle Prosthesis (Associated Project - translational research)	Minneapolis Veterans Administration Medical Center	William Durfee (University of Minnesota-Mechanical Engineering)		$2,625	$205,713

Table 2: Estimated Budgets by Research Thrust [1]						
Thrust	**Project Name**	**Organizational Sponsor**	**Project Leader**	**Investigators**	**Current Year Budget**	**Estimated Next Year Budget**
	CPS: Synergy: Integrated Modeling, Analysis and Synthesis of Miniature Medical Devices (Associated Project - NSF)		Pietro Valdastri (Vanderbilt University)		$250,000	
	Development of a Forearm Simulator to Recreate Abnormal Muscle Tone Due to Brain Lesions (Associated Project - translational research)	Jump Trading Simulation and Education Center	Elizabeth T. Hsiao-Wecksler (University of Illinois at Urbana-Champaign-Department of Mechanical Science & Engineering)		$9,991	
	Passive hydraulic medical training simulator for mimicking joint spasticity and rigidity (Associated Project)	Jump Trading Simulation and Education Center	Elizabeth T. Hsiao-Wecksler (University of Illinois at Urbana-Champaign-Department of Mechanical Science & Engineering)		$31,552	
	Wearable eMbots to Induce Recovery of Function (Associated Project - translational research)		William Durfee (University of Minnesota-Mechanical Engineering)		$65,463	
				Translational Research Projects Within Thrust	**$273,731**	
				Subtotal (all projects) for Thrust	**$715,819**	**$205,713**
				Total Number of Undergraduate Students in Thrust	**1**	
				Total Number of Graduate Students (M.S. and Ph.D.) in Thrust	**6**	
				Total Number of Postdocs in Thrust	**0**	
				Total Number of Personnel in Thrust	**14**	

[1] - The sum of personnel for all thrusts may be greater than the total number of personnel associated with the ERC if personnel are associated with projects under multiple thrusts.

Figure 2a: Research Project Investigators by Discipline

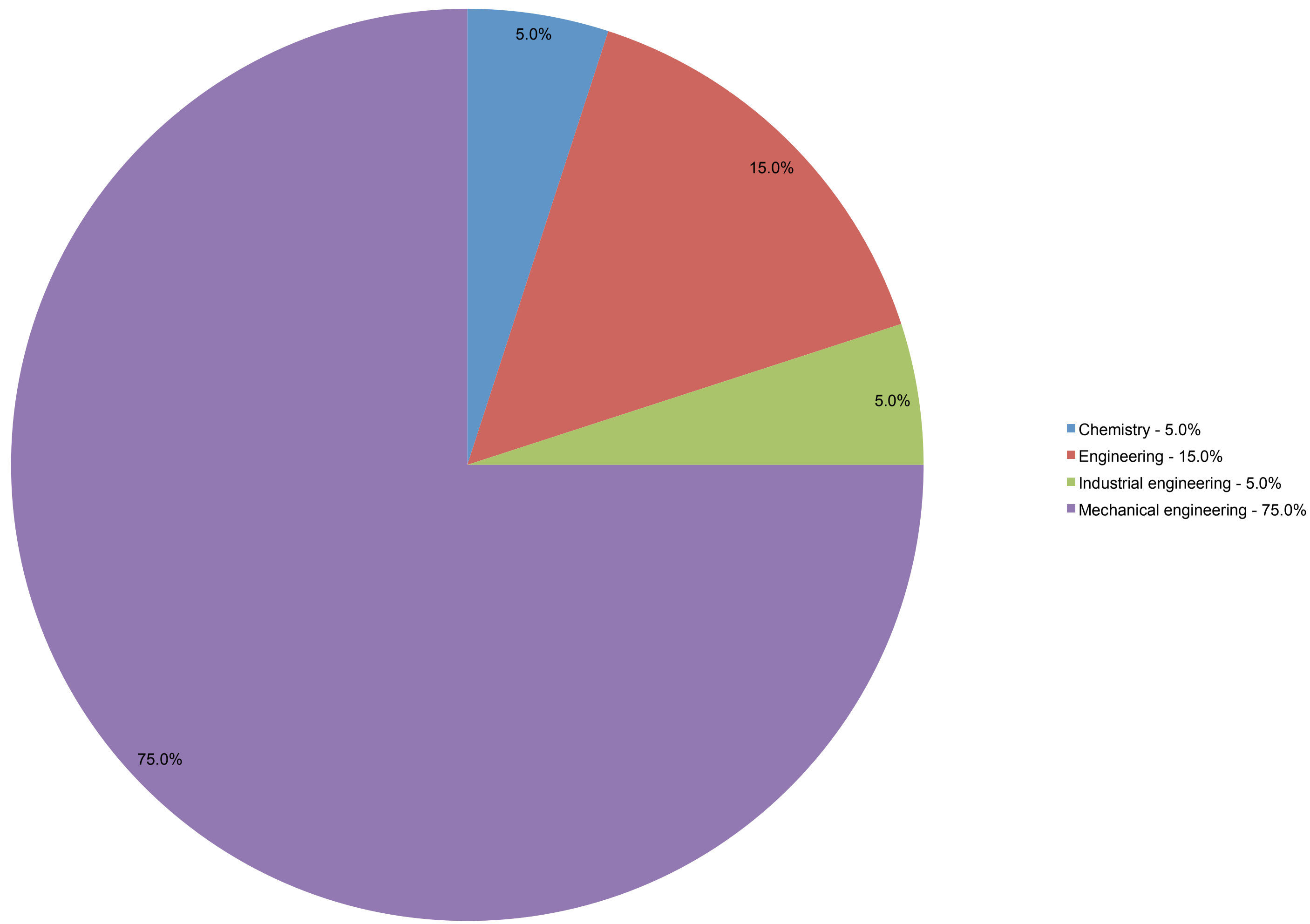
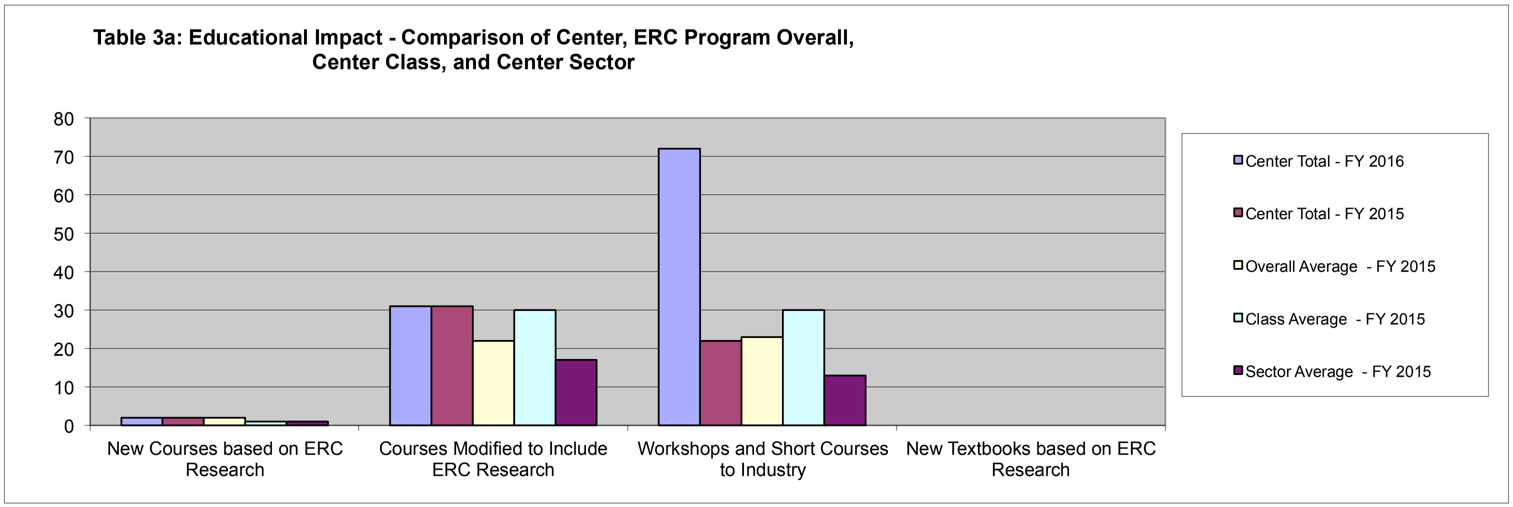


Table 3a: Educational Impact

	Total from Table 1: Quantifiable Outputs	With Engineered Systems Focus		With Multidisciplinary Content		Team Taught by Faculty From More Than 1 Department		Undergraduate Level		Graduate Level		Used at More Than 1 ERC Institution		Cumulative Total for All Years
		Feb 01, 2015-Jan 31, 2016	Percent	Feb 01, 2015-Jan 31, 2016	Percent	Feb 01, 2015-Jan 31, 2016	Percent	Feb 01, 2015-Jan 31, 2016	Percent	Feb 01, 2015-Jan 31, 2016	Percent	Feb 01, 2015-Jan 31, 2016	Percent	
New Courses Currently Offered [1]	2	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%	24
Currently Offered Ongoing Courses With ERC Content [2]	31	31	100%	31	100%	10	32%	29	94%	0	0%	0	0%	N/A
Workshops, Short Courses, and Webinars	72	72	100%	72	100%	0	0%	0	0%	0	0%	18	25%	373
New textbooks based on ERC research	0	0	0%	0	0%	N/A	N/A	0	0%	0	0%	0	0%	4



[1] New courses currently offered and approved by the curriculum committee are only counted in the first year that they are offered so there is no multiple counting of these courses.

[2] The cumulative totals for "Currently offered, ongoing courses with ERC content" may count the same course more than once.
This is due to the fact that a single course can be modified in multiple years and therefore will be included in the cumulative total multiple times.

Table 3b: Ratio of Graduates to Undergraduates

Center Grouping	Undergraduates	Graduate Students	Ratio Grad/UG	REU Students	Total College Students	Young Scholars	Total Students (Graduate, Undergraduate, Young Scholar, and REU Students)
Average All Active ERCs FY 2015	60	91	1.5	18	170	13	183
Average Advanced Manufacturing Sector FY 2015	73	85	1.2	17	175	10	186
Average for Class of 2006 FY 2015	66	78	1.2	23	167	7	174
Minnesota Twin Cities-CCEFP FY 2015	50	92	1.8	25	167	0	167
Minnesota Twin Cities-CCEFP FY 2016	**100**	**77**	**0.8**	**22**	**199**	**0**	**199**

Table 4: Industrial/Practitioner Members, Innovation Partners, Funders of Sponsored Projects, Funders of Associated Projects, and Contributing Organizations

Summary:
0 - Industrial/Practitioner Member
0 - Innovation Partner
2 - Funders of Sponsored Projects
8 - Funders of Associated Projects
12 - Contributing Organizations

Section 1: 0 Industrial/Practitioner Member

Organization	Sector	Product Focus (Industry only)	Type of Financial Support	Type of Involvement	Domestic / Foreign	Size (Industry Only)	New Member (Yes/No)	Total # of Sponsored Projects	Total # of Associated Projects
There are no organizations of the organization type Industrial/Practitioner Member for which support has been received.									

Section 2: 0 Innovation Partner

Organization	Sector	Product Focus (Industry only)	Type of Involvement	Domestic / Foreign	Size (Industry Only)	New Partner (Yes/No)
There are no organizations of the organization type Innovation Partner.						

Section 3: 2 Funders of Sponsored Projects

Organization	Sector	Product Focus (Industry only)	Type of Financial Support	Type of Involvement	Domestic / Foreign	Size (Industry Only)	New Partner (Yes/No)	Total # of Sponsored Projects
Funders of Sponsored Projects That Have Already Provided Current Award Year Support.								
FORCE America	Industry	Fluid power components and systems	Restricted Cash Donations	Participation in education/outreach activities	Domestic	Small (<500 employees)	No	0
Mathers Hydraulics	Industry	Fluid power components and systems	Restricted Cash Donations	Participation in translational research	Foreign	Large (>1000 employees)	Yes	0

Section 4: 8 Funders of Associated Projects

Organization	Sector	Product Focus (Industry only)	Type of Financial Support	Type of Involvement	Domestic / Foreign	Size (Industry Only)	New Partner (Yes/No)	Total # of Associated Projects
Funders of Associated Projects That Have Already Provided Current Award Year Support.								
Casappa S.p.A.	Industry	Fluid power components and systems	Associated Project Support	Participates in science/engineering research projects	Foreign	Large (>1000 employees)	No	1
Confidential Organization (optional use for associated or sponsored projects only)	Other Sector	N/A	Associated Project Support	Participates in science/engineering research projects	Domestic	N/A	No	12
Dae Jin Hydraulics - TECPOS	Industry	Power Solutions	Associated Project Support	Participates in science/engineering research projects	Foreign	Small (<500 employees)	No	1
Jump Trading Simulation and Education Center	Other Sector	N/A	Associated Project Support	Participates in science/engineering research projects Participation in innovation/entrepreneurship activities	Domestic	N/A	Yes	2
Oerlikon Fairfield	Industry	Industrial Control Systems	Associated Project Support	Participates in science/engineering research projects	Domestic	Large (>1000 employees)	Yes	1
Proctor and Gamble	Industry	Consumer products	Associated Project Support	Participates in science/engineering research projects	Domestic	Large (>1000 employees)	Yes	1
Robert Bosch SpA	Industry	Consumer products	Associated Project Support	Participates in science/engineering research projects	Foreign	Large (>1000 employees)	Yes	1
Thomas Magnete GmbH	Industry	Automotive	Associated Project Support	Participates in science/engineering research projects	Foreign	Small (<500 employees)	No	2

Section 5: 12 Contributing Organizations

Organization	Sector	Product Focus (Industry only)	Type of Financial Support	Type of Involvement	Domestic / Foreign	Size (Industry Only)	New Partner (Yes/No)
Contributing Organizations That Have Already Provided Current Award Year Support.							
Bosch Rexroth	Industry	Industrial Control Systems	Restricted Cash Donations	Participation in education/outreach activities	Domestic	Large (>1000 employees)	Yes
Cat Pumps	Industry	Fluid power components and systems		Participates in science/engineering research projects	Domestic	Small (<500 employees)	No
CNH America, Inc.	Industry	Vehicle OEM	Associated Project Support In-Kind Donations	Participates in science/engineering research projects	Domestic	Large (>1000 employees)	No
Danfoss	Industry	Fluid power components and systems	Associated Project Support	Member of Center's Industrial Advisory Board Participates in science/engineering research projects Involvement in Technology Transfer	Domestic	Large (>1000 employees)	No
Donaldson Company	Industry	Fluid power components and systems	In-Kind Donations	Participation in translational research Involvement in Technology Transfer	Domestic	Large (>1000 employees)	No
Eaton Corporation	Industry	Fluid power components and systems	Restricted Cash Donations In-Kind Donations	Member of Center's Industrial Advisory Board Participates in science/engineering research projects Participation in education/outreach activities Participation in translational research Involvement in Technology Transfer	Domestic	Large (>1000 employees)	No
Environmental Protection Agency	U.S. Government (Not NSF)	N/A	In-Kind Donations	Participates in science/engineering research projects	Domestic	N/A	No
Exxon Mobil	Industry	Fluid power components and systems	In-Kind Donations	Participates in science/engineering research projects	Domestic	Large (>1000 employees)	No
Minneapolis Veterans Administration Medical Center	U.S. Government (Not NSF)	N/A	Associated Project Support	Participates in science/engineering research projects	Domestic	N/A	No
National Fluid Power Association	Industrial Association	N/A	Unrestricted Cash Donations	Member of Center's Industrial Advisory Board Participates in science/engineering research projects Participation in education/outreach activities	Domestic	N/A	No

Section 5: 12 Contributing Organizations							
Organization	**Sector**	**Product Focus (Industry only)**	**Type of Financial Support**	**Type of Involvement**	**Domestic / Foreign**	**Size (Industry Only)**	**New Partner (Yes/No)**
NFPA Education and Technology Foundation	Private Foundation	N/A	Unrestricted Cash Donations	Member of Center's Industrial Advisory Board Participates in science/engineering research projects Participation in education/outreach activities	Domestic	N/A	No
SMC Corporation	Industry	Information Technology	In-Kind Donations	Participates in science/engineering research projects	Foreign	Large (>1000 employees)	Yes

Section 6: Summary					
Sector	**Industrial/Practitioner Members**	**Percent Foreign**	**Percent Small**	**Percent Medium**	**Percent Large**
Total	**0**	**0%**	**N/A**	**N/A**	**N/A**

Table 4a: Organization Involvement in Innovation and Entrepreneurship Activities

Organization Name	Innovation/Entrepreneurship Training Activities	Provides Incubation Facilities	Technology Screening Activities	Connections to Sources of Commercialization Funding	Other Activity
Jump Trading Simulation and Education Center		✔			

Table 5: Innovation Ecosystem Partners and Support, by Year

	Jun 01, 2012 - May 31, 2013	Jun 01, 2013 - May 31, 2014	Jun 01, 2014 - May 31, 2015	Jun 01, 2015 - May 31, 2016 [1]
Industrial/Practitioner Members	41	46	0	0
Innovation Partners	1	1	0	0
Funders of Sponsored Projects	0	1	1	2
Funders of Associated Projects	8	10	10	8
Contributing Organizations	6	4	12	12
Total Participating Organizations	**56**	**62**	**23**	**22**
Number of Member-Sponsored Projects	0	0	0	0
Number of Non-Member-Sponsored Projects	0	0	0	0
Total Number of Sponsored Projects	**0**	**0**	**0**	**0**
Membership Fees Received - Cash	$583,100	$454,717	$0	$0
Membership Fees Expected from Prior Year Members [2]	N/A	N/A	N/A	$0
Member-Sponsored Projects Total Dollar Amount	$0	$0	$0	$0
Member-Associated Projects Total Dollar Amount	$78,336	$115,269	$0	$0
Member In-Kind Total Dollar Amount [3]	$12,257	$0	$0	$0
Total Dollar Amount, Industrial/Practitioner Member Support to Center	**$673,693**	**$569,986**	**$0**	**$0**

[1] Partial Award Year data only.

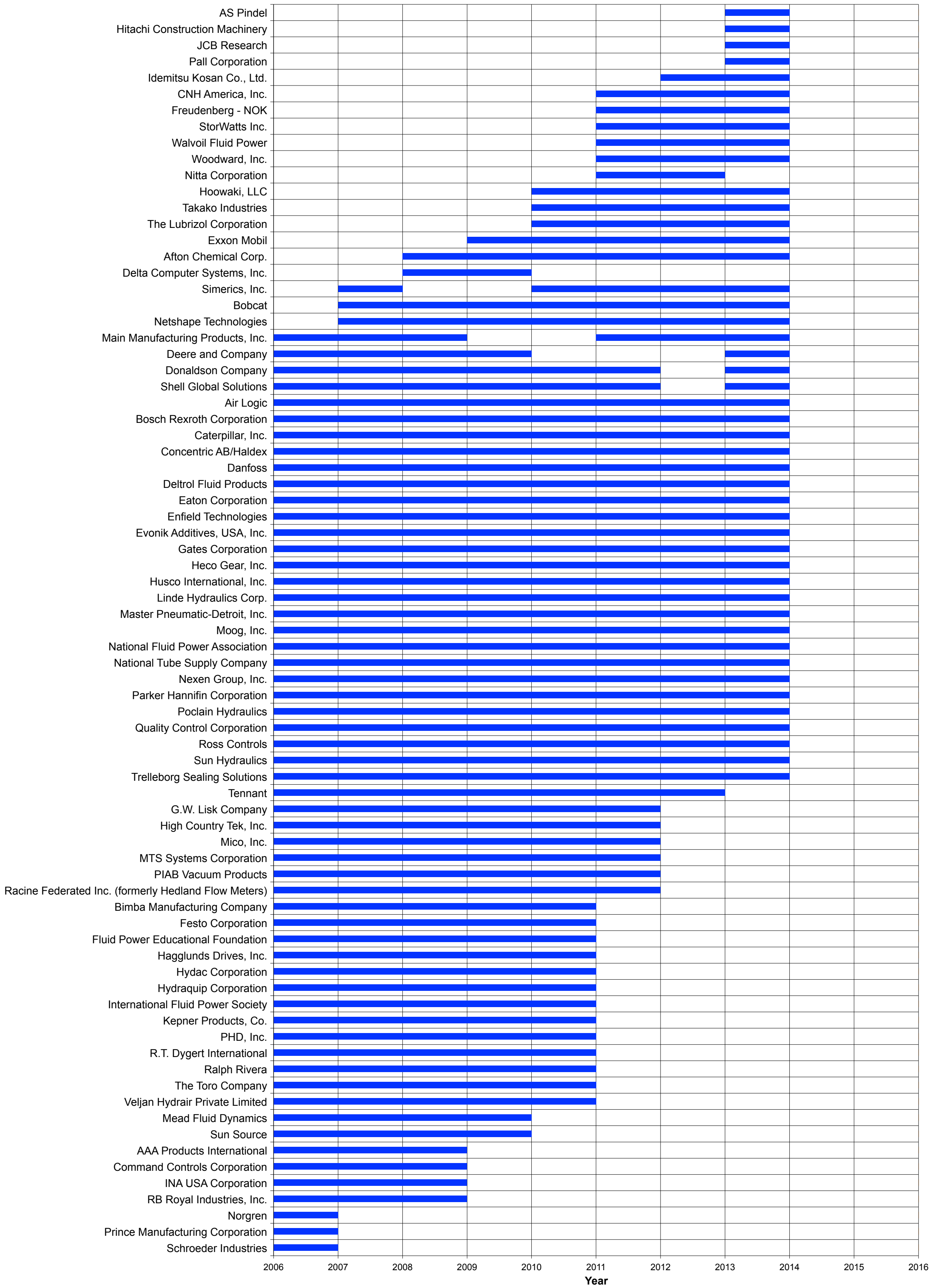
[2] Only applies for organizatons that were already Industrial/Practitioner Members in a prior year.

[3] Data for this row is from the In-Kind Support reported in the Organizations section. There is no data prior to 2010 since it is a new field that year.

Table 5a: Technology Transfer Activities

Organization Name	Faculty On Site at Organization	Faculty Instruction to Organization	Individual from Organization on Lead Institution Campus	Licensed Software	Licensed Technology (other than software)	Graduate Hired by Organization	Student On Site at Organization	Participation in Test Bed	Other Activities
Bosch Rexroth									
Casappa S.p.A.									
Cat Pumps									
CNH America, Inc.									
Confidential Organization (optional use for associated or sponsored projects only)									
Dae Jin Hydraulics - TECPOS									
Danfoss		✔			✔				
Donaldson Company		✔	✔						
Eaton Corporation	✔	✔			✔	✔	✔		
Environmental Protection Agency									
Exxon Mobil									
FORCE America									
Jump Trading Simulation and Education Center									
Mathers Hydraulics									
Minneapolis Veterans Administration Medical Center									
National Fluid Power Association									
NFPA Education and Technology Foundation									
Oerlikon Fairfield									
Proctor and Gamble									
Robert Bosch SpA									
SMC Corporation									
Thomas Magnete GmbH									

Figure 5b: Lifetime Industrial/Practitioner Membership History



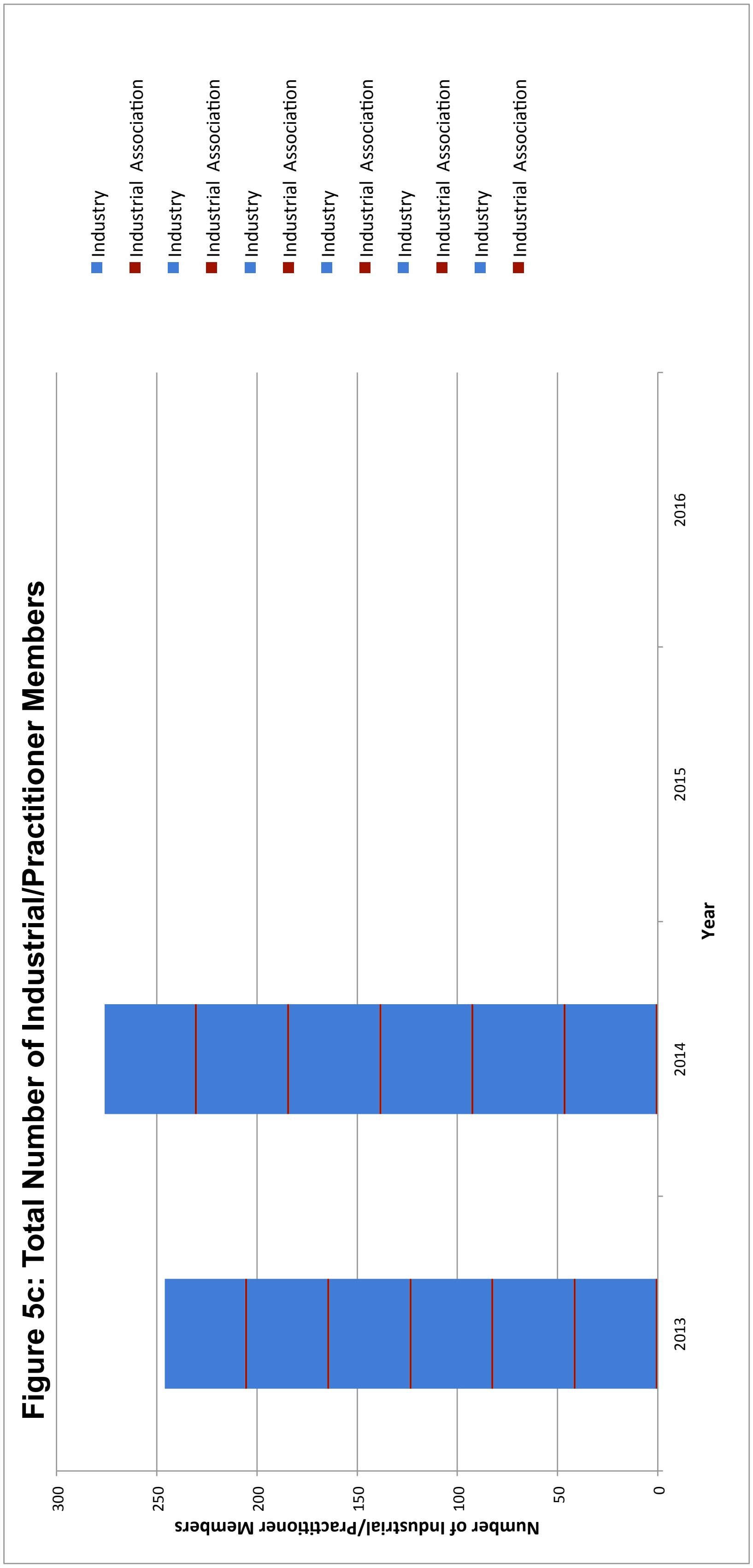
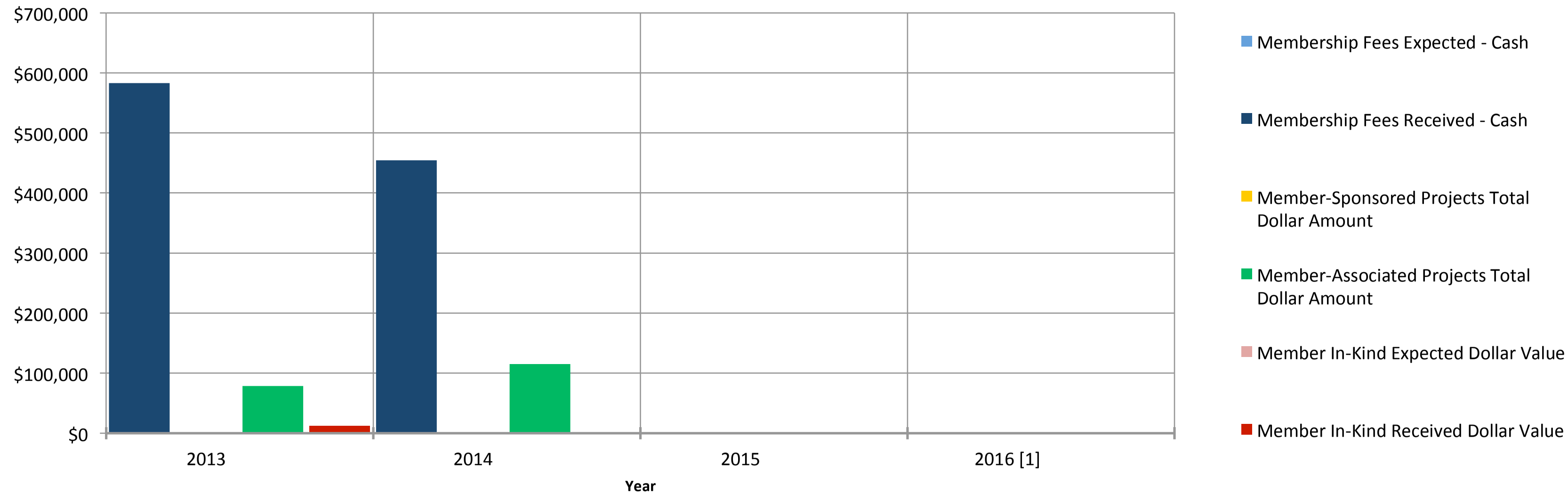


Figure 5c: Total Number of Industrial/Practitioner Members

Figure 5d: Industrial/Practitioner Member Support by Year, FY 2016

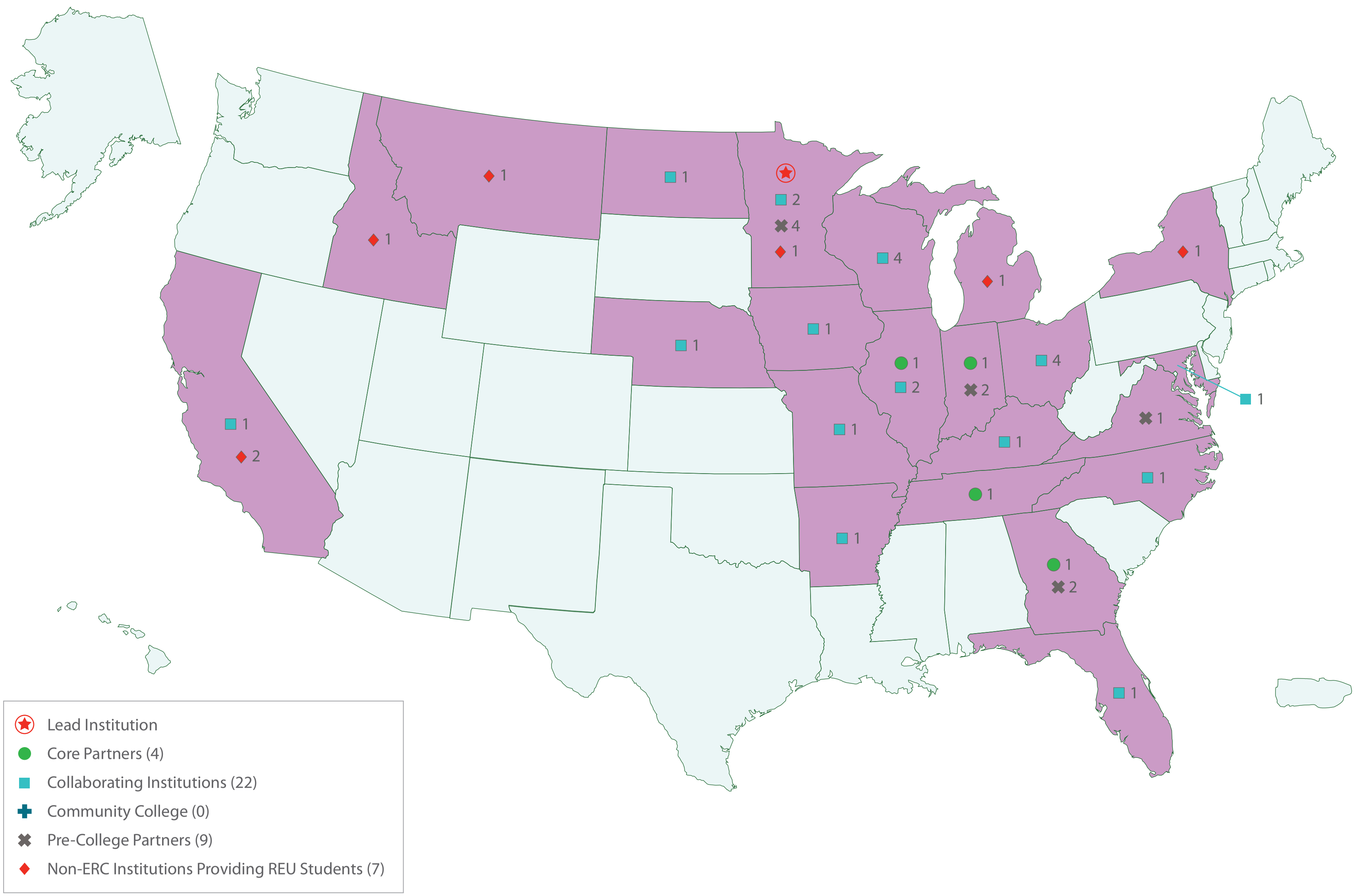


[1] - Member support provided through end of current reporting year (includes only partial data)

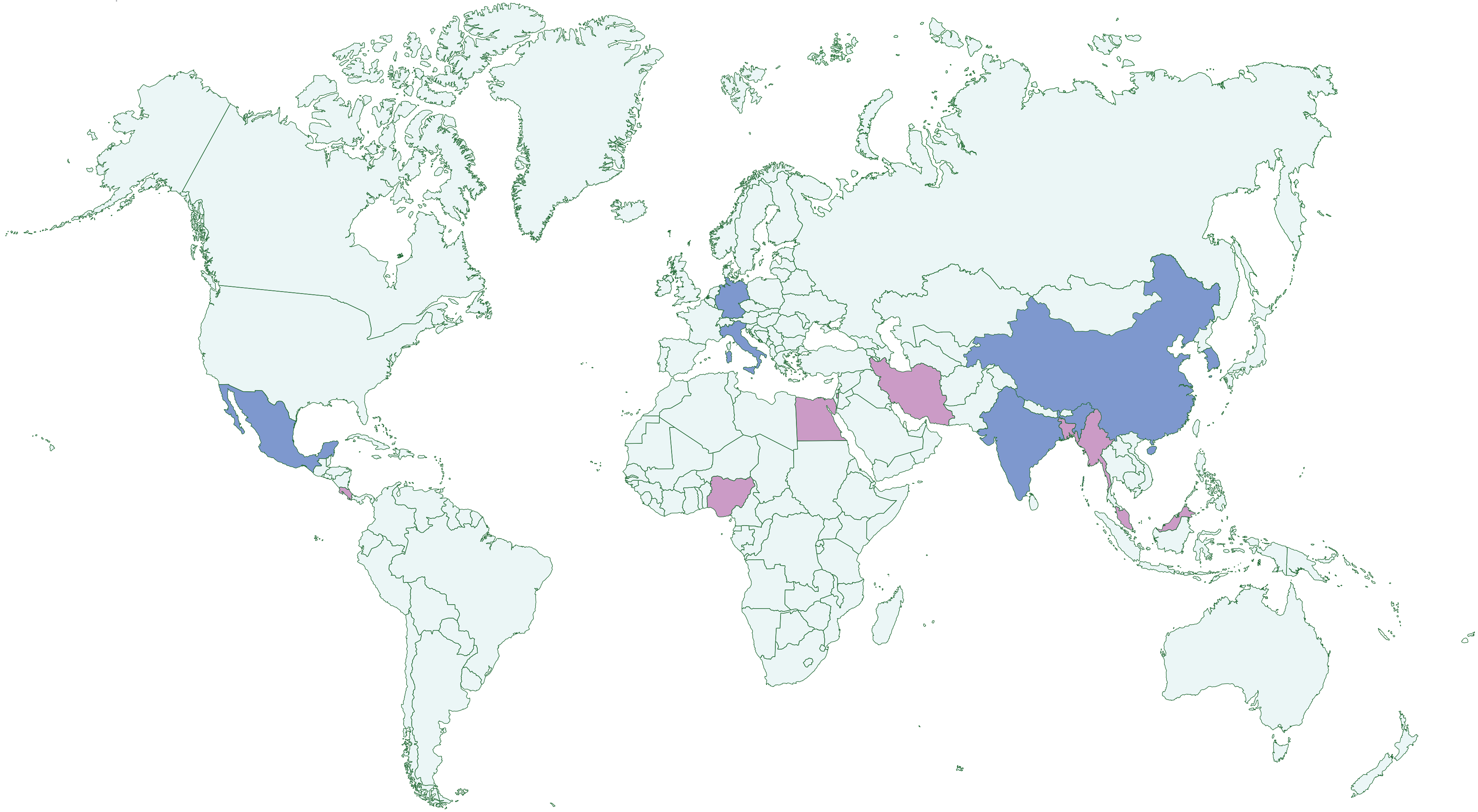
Table 6: Institutions Executing the ERC's Research, Technology Transfer, and Education Programs																
Institutions							Personnel in ERC Activities [1]									
Name and Type	Total	Female Serving	Minority Serving	HBCU	Hispanic Serving	Large Number of URM Students in Engineering	Faculty	Community College RET	Teachers (K-12)		Postdocs	Students				Young Scholars
												Graduate		UG Non-REU	REU	
									RET	Non-RET		Doctoral	Masters			
I. Lead	**1**	**0**	**1**	**0**	**0**	**0**	**10**	**N/A**	**N/A**	**N/A**	**0**	**8**	**12**	**16**	**1**	**N/A**
University of Minnesota, Minneapolis, MN			✔				10	N/A	N/A	N/A	0	8	12	16	1	N/A
II. Core Partners	**4**	**0**	**0**	**0**	**0**	**0**	**25**	**N/A**	**N/A**	**N/A**	**0**	**29**	**19**	**21**	**6**	**N/A**
Georgia Institute of Technology, Atlanta, GA							7	N/A	N/A	N/A	0	4	4	5	1	N/A
Purdue University, West Lafayette, IN							4	N/A	N/A	N/A	0	15	9	3	2	N/A
University of Illinois at Urbana-Champaign, Urbana, IL							10	N/A	N/A	N/A	0	5	5	10	3	N/A
Vanderbilt University, Nashville, TN							4	N/A	N/A	N/A	0	5	1	3	0	N/A
III. Collaborating Institutions	**22**	**0**	**2**	**1**	**1**	**2**	**20**	**N/A**	**N/A**	**N/A**	**0**	**2**	**7**	**63**	**6**	**N/A**
Cal Poly San Luis Obispo, San Luis Obispo, CA			✔		✔	✔	2	N/A	N/A	N/A	0	0	0	5	1	N/A
Cleveland State, Cleveland, OH							3	N/A	N/A	N/A	0	0	0	4	0	N/A
Illinois Institute of Technology, Chicago, IL							1	N/A	N/A	N/A	0	0	0	5	0	N/A
Iowa State University, Ames, IA							0	N/A	N/A	N/A	0	0	0	4	0	N/A
Milwaukee School of Engineering, Milwaukee, WI							1	N/A	N/A	N/A	0	0	5	3	0	N/A
Murray State, Murray, KY							2	N/A	N/A	N/A	0	0	0	11	0	N/A
North Carolina Agriculture and Technical State University, Greensboro, NC			✔	✔		✔	3	N/A	N/A	N/A	0	2	1	3	3	N/A
Ohio University, Athens, OH							2	N/A	N/A	N/A	0	0	0	4	0	N/A
Quality Evaluation Designs, Minneapolis, MN							0	N/A	N/A	N/A	0	0	0	0	0	N/A
Science Museum of Minnesota, St. Paul, MN							0	N/A	N/A	N/A	0	0	1	0	0	N/A
Triton College, River Grove, IL							0	N/A	N/A	N/A	0	0	0	1	0	N/A
University of Akron, Akron, OH							1	N/A	N/A	N/A	0	0	0	5	0	N/A
University of Central Arkansas, Conway, AR							1	N/A	N/A	N/A	0	0	0	3	1	N/A
University of Cincinnati, Cincinnati, OH							3	N/A	N/A	N/A	0	0	0	5	0	N/A
University of Florida, Gainesville, FL							0	N/A	N/A	N/A	0	0	0	1	0	N/A
University of Maryland, Baltimore, Baltimore, MD							0	N/A	N/A	N/A	0	0	0	1	0	N/A
University of Missouri, Columbia, MO							0	N/A	N/A	N/A	0	0	0	1	0	N/A
University of Nebraska, Omaha, NE							0	N/A	N/A	N/A	0	0	0	1	0	N/A
University of North Dakota, Fargo, ND							0	N/A	N/A	N/A	0	0	0	2	0	N/A
University of Wisconsin- Madison, Madison, WI							1	N/A	N/A	N/A	0	0	0	2	0	N/A
University of Wisconsin- Parkside, Kenosha, WI							0	N/A	N/A	N/A	0	0	0	1	0	N/A
University of Wisconsin- Platteville, Platteville, WI							0	N/A	N/A	N/A	0	0	0	1	1	N/A
IV. Non-ERC Institutions Providing REU Students	**7**	**0**	**1**	**0**	**1**	**1**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**10**	**N/A**
Binghamton University, Binghamton, NY							N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	1	N/A
Montana State University- Bozeman, Bozeman, MT							N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	3	N/A
St. John's University, St. Joseph, MN							N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	1	N/A
The College of Idaho, Caldwell, ID							N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	1	N/A
University of California Merced, Merced, CA			✔		✔	✔	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	1	N/A
University of Michigan- Ann Arbor, Ann Arbor, MI							N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	1	N/A
University of Southern California, Los Angeles, CA							N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	2	N/A
V. NSF Diversity Program Awardees	**3**	**0**	**2**	**0**	**1**	**2**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**0**	**0**	**0**	**0**	**N/A**
Alliances for Graduate Education and the Professoriate (AGEP)	**0**	**0**	**0**	**0**	**0**	**0**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**0**	**0**	**0**	**0**	**N/A**
No AGEP institutions were entered.																
Centers of Research Excellence in Science and Technology (CREST)	**0**	**0**	**0**	**0**	**0**	**0**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**0**	**0**	**0**	**0**	**N/A**
No CREST institutions were entered.																
Louis Stokes Alliances for Minority Participation (LSAMP)	**2**	**0**	**1**	**0**	**0**	**1**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**0**	**0**	**0**	**0**	**N/A**
North Star STEM Alliance						✔	N/A	N/A	N/A	N/A	N/A	0	0	0	0	N/A
SUNY Alliance for Minority Participation			✔				N/A	N/A	N/A	N/A	N/A	0	0	0	0	N/A
Tribal Colleges and Universities Program (TCUP)	**0**	**0**	**0**	**0**	**0**	**0**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**0**	**0**	**0**	**0**	**N/A**
No TCUP institutions were entered.																
NSF Diversity Program Collaborations (NSF Diversity Program Collaborations)	**1**	**0**	**1**	**0**	**1**	**1**	**0**	**N/A**	**N/A**	**N/A**	**0**	**0**	**0**	**0**	**0**	**N/A**
The National GEM Consortium			✔		✔	✔	0	N/A	N/A	N/A	0	0	0	0	0	N/A
VI. Precollege Partners	**9**	**0**	**0**	**0**	**0**	**0**	**N/A**	**N/A**	**0**	**15**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**0**
Capitol Hill Gifted and Talented Magnet, St Paul, MN							N/A	N/A	0	1	N/A	N/A	N/A	N/A	N/A	0
Gainesville Middle School, Gainesville, VA							N/A	N/A	0	1	N/A	N/A	N/A	N/A	N/A	0
Georgia Cyber Academy, Atlanta, GA							N/A	N/A	0	1	N/A	N/A	N/A	N/A	N/A	0
Lafayette Jefferson High School, Lafayette, IN							N/A	N/A	0	1	N/A	N/A	N/A	N/A	N/A	0
North Branch Area Public Schools, North Branch, MN							N/A	N/A	0	1	N/A	N/A	N/A	N/A	N/A	0
Northfield Middle School, Northfield, MN							N/A	N/A	0	1	N/A	N/A	N/A	N/A	N/A	0
Purdue University 4-H, West Lafayette, IN							N/A	N/A	0	7	N/A	N/A	N/A	N/A	N/A	0
Royalton Middle School, Royalton, MN							N/A	N/A	0	1	N/A	N/A	N/A	N/A	N/A	0
Sequoyah Middle School, Riverdale, GA							N/A	N/A	0	1	N/A	N/A	N/A	N/A	N/A	0
VII. Community Colleges	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**N/A**	**N/A**	**0**	**0**	**0**	**0**	**0**	**N/A**
No Community College institutions were entered.																
Total	**46**	**0**	**6**	**1**	**3**	**5**	**55**	**0**	**0**	**15**	**0**	**39**	**38**	**100**	**23**	**0**

[1] - Only ERC personnel executing the ERC mission are shown in this table.

6a Location of Lead, Core Partner, and All Domestic Collaborating Institutions



6c Country of Citizenship for ERC Foreign Personnel



ዶ = Number of ERC personnel from this country

- 1 person
- 2–10 people
- 11+ people

1 person ዶ	
Bangladesh	Iran
Burma	Malaysia
Costa Rica	Nigeria
Egypt	Palestine

2–10 people	ዶ
China	4
Germany	2
India	7

2–10 people	ዶ
Italy	2
Mexico	2
South Korea	2

	ዶ
Country Not Reported	0*

* Number of ERC personnel who are foreign and did not provide a country name

Table 7: ERC Personnel

Personnel Type	Total[1]	Gender: Male	Gender: Female	Gender: Gender Not Reported	Citizenship Status — Race—U.S. citizens and permanent residents only: AI/AN	NH/PI	B/AA	W	A	More than one race reported, minority	More than one race reported, non-minority	Race Not Reported	Citizenship Foreign/Temp Visa	Citizenship Not Reported	Ethnicity: Hispanic — U.S. Citizen/Perm Resident	Citizenship Foreign/Temp Visa	Citizenship Not Reported	Disability
Total All Institutions																		
Total [2]	274	162	44	68	0	0	4	91	8	2	2	6	28	133	4	3	3	1
Leadership/Administration																		
Directors	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Thrust Leaders	3	2	1	0	0	0	0	2	0	1	0	0	0	0	0	0	0	0
Research Thrust Management and Strategic Planning	2	2	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0
Industrial Liaison Officer (ILO)	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Education Program Leaders	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Administrative Director	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Staff	6	3	3	0	0	0	1	4	0	0	0	1	0	0	0	0	0	0
Subtotal	**15**	**10**	**5**	**0**	**0**	**0**	**1**	**11**	**1**	**1**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**
Research Under Strategic Research Plan																		
Senior Faculty	30	22	4	4	0	0	0	17	4	2	0	1	0	6	0	0	0	0
Junior Faculty	10	10	0	0	0	0	0	6	1	0	0	0	2	1	0	0	0	0
Research Staff	5	5	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0
Total Doctoral Students	39	22	10	7	0	0	3	11	0	0	0	1	15	9	0	1	0	0
Total Master's Students	38	21	7	10	0	0	0	14	1	0	2	1	6	14	1	1	0	0
Other Visiting College Students	2	0	1	1	0	0	0	0	0	0	0	0	0	2	0	0	0	0
Subtotal	**124**	**80**	**22**	**22**	**0**	**0**	**3**	**53**	**6**	**2**	**2**	**3**	**23**	**32**	**1**	**2**	**0**	**0**
Curriculum Development and Outreach																		
Senior Faculty	42	23	4	15	0	0	0	17	4	2	0	1	0	18	0	0	0	0
Junior Faculty	13	10	1	2	0	0	0	7	1	0	0	0	2	3	1	0	0	0
Research Staff	8	4	3	1	0	0	0	7	0	0	0	0	0	1	0	0	0	1
Total Undergraduate Students	100	65	14	21	0	0	0	21	2	0	0	0	5	72	2	1	3	0
Subtotal	**163**	**102**	**22**	**39**	**0**	**0**	**0**	**52**	**7**	**2**	**0**	**1**	**7**	**94**	**3**	**1**	**3**	**1**
ERC REU Students																		
NSF REU Site Award Students	22	14	8	0	0	0	0	3	0	0	0	0	0	19	0	0	3	0
Subtotal	**22**	**14**	**8**	**0**	**0**	**0**	**0**	**3**	**0**	**0**	**0**	**0**	**0**	**19**	**0**	**0**	**3**	**0**
Precollege (K-12)																		
Teachers (non-RET)	15	4	0	11	0	0	0	2	0	0	0	2	0	11	0	0	0	0
Subtotal	**15**	**4**	**0**	**11**	**0**	**0**	**0**	**2**	**0**	**0**	**0**	**2**	**0**	**11**	**0**	**0**	**0**	**0**
University of Minnesota - Lead Institution																		
Total [2]	57	38	12	7	0	0	1	30	2	0	1	1	8	14	2	1	0	0
Leadership/Administration																		
Directors	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Research Thrust Management and Strategic Planning	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Industrial Liaison Officer (ILO)	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Education Program Leaders	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Administrative Director	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Staff	6	3	3	0	0	0	1	4	0	0	0	1	0	0	0	0	0	0
Subtotal	**11**	**7**	**4**	**0**	**0**	**0**	**1**	**8**	**1**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**
Research Under Strategic Research Plan																		
Senior Faculty	8	6	2	0	0	0	0	7	1	0	0	0	0	0	0	0	0	0
Junior Faculty	2	2	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0
Total Doctoral Students	8	7	0	1	0	0	0	2	0	0	0	0	5	1	0	0	0	0
Total Master's Students	12	8	1	3	0	0	0	6	0	0	1	0	1	4	0	0	0	0
Other Visiting College Students	2	0	1	1	0	0	0	0	0	0	0	0	0	2	0	0	0	0
Subtotal	**32**	**23**	**4**	**5**	**0**	**0**	**0**	**16**	**2**	**0**	**1**	**0**	**6**	**7**	**0**	**0**	**0**	**0**
Curriculum Development and Outreach																		
Senior Faculty	8	6	2	0	0	0	0	7	1	0	0	0	0	0	0	0	0	0
Junior Faculty	2	2	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0
Research Staff	2	0	1	1	0	0	0	1	0	0	0	0	0	1	0	0	0	0
Total Undergraduate Students	16	11	4	1	0	0	0	8	0	0	0	0	2	6	2	1	0	0
Subtotal	**28**	**19**	**7**	**2**	**0**	**0**	**0**	**17**	**2**	**0**	**0**	**0**	**2**	**7**	**2**	**1**	**0**	**0**
ERC REU Students																		
NSF REU Site Award Students	1	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Subtotal	**1**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**
Georgia Institute of Technology - Core Partner																		
Total [2]	23	18	5	0	0	0	0	17	1	0	0	0	1	4	0	0	2	0
Leadership/Administration																		
Thrust Leaders	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Research Under Strategic Research Plan																		
Senior Faculty	6	6	0	0	0	0	0	4	1	0	0	0	0	1	0	0	0	0
Junior Faculty	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Research Staff	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Total Doctoral Students	4	1	3	0	0	0	0	3	0	0	0	0	1	0	0	0	0	0
Total Master's Students	4	4	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0
Subtotal	**16**	**13**	**3**	**0**	**0**	**0**	**0**	**13**	**1**	**0**	**0**	**0**	**1**	**1**	**0**	**0**	**0**	**0**
Curriculum Development and Outreach																		
Senior Faculty	6	6	0	0	0	0	0	4	1	0	0	0	0	1	0	0	0	0
Junior Faculty	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Research Staff	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Total Undergraduate Students	5	4	1	0	0	0	0	2	0	0	0	0	0	3	0	0	2	0
Subtotal	**13**	**11**	**2**	**0**	**0**	**0**	**0**	**8**	**1**	**0**	**0**	**0**	**0**	**4**	**0**	**0**	**2**	**0**
ERC REU Students																		
NSF REU Site Award Students	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Purdue University - Core Partner																		
Total [2]	33	22	6	5	0	0	0	10	0	1	0	1	9	12	0	2	0	0
Leadership/Administration																		
Thrust Leaders	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Subtotal	**1**	**0**	**1**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Research Under Strategic Research Plan																		
Senior Faculty	3	2	1	0	0	0	0	2	0	1	0	0	0	0	0	0	0	0
Junior Faculty	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Total Doctoral Students	15	10	2	3	0	0	0	4	0	0	0	1	6	4	0	1	0	0
Total Master's Students	9	5	2	2	0	0	0	3	0	0	0	0	3	3	0	1	0	0
Subtotal	**28**	**18**	**5**	**5**	**0**	**0**	**0**	**10**	**0**	**1**	**0**	**1**	**9**	**7**	**0**	**2**	**0**	**0**
Curriculum Development and Outreach																		
Senior Faculty	3	2	1	0	0	0	0	2	0	1	0	0	0	0	0	0	0	0
Junior Faculty	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Total Undergraduate Students	3	3	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0
Subtotal	**7**	**6**	**1**	**0**	**0**	**0**	**0**	**3**	**0**	**1**	**0**	**0**	**0**	**3**	**0**	**0**	**0**	**0**
ERC REU Students																		
NSF REU Site Award Students	2	1	1	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0
Subtotal	**2**	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**2**	**0**	**0**	**0**	**0**
University of Illinois at Urbana-Champaign - Core Partner																		
Total [2]	33	22	6	5	0	0	0	6	4	1	1	0	7	14	0	0	0	0
Leadership/Administration																		
Thrust Leaders	1	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Research Under Strategic Research Plan																		
Senior Faculty	6	3	1	2	0	0	0	1	1	1	0	0	0	3	0	0	0	0

Table 7: ERC Personnel																		
		Gender			Citizenship Status										Ethnicity: Hispanic			
					Race—U.S. citizens and permanent residents only													
Personnel Type	Total[1]	Male	Female	Gender Not Reported	AI/AN	NH/PI	B/AA	W	A	More than one race reported, minority	More than one race reported, non-minority	Race Not Reported	Citizenship Foreign/Temp Visa	Citizenship Not Reported	U.S. Citizen/Perm Resident	Citizenship Foreign/Temp Visa	Citizenship Not Reported	Disability
Total All Institutions																		
Junior Faculty	4	4	0	0	0	0	0	2	0	0	0	0	1	1	0	0	0	0
Total Doctoral Students	5	2	1	2	0	0	0	1	0	0	0	0	2	2	0	0	0	0
Total Master's Students	5	2	2	1	0	0	0	0	1	0	1	0	2	1	0	0	0	0
Subtotal	**20**	**11**	**4**	**5**	**0**	**0**	**0**	**4**	**2**	**1**	**1**	**0**	**5**	**7**	**0**	**0**	**0**	**0**
Curriculum Development and Outreach																		
Senior Faculty	6	3	1	2	0	0	0	1	1	1	0	0	0	3	0	0	0	0
Junior Faculty	4	4	0	0	0	0	0	2	0	0	0	0	1	1	0	0	0	0
Total Undergraduate Students	10	9	1	0	0	0	0	2	2	0	0	0	2	4	0	0	0	0
Subtotal	**20**	**16**	**2**	**2**	**0**	**0**	**0**	**5**	**3**	**1**	**0**	**0**	**3**	**8**	**0**	**0**	**0**	**0**
ERC REU Students																		
NSF REU Site Award Students	3	2	1	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0
Subtotal	**3**	**2**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**3**	**0**	**0**	**0**	**0**
Vanderbilt University - Core Partner																		
Total [2]	13	8	3	2	0	0	1	4	0	0	0	1	1	6	0	0	1	0
Leadership/Administration																		
Research Thrust Management and Strategic Planning	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Research Under Strategic Research Plan																		
Senior Faculty	3	2	0	1	0	0	0	2	0	0	0	0	0	1	0	0	0	0
Junior Faculty	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Total Doctoral Students	5	2	2	1	0	0	1	1	0	0	0	0	1	2	0	0	0	0
Total Master's Students	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Subtotal	**10**	**6**	**2**	**2**	**0**	**0**	**1**	**4**	**0**	**0**	**0**	**1**	**1**	**3**	**0**	**0**	**0**	**0**
Curriculum Development and Outreach																		
Senior Faculty	3	2	0	1	0	0	0	2	0	0	0	0	0	1	0	0	0	0
Junior Faculty	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Total Undergraduate Students	3	2	1	0	0	0	0	0	0	0	0	0	0	3	0	0	1	0
Subtotal	**7**	**5**	**1**	**1**	**0**	**0**	**0**	**3**	**0**	**0**	**0**	**0**	**0**	**4**	**0**	**0**	**1**	**0**
Cal Poly San Luis Obispo - Collaborating Institution																		
Total [2]	8	1	1	6	0	0	0	2	0	0	0	0	0	6	0	0	0	0
Curriculum Development and Outreach																		
Senior Faculty	1	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Junior Faculty	1	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Total Undergraduate Students	5	0	1	4	0	0	0	1	0	0	0	0	0	4	0	0	0	0
Subtotal	**7**	**0**	**1**	**6**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**6**	**0**	**0**	**0**	**0**
ERC REU Students																		
NSF REU Site Award Students	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Cleveland State - Collaborating Institution																		
Total [2]	7	3	1	3	0	0	0	0	0	0	0	0	0	7	0	0	0	0
Curriculum Development and Outreach																		
Senior Faculty	3	0	0	3	0	0	0	0	0	0	0	0	0	3	0	0	0	0
Total Undergraduate Students	4	3	1	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0
Subtotal	**7**	**3**	**1**	**3**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**7**	**0**	**0**	**0**	**0**
Illinois Institute of Technology - Collaborating Institution																		
Total [2]	6	5	0	1	0	0	0	4	0	0	0	0	1	1	0	0	0	0
Research Under Strategic Research Plan																		
Senior Faculty	1	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Subtotal	**1**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**
Curriculum Development and Outreach																		
Senior Faculty	1	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Total Undergraduate Students	5	5	0	0	0	0	0	4	0	0	0	0	1	0	0	0	0	0
Subtotal	**6**	**5**	**0**	**1**	**0**	**0**	**0**	**4**	**0**	**0**	**0**	**0**	**1**	**1**	**0**	**0**	**0**	**0**
Iowa State University - Collaborating Institution																		
Total [2]	4	4	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0
Curriculum Development and Outreach																		
Total Undergraduate Students	4	4	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0
Subtotal	**4**	**4**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**4**	**0**	**0**	**0**	**0**
Milwaukee School of Engineering - Collaborating Institution																		
Total [2]	13	6	4	3	0	0	0	5	0	0	0	0	0	8	0	0	0	0
Research Under Strategic Research Plan																		
Senior Faculty	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Research Staff	4	4	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0
Total Master's Students	5	0	2	3	0	0	0	0	0	0	0	0	0	5	0	0	0	0
Subtotal	**10**	**5**	**2**	**3**	**0**	**0**	**0**	**5**	**0**	**0**	**0**	**0**	**0**	**5**	**0**	**0**	**0**	**0**
Curriculum Development and Outreach																		
Senior Faculty	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Total Undergraduate Students	3	1	2	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0
Subtotal	**4**	**2**	**2**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**3**	**0**	**0**	**0**	**0**
Murray State - Collaborating Institution																		
Total [2]	13	0	0	13	0	0	0	0	0	0	0	0	0	13	0	0	0	0
Curriculum Development and Outreach																		
Senior Faculty	2	0	0	2	0	0	0	0	0	0	0	0	0	2	0	0	0	0
Total Undergraduate Students	11	0	0	11	0	0	0	0	0	0	0	0	0	11	0	0	0	0
Subtotal	**13**	**0**	**0**	**13**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**13**	**0**	**0**	**0**	**0**
North Carolina Agriculture and Technical State University - Collaborating Institution																		
Total [2]	9	4	4	1	0	0	2	0	1	0	0	1	1	4	0	0	0	0
Research Under Strategic Research Plan																		
Senior Faculty	2	2	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0
Junior Faculty	1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Total Doctoral Students	2	0	2	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0
Total Master's Students	1	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Subtotal	**6**	**3**	**2**	**1**	**0**	**0**	**2**	**0**	**1**	**0**	**0**	**1**	**1**	**1**	**0**	**0**	**0**	**0**
Curriculum Development and Outreach																		
Senior Faculty	2	2	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0
Junior Faculty	1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Total Undergraduate Students	3	1	2	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0
Subtotal	**6**	**4**	**2**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**1**	**1**	**3**	**0**	**0**	**0**	**0**
ERC REU Students																		
NSF REU Site Award Students	3	1	2	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0
Subtotal	**3**	**1**	**2**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**3**	**0**	**0**	**0**	**0**
Ohio University - Collaborating Institution																		
Total [2]	6	0	0	6	0	0	0	0	0	0	0	0	0	6	0	0	0	0
Curriculum Development and Outreach																		
Senior Faculty	1	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Junior Faculty	1	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Total Undergraduate Students	4	0	0	4	0	0	0	0	0	0	0	0	0	4	0	0	0	0
Subtotal	**6**	**0**	**0**	**6**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**6**	**0**	**0**	**0**	**0**

Table 7: ERC Personnel

Personnel Type	Total[1]	Gender			Citizenship Status										Ethnicity: Hispanic			Disability
					Race—U.S. citizens and permanent residents only													
		Male	Female	Gender Not Reported	AI/AN	NH/PI	B/AA	W	A	More than one race reported, minority	More than one race reported, non-minority	Race Not Reported	Citizenship Foreign/Temp Visa	Citizenship Not Reported	U.S. Citizen/Perm Resident	Citizenship Foreign/Temp Visa	Citizenship Not Reported	
Total All Institutions																		
Quality Evaluation Designs - Collaborating Institution																		
Total [2]	2	1	1	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0
Curriculum Development and Outreach																		
Research Staff	2	1	1	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0
Subtotal	**2**	**1**	**1**	**0**	**0**	**0**	**0**	**2**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Science Museum of Minnesota - Collaborating Institution																		
Total [2]	4	4	0	0	0	0	0	4	0	0	0	0	0	0	1	0	0	1
Research Under Strategic Research Plan																		
Total Master's Students	1	1	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**
Curriculum Development and Outreach																		
Research Staff	3	3	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	1
Subtotal	**3**	**3**	**0**	**0**	**0**	**0**	**0**	**3**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**
Triton College - Collaborating Institution																		
Total [2]	1	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Curriculum Development and Outreach																		
Total Undergraduate Students	1	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**
University of Akron - Collaborating Institution																		
Total [2]	6	5	0	1	0	0	0	4	0	0	0	0	0	2	0	0	0	0
Curriculum Development and Outreach																		
Senior Faculty	1	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Total Undergraduate Students	5	5	0	0	0	0	0	4	0	0	0	0	0	1	0	0	0	0
Subtotal	**6**	**5**	**0**	**1**	**0**	**0**	**0**	**4**	**0**	**0**	**0**	**0**	**0**	**2**	**0**	**0**	**0**	**0**
University of Central Arkansas - Collaborating Institution																		
Total [2]	5	3	0	2	0	0	0	0	0	0	0	0	0	5	0	0	0	0
Curriculum Development and Outreach																		
Senior Faculty	1	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Total Undergraduate Students	3	2	0	1	0	0	0	0	0	0	0	0	0	3	0	0	0	0
Subtotal	**4**	**2**	**0**	**2**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**4**	**0**	**0**	**0**	**0**
ERC REU Students																		
NSF REU Site Award Students	1	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**
University of Cincinnati - Collaborating Institution																		
Total [2]	8	5	1	2	0	0	0	0	0	0	0	0	0	8	0	0	0	0
Curriculum Development and Outreach																		
Senior Faculty	3	1	0	2	0	0	0	0	0	0	0	0	0	3	0	0	0	0
Total Undergraduate Students	5	4	1	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0
Subtotal	**8**	**5**	**1**	**2**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**8**	**0**	**0**	**0**	**0**
University of Florida - Collaborating Institution																		
Total [2]	1	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Curriculum Development and Outreach																		
Total Undergraduate Students	1	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**
University of Maryland, Baltimore - Collaborating Institution																		
Total [2]	1	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Curriculum Development and Outreach																		
Total Undergraduate Students	1	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**
University of Missouri - Collaborating Institution																		
Total [2]	1	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Curriculum Development and Outreach																		
Total Undergraduate Students	1	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**
University of Nebraska - Collaborating Institution																		
Total [2]	1	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Curriculum Development and Outreach																		
Total Undergraduate Students	1	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**
University of North Dakota - Collaborating Institution																		
Total [2]	2	2	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0
Curriculum Development and Outreach																		
Total Undergraduate Students	2	2	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0
Subtotal	**2**	**2**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**2**	**0**	**0**	**0**	**0**
University of Wisconsin- Madison - Collaborating Institution																		
Total [2]	3	2	1	0	0	0	0	1	0	0	0	0	0	2	1	0	0	0
Curriculum Development and Outreach																		
Junior Faculty	1	0	1	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0
Total Undergraduate Students	2	2	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0
Subtotal	**3**	**2**	**1**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**2**	**1**	**0**	**0**	**0**
University of Wisconsin- Parkside - Collaborating Institution																		
Total [2]	1	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Curriculum Development and Outreach																		
Total Undergraduate Students	1	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**
University of Wisconsin- Platteville - Collaborating Institution																		
Total [2]	2	2	0	0	0	0	0	0	0	0	0	0	0	2	0	0	1	0
Curriculum Development and Outreach																		
Total Undergraduate Students	1	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**
ERC REU Students																		
NSF REU Site Award Students	1	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**1**	**0**
Binghamton University - Non-ERC Institution Providing REU Students																		
Total [2]	1	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
ERC REU Students																		
NSF REU Site Award Students	1	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**
Montana State University- Bozeman - Non-ERC Institution Providing REU Students																		
Total [2]	3	2	1	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0
ERC REU Students																		
NSF REU Site Award Students	3	2	1	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0
Subtotal	**3**	**2**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**3**	**0**	**0**	**0**	**0**

Table 7: ERC Personnel

Personnel Type	Total[1]	Gender			Citizenship Status										Ethnicity: Hispanic			Disability
					Race—U.S. citizens and permanent residents only													
		Male	Female	Gender Not Reported	AI/AN	NH/PI	B/AA	W	A	More than one race reported, minority	More than one race reported, non-minority	Race Not Reported	Citizenship Foreign/Temp Visa	Citizenship Not Reported	U.S. Citizen/Perm Resident	Citizenship Foreign/Temp Visa	Citizenship Not Reported	
Total All Institutions																		
St. John's University - Non-ERC Institution Providing REU Students																		
Total [2]	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
ERC REU Students																		
NSF REU Site Award Students	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
The College of Idaho - Non-ERC Institution Providing REU Students																		
Total [2]	1	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0
ERC REU Students																		
NSF REU Site Award Students	1	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0
Subtotal	**1**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**1**	**0**
University of California Merced - Non-ERC Institution Providing REU Students																		
Total [2]	1	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0
ERC REU Students																		
NSF REU Site Award Students	1	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**1**	**0**
University of Michigan- Ann Arbor - Non-ERC Institution Providing REU Students																		
Total [2]	1	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
ERC REU Students																		
NSF REU Site Award Students	1	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**
University of Southern California - Non-ERC Institution Providing REU Students																		
Total [2]	2	1	1	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0
ERC REU Students																		
NSF REU Site Award Students	2	1	1	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0
Subtotal	**2**	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**2**	**0**	**0**	**0**	**0**
Capitol Hill Gifted and Talented Magnet - Pre-college Partner																		
Total [2]	1	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Precollege (K-12)																		
Teachers (non-RET)	1	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Subtotal	**1**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**
Gainesville Middle School - Pre-college Partner																		
Total [2]	1	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Precollege (K-12)																		
Teachers (non-RET)	1	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Subtotal	**1**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**
Georgia Cyber Academy - Pre-college Partner																		
Total [2]	1	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Precollege (K-12)																		
Teachers (non-RET)	1	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Subtotal	**1**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**
Lafayette Jefferson High School - Pre-college Partner																		
Total [2]	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Precollege (K-12)																		
Teachers (non-RET)	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
North Branch Area Public Schools - Pre-college Partner																		
Total [2]	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Precollege (K-12)																		
Teachers (non-RET)	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Northfield Middle School - Pre-college Partner																		
Total [2]	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Precollege (K-12)																		
Teachers (non-RET)	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**
Purdue University 4-H - Pre-college Partner																		
Total [2]	7	0	0	7	0	0	0	0	0	0	0	0	0	7	0	0	0	0
Precollege (K-12)																		
Teachers (non-RET)	7	0	0	7	0	0	0	0	0	0	0	0	0	7	0	0	0	0
Subtotal	**7**	**0**	**0**	**7**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**7**	**0**	**0**	**0**	**0**
Royalton Middle School - Pre-college Partner																		
Total [2]	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Precollege (K-12)																		
Teachers (non-RET)	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**
Sequoyah Middle School - Pre-college Partner																		
Total [2]	1	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Precollege (K-12)																		
Teachers (non-RET)	1	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Subtotal	**1**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**
North Star STEM Alliance - LSAMP																		
SUNY Alliance for Minority Participation - LSAMP																		
The National GEM Consortium - Alliance with NSF Diversity Awardees																		

[1] The Total column will not equal the sum of the values in each row. This is because an individual will be reported more than once across Gender, Citizenship Status, Ethnicity: Hispanic, and Disability.

[2] If ERC Personnel were entered at the individual level the Total row may not equal the sum of the line items. This is because an individual may be reported in more than one personnel category but is only counted once for the purposes of the Total.

Legend

AI/AN: American Indian or Alaska Native

NH/PI: Native Hawaiian or Other Pacific Islander

B/AA: Black/African American

W: White

A: Asian, e.g., Asian Indian, Chinese, Filipino, Japanese, Korean, Vietnamese, Other Asian

More than one race reported, minority - Personnel reporting a) two or more race categories and b) one or more of the reported categories includes American Indian or Alaska Native, Black or African American, or Native Hawaiian or Other Pacific Islander

More than one race reported, non-minority - Personnel reporting a) both White and Asian and b) no other categories in addition to White and Asian

US/Perm: U.S. citizens and legal permanent residents

Non-US: Non-U.S. citizens/Non-legal permanent residents

Table 7a: Diversity Statistics for ERC Faculty and Students

	U.S. Citizens or Permanent Residents							Foreign (Temporary Visa Holders)						Citizenship Not Reported					
	Leadership Team [4]	Faculty [5]	Postdocs	Doctoral Students	Masters Students	Undergrad Non-REU	REU Students	Leadership Team [4]	Faculty [5]	Postdocs	Doctoral Students	Masters Students	Undergrad Non-REU	Leadership Team [4]	Faculty [5]	Postdocs	Doctoral Students	Masters Students	Undergrad Non-REU
Center Total	**9**	**32**	**0**	**15**	**18**	**23**	**3**	**0**	**2**	**0**	**15**	**6**	**5**	**0**	**21**	**0**	**9**	**14**	**72**
Women																			
Category Total	2	5	0	7	3	4	0	0	0	0	2	2	1	0	0	0	1	2	9
Center Percent	22.2%	15.6%	0	46.7%	16.7%	17.4%	0.0%	0	0.0%	0	13.3%	33.3%	20.0%	0	0.0%	0	11.1%	14.3%	12.5%
National Percent [1][2]	N/A	15.2%	N/A	24.5%	22.1%	20.4%	N/A	N/A	N/A	N/A	23.3%	26.8%	19.2%	N/A	N/A	N/A	N/A	N/A	N/A
Underrepresented Racial Minorities																			
Category Total	1	2	0	3	0	0	0	0	0	0	0	0	1	0	0	0	0	0	3
Center Percent	11.1%	6.3%	0	20.0%	0.0%	0.0%	0.0%	0	0.0%	0	0.0%	0.0%	20.0%	0	0.0%	0	0.0%	0.0%	4.2%
National Percent [1][2]	N/A	2.5%	N/A	4.8%	6.2%	5.9%	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Hispanic or Latino																			
Category Total	0	1	0	0	1	2	0	0	0	0	1	1	1	0	0	0	0	0	3
Center Percent	0.0%	3.1%	0	0.0%	5.6%	8.7%	0.0%	0	0.0%	0	6.7%	16.7%	20.0%	0	0.0%	0	0.0%	0.0%	4.2%
National Percent [1][2]	N/A	3.7%	N/A	6.8%	9.5%	13.0%	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Persons With Disabilities																			
Category Total	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Center Percent	0.0%	0.0%	0	0.0%	0.0%	0.0%	0.0%	0	0.0%	0	0.0%	0.0%	0.0%	0	0.0%	0	0.0%	0.0%	0.0%
National Percent [1][2] [3]	N/A	7.4%	N/A	7.1%	7.1%	10.3%	N/A	N/A	7.4%	N/A	7.1%	7.1%	10.3%	N/A	N/A	N/A	N/A	N/A	N/A

[1]The national percentages for Underrepresented Racial Minorities and Hispanic or Latino are only available for U.S. citizens and permanent residents.

[2]Most recent national percentages available are from the following years: Women - 2014, Underrepresented Racial Minorities - 2014, Hispanic or Latino - 2014, and Persons with Disabilities - 2008.

[3]The national percentages for Persons with Disabilities are for all persons, regardless of citizenship. The national percentages for Doctoral students with disabilities and Masters students with disabilities are from the national percentages for Graduate students (Masters and Doctoral students combined).

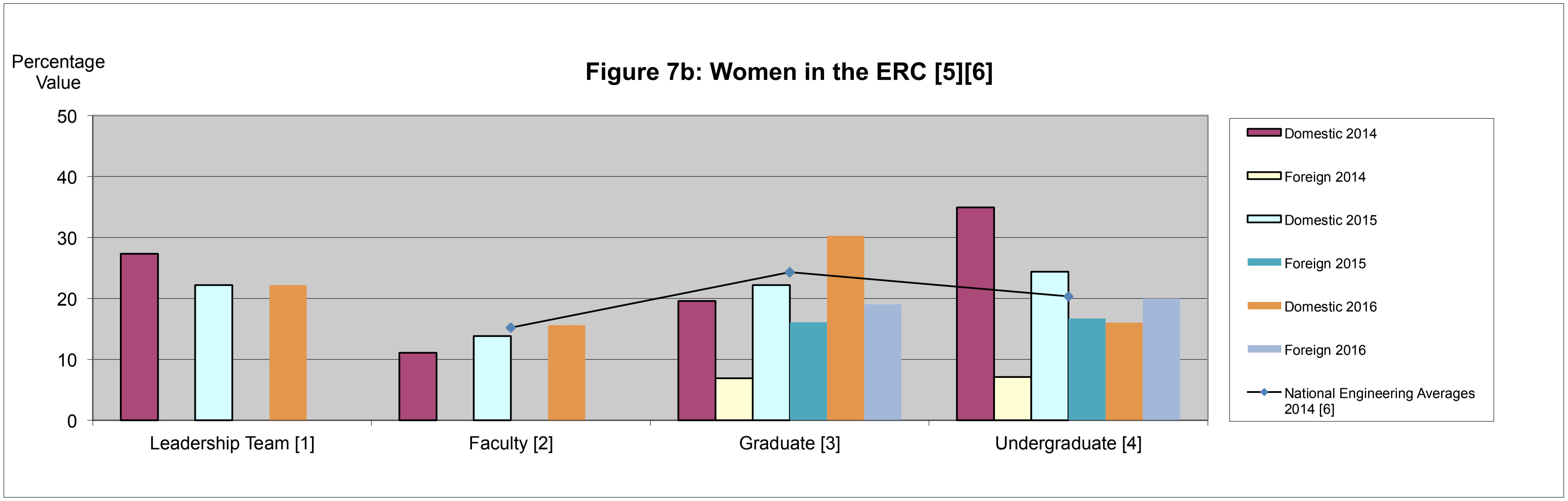
[4]Leadership Team includes Directors, Thrust Leaders, Education Program Leaders, Industrial Liason Officer, Administrative Director, and Research Thrust Management and Strategic Planning.

[5]Faculty includes Research - Senior Faculty, Research - Junior Faculty, Research - Visiting Faculty, Curriculum Development and Outreach - Senior Faculty, Curriculum Development and Outreach - Junior Faculty, and Curriculum Development and Outreach - Visiting Faculty.

Table 7a Summary: Count of ERC Personnel

Faculty	Community College RET	K-12 Teachers		Postdocs	Students				Young Scholars	Other [6]	Total
					Graduate		UG Non-REU	REU			
		RET	Non-RET		Doctoral	Masters					
55	0	0	15	0	39	38	100	22	0	24	274

[6]Other includes Industrial Liaison Officer, Administrative Director, Research Thrust Management and Strategic Planning, Staff, Research - Industry Researchers, Research - Other Visiting College Students, Research - Research Staff, Curriculum Development and Outreach - Industry Researchers, Curriculum Development and Outreach - Other Visiting College Students and Curriculum Development and Outreach - Staff.



Averages	Leadership Team	Faculty	Graduate	Undergraduate
National Engineering Averages 2014 [6]	N/A	15.2%	24.3%	20.3%
All ERC's 2015 (Domestic)	31.1%	24.6%	30.8%	38.3%
All ERC's 2015 (Foreign)	9.1%	18%	26.2%	37.9%
Domestic Percentage for Engineering Research Center for Compact and Efficient Fluid Power at the University of Minnesota – Twin Cities 2016	22.2%	15.6%	30.3%	16%
Foreign Percentage for Engineering Research Center for Compact and Efficient Fluid Power at the University of Minnesota – Twin Cities 2016	0%	0%	19%	20%

[1] The Leadership Team includes Directors, Thrust Leaders, Industrial Liaison Officer, Education Program Leaders, Administrative Directors, and Research Thrust Management and Strategic Planning.

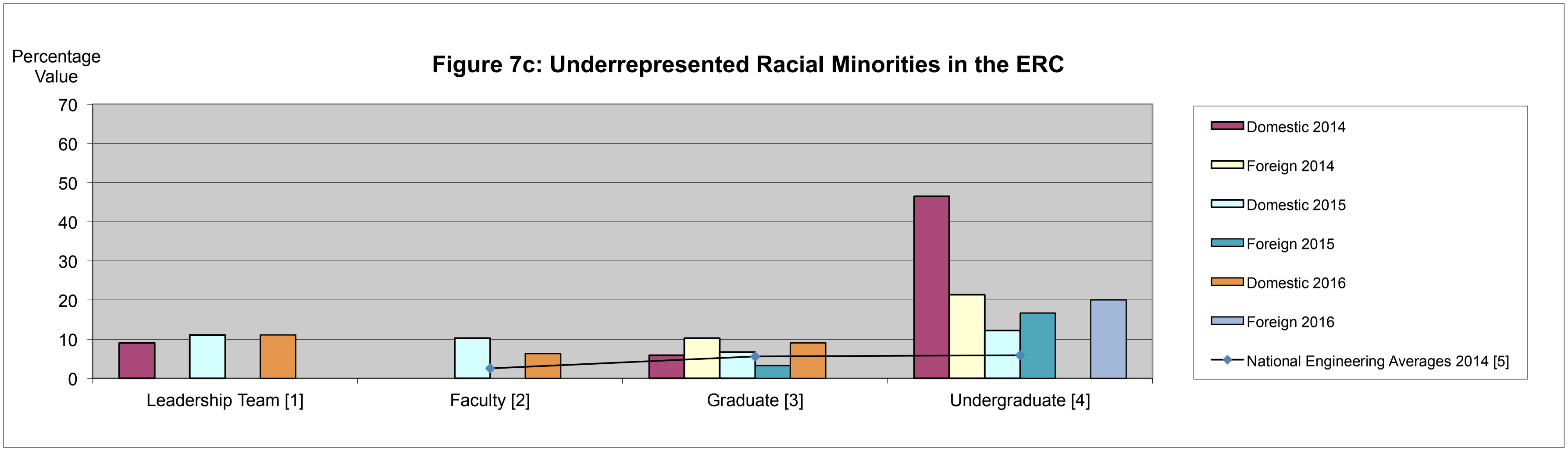
[2] Faculty includes Research - Senior Faculty, Research - Junior Faculty, Research - Visiting Faculty, Curriculum Development and Outreach - Senior Faculty, Curriculum Development and Outreach - Junior Faculty, and Curriculum Development and Outreach - Visiting Faculty.

[3] Graduate students include Doctoral and Master's students.

[4] Undergraduate students include non-REU and REU students.

[5] The number of personnel for whom gender was not reported are not excluded from the percentage calculations.

[6] National Engineering Averages for faculty are for U.S. citizens only.



Averages	Leadership Team	Faculty	Graduate	Undergraduate
National Engineering Averages 2014 [5]	N/A	2.5%	5.6%	5.9%
All ERC's 2015 (Domestic)	9.1%	8.1%	9.1%	16.5%
All ERC's 2015 (Foreign)	0%	1.8%	2.3%	12.1%
Domestic Percentage for Engineering Research Center for Compact and Efficient Fluid Power at the University of Minnesota – Twin Cities 2016	11.1%	6.3%	9.1%	0%
Foreign Percentage for Engineering Research Center for Compact and Efficient Fluid Power at the University of Minnesota – Twin Cities 2016	0%	0%	0%	20%

[1] The Leadership Team includes Directors, Thrust Leaders, Industrial Liaison Officer, Education Program Leaders, Administrative Directors, and Research Thrust Management and Strategic Planning.

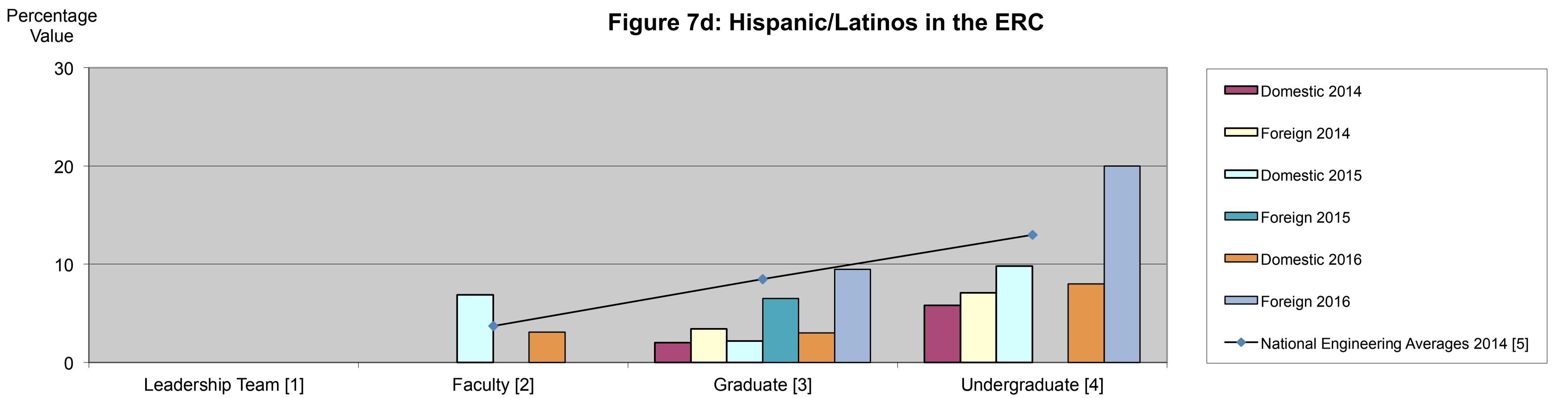
[2] Faculty includes Research - Senior Faculty, Research - Junior Faculty, Research - Visiting Faculty, Curriculum Development and Outreach - Senior Faculty, Curriculum Development and Outreach - Junior Faculty, and Curriculum Development and Outreach - Visiting Faculty.

[3] Graduate students include Doctoral and Master's students.

[4] Undergraduate students include non-REU and REU students.

[5] National Engineering Averages are for U.S. citizens only.

Figure 7d: Hispanic/Latinos in the ERC



Averages	Leadership Team	Faculty	Graduate	Undergraduate
National Engineering Averages 2014 [5]	N/A	3.7%	8.5%	13%
All ERC's 2015 (Domestic)	5.1%	5.5%	9.5%	19.1%
All ERC's 2015 (Foreign)	9.1%	2.7%	4.1%	12.1%
Domestic Percentage for Engineering Research Center for Compact and Efficient Fluid Power at the University of Minnesota – Twin Cities 2016	0%	3.1%	3%	8%
Foreign Percentage for Engineering Research Center for Compact and Efficient Fluid Power at the University of Minnesota – Twin Cities 2016	0%	0%	9.5%	20%

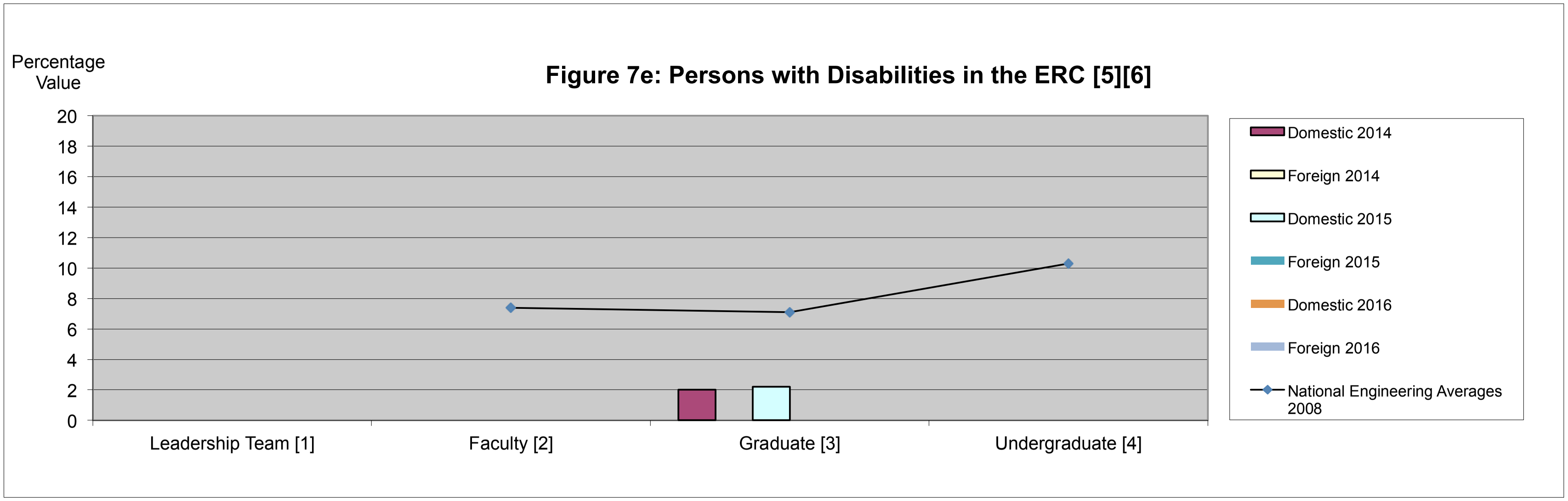
[1] The Leadership Team includes Directors, Thrust Leaders, Industrial Liaison Officer, Education Program Leaders, Administrative Directors, and Research Thrust Management and Strategic Planning.

[2] Faculty includes Research - Senior Faculty, Research - Junior Faculty, Research - Visiting Faculty, Curriculum Development and Outreach - Senior Faculty, Curriculum Development and Outreach - Junior Faculty, and Curriculum Development and Outreach - Visiting Faculty.

[3] Graduate students include Doctoral and Master's students.

[4] Undergraduate students include non-REU and REU students.

[5] National Engineering Averages are for U.S. citizens only.



Averages	Leadership Team	Faculty	Graduate	Undergraduate
National Engineering Averages 2008	N/A	7.4%	7.1%	10.3%
All ERC's 2015 (Domestic)	4.3%	1.8%	1.3%	2%
All ERC's 2015 (Domestic)	0%	0%	0.3%	1.7%
Domestic Percentage for Engineering Research Center for Compact and Efficient Fluid Power at the University of Minnesota – Twin Cities 2016	0%	0%	0%	0%
Foreign Percentage for Engineering Research Center for Compact and Efficient Fluid Power at the University of Minnesota – Twin Cities 2016	0%	0%	0%	0%

[1] The Leadership Team includes Directors, Thrust Leaders, Industrial Liaison Officer, Education Program Leaders, Administrative Directors, and Research Thrust Management and Strategic Planning.

[2] Faculty includes Research - Senior Faculty, Research - Junior Faculty, Research - Visiting Faculty, Curriculum Development and Outreach - Senior Faculty, Curriculum Development and Outreach - Junior Faculty, and Curriculum Development and Outreach - Visiting Faculty.

[3] Graduate students include Doctoral and Master's students.

[4] Undergraduate students include non-REU and REU students.

[5] The number of personnel for whom disability was not reported are not excluded from the percentage calculations.

Table 7f: Center Diversity, by Institution

Institution	Women [1]		Underrepresented Racial Minorities [1] [2]		Hispanics [1]	
	Number	Percent	Number	Percent	Number	Percent
Lead Institution						
University of Minnesota	9	26%	1	3%	2	6%
Core Partners						
Georgia Institute of Technology	3	17%	0	0%	0	0%
Purdue University	3	25%	1	8%	0	0%
University of Illinois at Urbana-Champaign	4	33%	1	8%	0	0%
Vanderbilt University	1	17%	1	17%	0	0%
Collaborating Institutions						
Cal Poly San Luis Obispo	1	50%	0	0%	0	0%
Cleveland State	0	0%	0	0%	0	0%
Illinois Institute of Technology	0	0%	0	0%	0	0%
Iowa State University	0	0%	0	0%	0	0%
Milwaukee School of Engineering	0	0%	0	0%	0	0%
Murray State	0	0%	0	0%	0	0%
North Carolina Agriculture and Technical State University	2	50%	2	50%	0	0%
Ohio University	0	0%	0	0%	0	0%
Quality Evaluation Designs	1	50%	0	0%	0	0%
Science Museum of Minnesota	0	0%	0	0%	1	25%
Triton College	0	0%	0	0%	0	0%
University of Akron	0	0%	0	0%	0	0%
University of Central Arkansas	0	0%	0	0%	0	0%
University of Cincinnati	0	0%	0	0%	0	0%
University of Florida	0	0%	0	0%	0	0%
University of Maryland, Baltimore	0	0%	0	0%	0	0%
University of Missouri	0	0%	0	0%	0	0%
University of Nebraska	0	0%	0	0%	0	0%
University of North Dakota	0	0%	0	0%	0	0%
University of Wisconsin- Madison	1	100%	0	0%	1	100%
University of Wisconsin- Parkside	0	0%	0	0%	0	0%
University of Wisconsin- Platteville	0	0%	0	0%	0	0%
Non-ERC Institutions Providing REU Students						
Binghamton University	0	0%	0	0%	0	0%
Montana State University- Bozeman	0	0%	0	0%	0	0%
St. John's University	0	0%	0	0%	0	0%
The College of Idaho	0	0%	0	0%	0	0%
University of California Merced	0	0%	0	0%	0	0%
University of Michigan- Ann Arbor	0	0%	0	0%	0	0%
University of Southern California	0	0%	0	0%	0	0%
Precollege Partners						
Capitol Hill Gifted and Talented Magnet	0	0%	0	0%	0	0%
Gainesville Middle School	0	0%	0	0%	0	0%
Georgia Cyber Academy	0	0%	0	0%	0	0%
Lafayette Jefferson High School	0	0%	0	0%	0	0%
North Branch Area Public Schools	0	0%	0	0%	0	0%
Northfield Middle School	0	0%	0	0%	0	0%
Purdue University 4-H	0	0%	0	0%	0	0%
Royalton Middle School	0	0%	0	0%	0	0%
Sequoyah Middle School	0	0%	0	0%	0	0%

[1] - This data includes U.S. Citizens and Legal Permanent Residents only.

[2] - Underrepresented Racial Minorities is a sum of all personnel entered in the following categories: American Indian or Alaska Native, Black or African American, Native Hawaiian or Other Pacific Islander, or More than one race reported, minority.

Table 8: Current Award Year Functional Budget

Function	Direct Support		Direct Support Total	Associated Projects	Total Budget
	Unrestricted Cash(Core Projects)	Restricted Cash(Sponsored Projects)			
1: Efficiency	$401,338	$0	$401,338	$1,663,977	$2,065,315
2: Compactness	$418,060	$0	$418,060	$0	$418,060
3: Effectiveness	$269,734	$0	$269,734	$408,782	$678,516
5. Manufacturing	$0	$0	$0	$135,944	$135,944
Test Beds	$356,188	$0	$356,188	$359,631	$715,819
Research Total	**$1,445,320**	**$0**	**$1,445,320**	**$2,568,334**	**$4,013,654**
Educational Program Total	$403,491	$112,540	$516,031	$0	$516,031
General Shared Equipment	$0	$0	$0	$0	$0
New Facilities/New Construction	$0	$0	$0	$0	$0
Leadership/Administration/Management	$714,414	$0	$714,414	$0	$714,414
Industrial Collaboration/Innovation Program	$280,255	$0	$280,255	$0	$280,255
Center Related Travel	$109,800	$0	$109,800	$0	$109,800
Indirect Cost	$1,117,763	$11,542	$1,129,305	N/A	$1,129,305
Functional and Educational Budget Total	**$3,747,992**	**$124,082**	**$3,872,074**	**$0**	**$3,872,074**
Support Reserved for Future Years	N/A	N/A	$0	N/A	$0
Residual Funds Remaining	$1,122,269	$0	$1,122,269	N/A	$1,122,269
Total	**$5,193,312**	**$124,082**	**$5,317,394**	**$2,568,334**	**$7,885,728**

Figure 8a: Functional Budget as a percentage of Direct Support

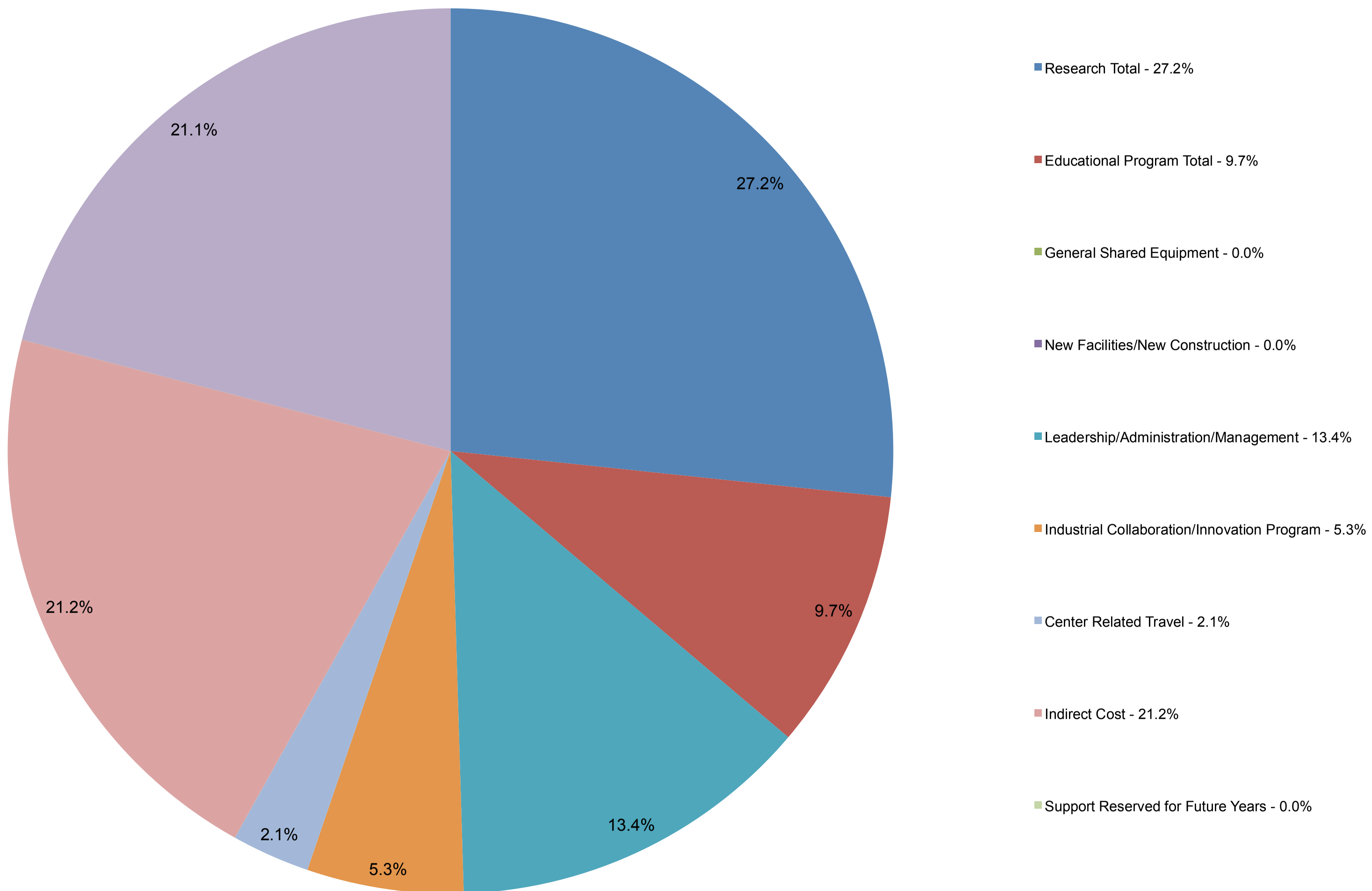


Figure 8b: Functional Budget as a percentage of Associated Project Support

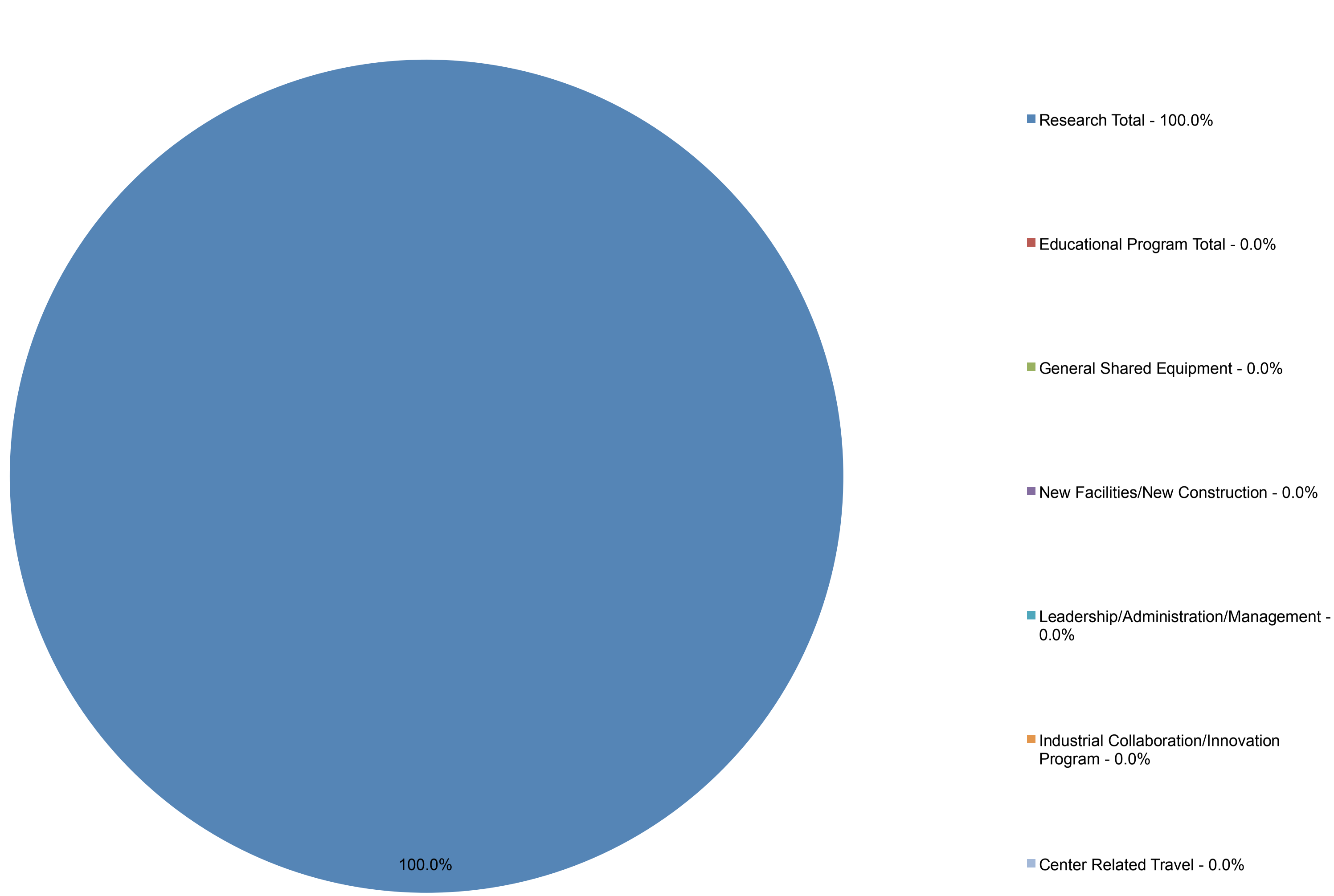


Table 8c: Current Award Year Education Functional Budget

Education Programs	Direct Support		Direct Support Total	Associated Projects	Total Budget
	Unrestricted Cash OR Core Projects	Restricted Cash OR Sponsored Projects			
Precollege Education Activities	$29,600	$0	**$29,600**	$0	**$29,600**
University Education	$83,021	$0	**$83,021**	$0	**$83,021**
Student Leadership Council	$15,200	$0	**$15,200**	$0	**$15,200**
Young Scholars	$0	$0	**$0**	$0	**$0**
REU	$61,434	$112,540	**$173,974**	$0	**$173,974**
RET	$0	$0	**$0**	$0	**$0**
Assessment	$50,000	$0	**$50,000**	$0	**$50,000**
Community College activities	$0	$0	**$0**	$0	**$0**
Other	$164,236	$0	**$164,236**	$0	**$164,236**
Education Program Total	**$403,491**	**$112,540**	**$516,031**	**$0**	**$516,031**

Table 9: Sources of Support

Sources of Support	Early Cumulative Total	Jun 1, 2011 - May 31, 2012	Jun 1, 2012 - May 31, 2013	Jun 1, 2013 - May 31, 2014	Jun 1, 2014 - May 31, 2015	Jun 1, 2015 - May 31, 2016			Cumulative Total [1]
						Received	Promised	Total	
Unrestricted Cash									
Government									
NSF Funding									
NSF ERC Base Award	$16,456,020	$4,000,000	$4,000,000	$4,000,000	$2,681,000	$1,795,600	$0	$1,795,600	$32,932,620
Other NSF (Not ERC Program)	$0	$0	$0	$390,000	$0	$0	$0	$0	$390,000
TOTAL NSF FUNDING	**$16,456,020**	**$4,000,000**	**$4,000,000**	**$4,390,000**	**$2,681,000**	**$1,795,600**	**$0**	**$1,795,600**	**$33,322,620**
Other U.S. Government (Not NSF)	$0	$0	$3,500	$0	$0	$0	$0	$0	$3,500
State Government	$0	$0	$0	$0	$0	$0	$0	$0	$0
Local Government	$0	$0	$0	$0	$0	$0	$0	$0	$0
Foreign Government	$0	$0	$0	$0	$0	$0	$0	$0	$0
Quasi-government research organization	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL GOVERNMENT FUNDING	**$16,456,020**	**$4,000,000**	**$4,003,500**	**$4,390,000**	**$2,681,000**	**$1,795,600**	**$0**	**$1,795,600**	**$33,326,120**
Industry									
U.S. Industry	$2,371,958	$583,817	$443,100	$568,767	$0	$0	$0	$0	$3,967,642
Foreign Industry	$488,000	$112,000	$102,000	$122,750	$0	$0	$0	$0	$824,750
Industrial Association	$51,000	$41,000	$41,000	$105,549	$114,228	$11,092	$81,000	$92,092	$444,869
TOTAL INDUSTRY FUNDING	**$2,910,958**	**$736,817**	**$586,100**	**$797,066**	**$114,228**	**$11,092**	**$81,000**	**$92,092**	**$5,237,261**
University									
U.S. University	$3,509,294	$800,000	$840,543	$800,000	$258,688	$0	$359,120	$359,120	$6,567,645
Foreign University	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL UNIVERSITY FUNDING	**$3,509,294**	**$800,000**	**$840,543**	**$800,000**	**$258,688**	**$0**	**$359,120**	**$359,120**	**$6,567,645**
Other									
Private Foundation	$1,000	$0	$0	$0	$655,000	$491,250	$163,750	$655,000	$1,311,000
Medical Facility	$0	$0	$0	$0	$0	$0	$0	$0	$0
Non Profit	$0	$0	$0	$0	$0	$0	$0	$0	$0
Venture Capitalist	$0	$0	$0	$0	$0	$0	$0	$0	$0
Other	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL OTHER FUNDING	**$1,000**	**$0**	**$0**	**$0**	**$655,000**	**$491,250**	**$163,750**	**$655,000**	**$1,311,000**
Total Unrestricted Cash	**$22,877,272**	**$5,536,817**	**$5,430,143**	**$5,987,066**	**$3,708,916**	**$2,297,942**	**$603,870**	**$2,901,812**	**$46,442,026**
Restricted Cash									
NSF Funding									
NSF ERC Program Special Purpose Awards and Supplements	$451,472	$39,989	$52,000	$5,120	$0	$244,989	$0	$244,989	$793,570
Other NSF (Not ERC Program)	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL NSF FUNDING	**$451,472**	**$39,989**	**$52,000**	**$5,120**	**$0**	**$244,989**	**$0**	**$244,989**	**$793,570**
Restricted Cash - Non Translational									
Government									
Other U.S. Government (Not NSF)	$0	$0	$0	$0	$0	$0	$0	$0	$0
State Government	$0	$0	$0	$0	$0	$0	$0	$0	$0
Local Government	$0	$0	$0	$0	$0	$0	$0	$0	$0
Foreign Government	$0	$0	$0	$0	$0	$0	$0	$0	$0
Quasi-government research organization	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL GOVERNMENT FUNDING	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
Industry									
U.S. Industry	$0	$0	$0	$500	$5,500	$1,000	$2,000	$3,000	$9,000
Foreign Industry	$0	$0	$0	$0	$0	$0	$0	$0	$0
Industrial Association	$0	$0	$0	$0	$500	$0	$0	$0	$500
TOTAL INDUSTRY FUNDING	**$0**	**$0**	**$0**	**$500**	**$6,000**	**$1,000**	**$2,000**	**$3,000**	**$9,500**
University									
U.S. University	$0	$0	$0	$500	$1,500	$1,500	$0	$1,500	$3,500
Foreign University	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL UNIVERSITY FUNDING	**$0**	**$0**	**$0**	**$500**	**$1,500**	**$1,500**	**$0**	**$1,500**	**$3,500**
Other									
Private Foundation	$0	$0	$0	$0	$10,000	$0	$0	$0	$10,000
Medical Facility	$0	$0	$0	$0	$0	$0	$0	$0	$0
Non Profit	$0	$0	$0	$0	$0	$0	$0	$0	$0
Venture Capitalist	$0	$0	$0	$0	$0	$0	$0	$0	$0
Other	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL OTHER FUNDING	**$0**	**$0**	**$0**	**$0**	**$10,000**	**$0**	**$0**	**$0**	**$10,000**
Total Restricted Cash - Non Translational	**$0**	**$0**	**$0**	**$1,000**	**$17,500**	**$2,500**	**$2,000**	**$4,500**	**$23,000**
Restricted Cash - Translational									
Government									
Other U.S. Government (Not NSF)	$0	$0	$0	$0	$0	$0	$0	$0	$0
State Government	$0	$0	$0	$0	$0	$0	$0	$0	$0
Local Government	$0	$0	$0	$0	$0	$0	$0	$0	$0
Foreign Government	$0	$0	$0	$0	$0	$0	$0	$0	$0
Quasi-government research organization	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL GOVERNMENT FUNDING	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
Industry									
U.S. Industry	$0	$0	$0	$0	$0	$0	$0	$0	$0
Foreign Industry	$0	$0	$0	$0	$0	$16,700	$0	$16,700	$16,700
Industrial Association	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL INDUSTRY FUNDING	**$0**	**$0**	**$0**	**$0**	**$0**	**$16,700**	**$0**	**$16,700**	**$16,700**
University									
U.S. University	$0	$0	$0	$0	$0	$0	$0	$0	$0
Foreign University	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL UNIVERSITY FUNDING	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**

Table 9: Sources of Support									
Sources of Support	Early Cumulative Total	Jun 1, 2011 - May 31, 2012	Jun 1, 2012 - May 31, 2013	Jun 1, 2013 - May 31, 2014	Jun 1, 2014 - May 31, 2015	Jun 1, 2015 - May 31, 2016			Cumulative Total [1]
						Received	Promised	Total	
Other									
Private Foundation	$0	$0	$0	$0	$0	$0	$0	$0	$0
Medical Facility	$0	$0	$0	$0	$0	$0	$0	$0	$0
Non Profit	$0	$0	$0	$0	$0	$0	$0	$0	$0
Venture Capitalist	$0	$0	$0	$0	$0	$0	$0	$0	$0
Other	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL OTHER FUNDING	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
Total Restricted Cash - Translational	**$0**	**$0**	**$0**	**$0**	**$0**	**$16,700**	**$0**	**$16,700**	**$16,700**
Total Restricted Cash	**$451,472**	**$39,989**	**$52,000**	**$6,120**	**$17,500**	**$264,189**	**$2,000**	**$266,189**	**$833,270**
Multi-year support carried over from prior years									
Government									
Other U.S. Government (Not NSF)	$0	$0	$0	$0	$0	$0	N/A	$0	N/A
State Government	$0	$0	$0	$0	$0	$0	N/A	$0	N/A
Local Government	$0	$0	$0	$0	$0	$0	N/A	$0	N/A
Foreign Government	$0	$0	$0	$0	$0	$0	N/A	$0	N/A
Quasi-government research organization	$0	$0	$0	$0	$0	$0	N/A	$0	N/A
TOTAL GOVT Multi-year Support from Prior Years	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**N/A**	**$0**	**N/A**
Industry									
U.S. Industry	$0	$0	$0	$0	$0	$0	N/A	$0	N/A
Foreign Industry	$0	$0	$0	$0	$0	$0	N/A	$0	N/A
Industrial Association	$0	$0	$0	$0	$0	$0	N/A	$0	N/A
TOTAL INDUSTRY Multi-year Support from Prior Years	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**N/A**	**$0**	**N/A**
Other									
Private Foundation	$0	$0	$0	$0	$0	$0	N/A	$0	N/A
Medical Facility	$0	$0	$0	$0	$0	$0	N/A	$0	N/A
Non Profit	$0	$0	$0	$0	$0	$0	N/A	$0	N/A
Venture Capitalist	$0	$0	$0	$0	$0	$0	N/A	$0	N/A
Other	$0	$0	$0	$0	$0	$0	N/A	$0	N/A
TOTAL OTHER Multi-year Support from Prior Years	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**N/A**	**$0**	**N/A**
Total Multi-year support carried over from prior years	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**N/A**	**$0**	**N/A**
Residual Funds carried over from prior years [2]									
Government									
NSF Funding									
NSF ERC Base Award	$2,632,887	$589,405	$1,975,463	$2,179,981	$2,065,994	$1,044,455	N/A	$1,044,455	N/A
Other NSF (Not ERC Program)	$49,656	$0	$0	$0	$0	$0	N/A	$0	N/A
TOTAL NSF Residual Funds from Prior Years	**$2,682,543**	**$589,405**	**$1,975,463**	**$2,179,981**	**$2,065,994**	**$1,044,455**	**N/A**	**$1,044,455**	**N/A**
Other U.S. Government (Not NSF)	$0	$0	$0	$0	$0	$0	N/A	$0	N/A
State Government	$0	$0	$0	$0	$0	$0	N/A	$0	N/A
Local Government	$0	$0	$0	$0	$0	$0	N/A	$0	N/A
Foreign Government	$0	$0	$0	$0	$0	$0	N/A	$0	N/A
Quasi-government research organization	$0	$0	$0	$0	$0	$0	N/A	$0	N/A
TOTAL GOVT Residual Funds from Prior Years	**$2,682,543**	**$589,405**	**$1,975,463**	**$2,179,981**	**$2,065,994**	**$1,044,455**	**N/A**	**$1,044,455**	**N/A**
Industry									
U.S. Industry	$2,266,798	$464,648	$455,211	$621,271	$868,843	$1,104,938	N/A	$1,104,938	N/A
Foreign Industry	$0	$0	$0	$0	$0	$0	N/A	$0	N/A
Industrial Association	$0	$0	$0	$0	$0	$0	N/A	$0	N/A
TOTAL INDUSTRY Residual Funds from Prior Years	**$2,266,798**	**$464,648**	**$455,211**	**$621,271**	**$868,843**	**$1,104,938**	**N/A**	**$1,104,938**	**N/A**
University									
U.S. University	$1,172,790	$184,201	$0	$0	$0	$0	N/A	$0	N/A
Foreign University	$0	$0	$0	$0	$0	$0	N/A	$0	N/A
TOTAL UNIVERSITY Residual Funds from Prior Years	**$1,172,790**	**$184,201**	**$0**	**$0**	**$0**	**$0**	**N/A**	**$0**	**N/A**
Other									
Private Foundation	$0	$0	$0	$0	$0	$0	N/A	$0	N/A
Medical Facility	$0	$0	$0	$0	$0	$0	N/A	$0	N/A
Non Profit	$0	$0	$0	$0	$0	$0	N/A	$0	N/A
Venture Capitalist	$0	$0	$0	$0	$0	$0	N/A	$0	N/A
Other	$0	$0	$0	$0	$0	$0	N/A	$0	N/A
TOTAL OTHER Residual Funds from Prior Years	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**N/A**	**$0**	**N/A**
Total Residual Funds carried over from prior years [2]	**$6,122,131**	**$1,238,254**	**$2,430,674**	**$2,801,252**	**$2,934,837**	**$2,149,393**	**N/A**	**$2,149,393**	**N/A**
Associated Projects [3]									
NSF Funding									
NSF ERC Program	$640,109	$0	$0	$0	$0	$0	$0	$0	$640,109
Other NSF (Not ERC Program)	$981,292	$591,183	$508,500	$635,485	$552,842	$602,686	$287,641	$890,327	$4,159,629
TOTAL NSF FUNDING	**$1,621,401**	**$591,183**	**$508,500**	**$635,485**	**$552,842**	**$602,686**	**$287,641**	**$890,327**	**$4,799,738**
Associated Projects - Non Translational [3]									
Government									
Other U.S. Government (Not NSF)	$2,246,436	$13,320	$69,707	$10,629	$15,429	$0	$0	$0	$2,355,521
State Government	$0	$0	$0	$0	$0	$0	$0	$0	$0
Local Government	$0	$0	$0	$0	$0	$0	$0	$0	$0
Foreign Government	$0	$0	$0	$0	$0	$0	$0	$0	$0

Table 9: Sources of Support									
Sources of Support	Early Cumulative Total	Jun 1, 2011 - May 31, 2012	Jun 1, 2012 - May 31, 2013	Jun 1, 2013 - May 31, 2014	Jun 1, 2014 - May 31, 2015	Jun 1, 2015 - May 31, 2016			Cumulative Total [1]
						Received	Promised	Total	
Quasi-government research organization	$57,276	$0	$0	$0	$0	$0	$0	$0	$57,276
TOTAL GOVERNMENT FUNDING	**$2,303,712**	**$13,320**	**$69,707**	**$10,629**	**$15,429**	**$0**	**$0**	**$0**	**$2,412,797**
Industry									
U.S. Industry	$3,190,670	$0	$1,974	$93,366	$7,962	$81,875	$40,937	$122,812	$3,416,784
Foreign Industry	$52,865	$78,000	$70,417	$167,562	$190,414	$65,230	$12,842	$78,072	$637,330
Industrial Association	$71,067	$0	$0	$0	$0	$0	$0	$0	$71,067
TOTAL INDUSTRY FUNDING	**$3,314,602**	**$78,000**	**$72,391**	**$260,928**	**$198,376**	**$147,105**	**$53,779**	**$200,884**	**$4,125,181**
University									
U.S. University	$0	$128,550	$5,826	$500	$28,250	$43,642	$21,821	$65,463	$228,589
Foreign University	$32,000	$13,714	$3,077	$0	$0	$0	$0	$0	$48,791
TOTAL UNIVERSITY FUNDING	**$32,000**	**$142,264**	**$8,903**	**$500**	**$28,250**	**$43,642**	**$21,821**	**$65,463**	**$277,380**
Other									
Private Foundation	$0	$0	$0	$0	$0	$0	$0	$0	$0
Medical Facility	$0	$0	$0	$0	$0	$0	$0	$0	$0
Non Profit	$0	$0	$0	$0	$0	$0	$0	$0	$0
Venture Capitalist	$0	$0	$0	$0	$0	$0	$0	$0	$0
Other	$694,008	$1,099,920	$1,549,850	$0	$0	$111,664	$55,832	$167,496	$3,511,274
TOTAL OTHER FUNDING	**$694,008**	**$1,099,920**	**$1,549,850**	**$0**	**$0**	**$111,664**	**$55,832**	**$167,496**	**$3,511,274**
Total Associated Projects - Non Translational	**$6,344,322**	**$1,333,504**	**$1,700,851**	**$272,057**	**$242,055**	**$302,411**	**$131,432**	**$433,843**	**$10,326,632**
Associated Projects - Translational [3]									
Government									
Other U.S. Government (Not NSF)	$0	$187,208	$60,667	$0	$3,600	$2,625	$0	$2,625	$254,100
State Government	$0	$0	$0	$0	$0	$0	$0	$0	$0
Local Government	$0	$0	$0	$0	$0	$0	$0	$0	$0
Foreign Government	$0	$0	$0	$0	$0	$0	$0	$0	$0
Quasi-government research organization	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL GOVERNMENT FUNDING	**$0**	**$187,208**	**$60,667**	**$0**	**$3,600**	**$2,625**	**$0**	**$2,625**	**$254,100**
Industry									
U.S. Industry	$0	$115,701	$76,362	$183,430	$245,414	$112,812	$33,533	$146,345	$767,252
Foreign Industry	$5,000	$83,974	$37,583	$0	$0	$47,381	$13,429	$60,810	$187,367
Industrial Association	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL INDUSTRY FUNDING	**$5,000**	**$199,675**	**$113,945**	**$183,430**	**$245,414**	**$160,193**	**$46,962**	**$207,155**	**$954,619**
University									
U.S. University	$0	$0	$0	$0	$0	$0	$0	$0	$0
Foreign University	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL UNIVERSITY FUNDING	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
Other									
Private Foundation	$0	$0	$0	$0	$0	$0	$0	$0	$0
Medical Facility	$0	$0	$0	$0	$0	$0	$0	$0	$0
Non Profit	$0	$0	$0	$0	$0	$0	$0	$0	$0
Venture Capitalist	$0	$0	$0	$0	$0	$0	$0	$0	$0
Other	$0	$0	$44,750	$925,882	$1,381,928	$798,280	$236,104	$1,034,384	$3,386,944
TOTAL OTHER FUNDING	**$0**	**$0**	**$44,750**	**$925,882**	**$1,381,928**	**$798,280**	**$236,104**	**$1,034,384**	**$3,386,944**
Total Associated Projects - Translational	**$5,000**	**$386,883**	**$219,362**	**$1,109,312**	**$1,630,942**	**$961,098**	**$283,066**	**$1,244,164**	**$4,595,663**
Total Associated Projects	**$7,970,723**	**$2,311,570**	**$2,428,713**	**$2,016,854**	**$2,425,839**	**$1,866,195**	**$702,139**	**$2,568,334**	**$19,722,033**
Value of New Construction									
Government									
NSF Funding									
NSF ERC Base Award	$0	$0	$0	$0	$0	$0	$0	$0	$0
Other NSF (Not ERC Program)	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL NSF FUNDING	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
Other U.S. Government (Not NSF)	$0	$0	$0	$0	$0	$0	$0	$0	$0
State Government	$0	$0	$0	$0	$0	$0	$0	$0	$0
Local Government	$0	$0	$0	$0	$0	$0	$0	$0	$0
Foreign Government	$0	$0	$0	$0	$0	$0	$0	$0	$0
Quasi-government research organization	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL GOVERNMENT FUNDING	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
Industry									
U.S. Industry	$0	$0	$0	$0	$0	$0	$0	$0	$0
Foreign Industry	$0	$0	$0	$0	$0	$0	$0	$0	$0
Industrial Association	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL INDUSTRY FUNDING	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
University									
U.S. University	$0	$0	$0	$0	$0	$0	$0	$0	$0
Foreign University	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL UNIVERSITY FUNDING	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
Other									
Private Foundation	$0	$0	$0	$0	$0	$0	$0	$0	$0
Medical Facility	$0	$0	$0	$0	$0	$0	$0	$0	$0
Non Profit	$0	$0	$0	$0	$0	$0	$0	$0	$0
Venture Capitalist	$0	$0	$0	$0	$0	$0	$0	$0	$0
Other	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL OTHER FUNDING	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
Total Value of New Construction	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
Value of Equipment									
Government									

Table 9: Sources of Support									
Sources of Support	Early Cumulative Total	Jun 1, 2011 - May 31, 2012	Jun 1, 2012 - May 31, 2013	Jun 1, 2013 - May 31, 2014	Jun 1, 2014 - May 31, 2015	Jun 1, 2015 - May 31, 2016			Cumulative Total [1]
						Received	Promised	Total	
NSF Funding									
NSF ERC Base Award	$0	$0	$0	$0	$0	$0	$0	$0	$0
Other NSF (Not ERC Program)	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL NSF FUNDING	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
Other U.S. Government (Not NSF)	$0	$0	$0	$0	$0	$0	$0	$0	$0
State Government	$0	$0	$0	$0	$0	$0	$0	$0	$0
Local Government	$0	$0	$0	$0	$0	$0	$0	$0	$0
Foreign Government	$0	$0	$0	$0	$0	$0	$0	$0	$0
Quasi-government research organization	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL GOVERNMENT FUNDING	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
Industry									
U.S. Industry	$584,402	$39,253	$11,957	$275,816	$28,388	$65,000	$0	$65,000	$1,004,816
Foreign Industry	$0	$500	$2,300	$13,600	$6,000	$0	$0	$0	$22,400
Industrial Association	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL INDUSTRY FUNDING	**$584,402**	**$39,753**	**$14,257**	**$289,416**	**$34,388**	**$65,000**	**$0**	**$65,000**	**$1,027,216**
University									
U.S. University	$0	$0	$0	$15,550	$500	$0	$0	$0	$16,050
Foreign University	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL UNIVERSITY FUNDING	**$0**	**$0**	**$0**	**$15,550**	**$500**	**$0**	**$0**	**$0**	**$16,050**
Other									
Private Foundation	$0	$0	$0	$0	$0	$0	$0	$0	$0
Medical Facility	$0	$0	$0	$0	$0	$0	$0	$0	$0
Non Profit	$0	$0	$0	$0	$0	$0	$0	$0	$0
Venture Capitalist	$0	$0	$0	$0	$0	$0	$0	$0	$0
Other	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL OTHER FUNDING	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
Total Value of Equipment	**$584,402**	**$39,753**	**$14,257**	**$304,966**	**$34,888**	**$65,000**	**$0**	**$65,000**	**$1,043,266**
Value of New Facilities in Existing Buildings									
Government									
NSF Funding									
NSF ERC Base Award	$0	$0	$0	$0	$0	$0	$0	$0	$0
Other NSF (Not ERC Program)	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL NSF FUNDING	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
Other U.S. Government (Not NSF)	$0	$0	$0	$0	$0	$0	$0	$0	$0
State Government	$0	$0	$0	$0	$0	$0	$0	$0	$0
Local Government	$0	$0	$0	$0	$0	$0	$0	$0	$0
Foreign Government	$0	$0	$0	$0	$0	$0	$0	$0	$0
Quasi-government research organization	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL GOVERNMENT FUNDING	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
Industry									
U.S. Industry	$0	$0	$0	$0	$0	$0	$0	$0	$0
Foreign Industry	$0	$0	$0	$0	$0	$0	$0	$0	$0
Industrial Association	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL INDUSTRY FUNDING	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
University									
U.S. University	$625,591	$0	$0	$0	$0	$0	$0	$0	$625,591
Foreign University	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL UNIVERSITY FUNDING	**$625,591**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$625,591**
Other									
Private Foundation	$0	$0	$0	$0	$0	$0	$0	$0	$0
Medical Facility	$0	$0	$0	$0	$0	$0	$0	$0	$0
Non Profit	$0	$0	$0	$0	$0	$0	$0	$0	$0
Venture Capitalist	$0	$0	$0	$0	$0	$0	$0	$0	$0
Other	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL OTHER FUNDING	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
Total Value of New Facilities in Existing Buildings	**$625,591**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$625,591**
Value of Visting Personnel									
Government									
NSF Funding									
NSF ERC Base Award	$0	$0	$0	$0	$0	$0	$0	$0	$0
Other NSF (Not ERC Program)	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL NSF FUNDING	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
Other U.S. Government (Not NSF)	$0	$0	$0	$0	$0	$0	$0	$0	$0
State Government	$0	$0	$0	$0	$0	$0	$0	$0	$0
Local Government	$0	$0	$0	$0	$0	$0	$0	$0	$0
Foreign Government	$0	$0	$0	$0	$0	$0	$0	$0	$0
Quasi-government research organization	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL GOVERNMENT FUNDING	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
Industry									
U.S. Industry	$22,500	$0	$0	$1	$0	$0	$0	$0	$22,501
Foreign Industry	$0	$0	$0	$0	$0	$0	$0	$0	$0
Industrial Association	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL INDUSTRY FUNDING	**$22,500**	**$0**	**$0**	**$1**	**$0**	**$0**	**$0**	**$0**	**$22,501**
University									
U.S. University	$16,200	$8,000	$0	$0	$0	$0	$0	$0	$24,200
Foreign University	$59,500	$0	$0	$0	$0	$0	$0	$0	$59,500
TOTAL UNIVERSITY FUNDING	**$75,700**	**$8,000**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$83,700**
Other									

Table 9: Sources of Support									
Sources of Support	Early Cumulative Total	Jun 1, 2011 - May 31, 2012	Jun 1, 2012 - May 31, 2013	Jun 1, 2013 - May 31, 2014	Jun 1, 2014 - May 31, 2015	Jun 1, 2015 - May 31, 2016			Cumulative Total [1]
						Received	Promised	Total	
Private Foundation	$0	$0	$0	$0	$0	$0	$0	$0	$0
Medical Facility	$0	$0	$0	$0	$0	$0	$0	$0	$0
Non Profit	$0	$0	$0	$0	$0	$0	$0	$0	$0
Venture Capitalist	$0	$0	$0	$0	$0	$0	$0	$0	$0
Other	$0	$0	$0	$0	$270,000	$255,000	$0	$255,000	$525,000
TOTAL OTHER FUNDING	**$0**	**$0**	**$0**	**$0**	**$270,000**	**$255,000**	**$0**	**$255,000**	**$525,000**
Total Value of Visting Personnel	**$98,200**	**$8,000**	**$0**	**$1**	**$270,000**	**$255,000**	**$0**	**$255,000**	**$631,201**
Value of Other Assets									
Government									
NSF Funding									
NSF ERC Base Award	$0	$0	$0	$0	$0	$0	$0	$0	$0
Other NSF (Not ERC Program)	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL NSF FUNDING	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
Other U.S. Government (Not NSF)	$0	$0	$0	$0	$0	$75,000	$0	$75,000	$75,000
State Government	$0	$0	$0	$0	$0	$0	$0	$0	$0
Local Government	$0	$0	$0	$0	$0	$0	$0	$0	$0
Foreign Government	$0	$0	$0	$0	$0	$0	$0	$0	$0
Quasi-government research organization	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL GOVERNMENT FUNDING	**$0**	**$0**	**$0**	**$0**	**$0**	**$75,000**	**$0**	**$75,000**	**$75,000**
Industry									
U.S. Industry	$219,621	$106,408	$0	$0	$0	$8,000	$0	$8,000	$334,029
Foreign Industry	$9,000	$62,308	$0	$0	$0	$700	$0	$700	$72,008
Industrial Association	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL INDUSTRY FUNDING	**$228,621**	**$168,716**	**$0**	**$0**	**$0**	**$8,700**	**$0**	**$8,700**	**$406,037**
University									
U.S. University	$0	$0	$0	$0	$0	$0	$0	$0	$0
Foreign University	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL UNIVERSITY FUNDING	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
Other									
Private Foundation	$0	$0	$0	$0	$0	$0	$0	$0	$0
Medical Facility	$0	$0	$0	$0	$0	$0	$0	$0	$0
Non Profit	$0	$0	$0	$0	$0	$0	$0	$0	$0
Venture Capitalist	$0	$0	$0	$0	$0	$0	$0	$0	$0
Other	$169,032	$0	$0	$0	$0	$0	$0	$0	$169,032
TOTAL OTHER FUNDING	**$169,032**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$169,032**
Total Value of Other Assets	**$397,653**	**$168,716**	**$0**	**$0**	**$0**	**$83,700**	**$0**	**$83,700**	**$650,069**
Total In-Kind Support, All Sources	**$1,705,846**	**$216,469**	**$14,257**	**$304,967**	**$304,888**	**$403,700**	**$0**	**$403,700**	**$2,950,127**
Total Cash Support, All Sources [2]	**$29,450,875**	**$6,815,060**	**$7,912,817**	**$8,794,438**	**$6,661,253**	**$4,711,524**	**$605,870**	**$5,317,394**	**$47,275,296**
Percent Non-ERC Program Cash	**34%**	**32%**	**24%**	**30%**	**29%**	**35%**	**100%**	**42%**	**29%**
Total Cash + In-Kind	**$31,156,721**	**$7,031,529**	**$7,927,074**	**$9,099,405**	**$6,966,141**	**$5,115,224**	**$605,870**	**$5,721,094**	**$50,225,423**
Grand Total (Cash + In-Kind + Associated Projects)	**$39,127,444**	**$9,343,099**	**$10,355,787**	**$11,116,259**	**$9,391,980**	**$6,981,419**	**$1,308,009**	**$8,289,428**	**$69,947,456**

[1] - No Residual amounts or multi-year support carried over from prior years are included in the Cumulative Total column because the funds are by definition included in the year in which they were received.

[2] - Cash Total = The sum of Unrestricted Cash, Restricted Cash, and Residual Funds for a particular NSF Award Year, but NOT Support for Associated Projects. This cash amount in Table 9 is also the total for the 'Expenditure' column pertaining to the same Award Year in Table 10: Annual Expenditures and Budgets.

[3] - Associated project support is the sum of the received and promised amounts from the prior year. Actual amounts are not collected for associated project support.

Table 10: Annual Expenditures and Budgets

Total Direct Center Cash Support	Early Cumulative Total [1]	Jun-01-2011 - May-31-2012	Jun-01-2012 - May-31-2013	Jun-01-2013 - May-31-2014	Jun-01-2014 - May-31-2015	Jun-01-2015 - May-31-2016	Proposed Budget Next Award Year
Direct Cash Support (All Sources)	**$23,328,744**	**$5,576,806**	**$5,482,143**	**$5,993,186**	**$3,726,416**	**$3,168,001**	**N/A**
Multi-year Support brought forward from Prior Year (All Sources)	**N/A**	**N/A**	**$0**	**$0**	**$0**	**$0**	**N/A**
Residual Funds brought forward from Prior Year (All Sources)	**$6,122,131**	**$1,238,254**	**$2,430,674**	**$2,801,252**	**$2,934,837**	**$2,149,393**	**N/A**
Total Direct Center Cash Support	**$29,450,875**	**$6,815,060**	**$7,912,817**	**$8,794,438**	**$6,661,253**	**$5,317,394**	**N/A**

Expenses	Early Cumulative Total [1]	Jun-01-2011 - May-31-2012	Jun-01-2012 - May-31-2013	Jun-01-2013 - May-31-2014	Jun-01-2014 - May-31-2015	Jun-01-2015 - May-31-2016	Proposed Budget Next Award Year
Salaries & Benefits							
A. Senior Personnel: PI/PD, Co-PIs, Faculty and Other Senior Associates	$2,043,913	$741,340	$354,294	$559,711	$317,354	$503,226	$0
B. Other Personnel	$8,172,535	$1,133,600	$1,569,030	$1,667,187	$1,439,477	$995,948	$19,688
Postdoctoral associates	$504,623	$0	$46,368	$48,240	$19,392	$59,011	$0
Other professionals (technician, programmer, etc.)	$734,305	$112,105	$0	$59,841	$125,273	$369,183	$0
Graduate Students	$3,916,853	$799,764	$816,483	$937,392	$803,796	$492,086	$19,688
Undergraduate students	$553,567	$43,105	$80,342	$64,823	$51,323	$19,607	$0
Secretarial - clerical	N/A	$143,463	$104,769	$129,866	$70,923	$772	$0
Other	$2,275,083	$35,163	$521,068	$427,025	$368,770	$55,289	$0
C. Fringe Benefits	$2,438,381	$562,251	$440,533	$544,014	$311,530	$421,669	$17,805
Total Salaries & Benefits (A+B+C)	**$12,654,829**	**$2,437,191**	**$2,363,857**	**$2,770,912**	**$2,068,361**	**$1,920,843**	**$37,493**

Other Expenses							
D. Equipment	$980,024	$83,508	$91,183	$100,238	$52,950	$72,650	$55,000
E. Travel	N/A	$175,231	$250,789	$237,142	$237,052	$241,992	$0
F. Participant Support	N/A	$111,808	$160,576	$120,031	$23,705	$223,653	$5,000
G. Other Direct Costs	$3,586,594	$396,298	$830,931	$802,684	$758,713	$606,682	$0
H. Direct Costs Total (A through G)	**$17,636,114**	**$3,204,036**	**$3,697,336**	**$4,031,007**	**$3,140,781**	**$3,065,820**	**$97,493**
I. Indirect Costs	**$5,405,247**	**$993,916**	**$1,324,508**	**$1,341,857**	**$1,052,005**	**$1,129,305**	**$10,238**
TOTAL Expenditures and Budgets (A through I)	**$23,041,361**	**$4,197,952**	**$5,021,844**	**$5,372,864**	**$4,192,786**	**$4,195,125**	**$107,731**

Totals and Residuals	Early Cumulative Total [1]	Jun-01-2011 - May-31-2012	Jun-01-2012 - May-31-2013	Jun-01-2013 - May-31-2014	Jun-01-2014 - May-31-2015	Jun-01-2015 - May-31-2016	Proposed Budget Next Award Year
Total Direct Center Cash Support	**$29,450,875**	**$6,815,060**	**$7,912,817**	**$8,794,438**	**$6,661,253**	**$5,317,394**	**N/A**
J. TOTAL Expenditures and Budgets (A through I)	$23,041,361	$4,197,952	$5,021,844	$5,372,864	$4,192,786	$4,195,125	$107,731
K. Support Reserved for Future Years	N/A	N/A	$0	$0	$0	$0	N/A
L. Residual Funds Remaining	$5,516,927	$262,725	$2,890,973	$3,421,574	$2,468,467	$1,122,269	$0
Balance (Subtract J+K+L from Current Year Support)	**$892,587**	**$2,354,383**	**$0**	**$0**	**$0**	**$0**	**N/A**

[1] - For Centers in operation for more than five years.

Table 11: Modes of Support, by Industry and Other Practitioner Organizations

Organization	Jun 1, 2014 - May 31, 2015						Jun 1, 2015 - May 31, 2016						Promised Support
	Fees and Contributions	Sponsored Projects		Associated Projects		In-Kind Support	Fees and Contributions	Sponsored Projects		Associated Projects		In-Kind Support	
		Non-translational	Translational	Non-translational	Translational			Non-translational	Translational	Non-translational	Translational		
Industrial/Practitioner Member Organizations													
Total Members	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
Non-Member Organizations: Funders of Sponsored Projects, Funders of Associated Projects, and Contributing Organizations													
Bosch Rexroth	$0	$0	$0	$0	$0	$0	$0	$500	$0	$0	$0	$0	$0
Casappa S.p.A.	$0	$0	$0	$110,504	$0	$0	$0	$0	$0	$0	$13,810	$0	$0
Cat Pumps	$0	$0	$0	$0	$116,923	$0	$0	$0	$0	$0	$0	$0	$0
CNH America, Inc.	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$67,067	$55,000	$33,533
Confidential Organization (optional use for associated or sponsored projects only)	$0	$0	$0	$0	$1,381,928	$0	$0	$0	$0	$0	$791,619	$0	$232,774
Dae Jin Hydraulics - TECPOS	$0	$0	$0	$50,000	$0	$0	$0	$0	$0	$27,083	$0	$0	$0
Danfoss	$0	$0	$0	$0	$81,830	$4,400	$0	$0	$0	$0	$45,745	$0	$0
Deere and Company	$0	$0	$0	$0	$15,500	$0	$0	$0	$0	$0	$0	$0	$0
Donaldson Company	$0	$0	$0	$0	$0	$1	$0	$0	$0	$0	$0	$2,900	$0
Eaton Corporation	$0	$500	$0	$0	$0	$1,100	$0	$0	$0	$0	$0	$10,000	$0
Environmental Protection Agency	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$75,000	$0
Exxon Mobil	$0	$4,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	$5,100	$0
FORCE America	$0	$1,000	$0	$0	$0	$0	$0	$500	$0	$0	$0	$0	$0
Igus, Inc.	$0	$0	$0	$0	$0	$200	$0	$0	$0	$0	$0	$0	$0
International Fluid Power Society	$0	$500	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
John Crane	$0	$0	$0	$7,962	$0	$0	$0	$0	$0	$0	$0	$0	$0
Jump Trading Simulation and Education Center	$0	$0	$0	$0	$0	$0	$0	$0	$0	$21,035	$6,661	$0	$13,847
Lee Company	$0	$0	$0	$0	$0	$3,600	$0	$0	$0	$0	$0	$0	$0
Mathers Hydraulics	$0	$0	$0	$0	$0	$0	$0	$0	$16,700	$0	$0	$0	$0
Minneapolis Veterans Administration Medical Center	$0	$0	$0	$0	$3,600	$0	$0	$0	$0	$0	$2,625	$0	$0
Moog, Inc.	$0	$0	$0	$0	$0	$17,000	$0	$0	$0	$0	$0	$0	$0
National Defense Science and Engineering Fellowship Grant (NDSEG)	$0	$0	$0	$15,429	$0	$0	$0	$0	$0	$0	$0	$0	$0
National Fluid Power Association	$114,228	$0	$0	$0	$0	$0	$11,092	$0	$0	$0	$0	$0	$81,000
NFPA Education and Technology Foundation	$655,000	$10,000	$0	$0	$0	$0	$491,250	$0	$0	$0	$0	$0	$163,750
Oerlikon Fairfield	$0	$0	$0	$0	$0	$0	$0	$0	$0	$9,600	$0	$0	$4,800
Parker Hannifin Corporation	$0	$0	$0	$0	$0	$1,787	$0	$0	$0	$0	$0	$0	$0
Proctor and Gamble	$0	$0	$0	$0	$0	$0	$0	$0	$0	$72,275	$0	$0	$36,137
Robert Bosch SpA	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$33,571	$0	$13,429
SMC Corporation	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$700	$0
Takako Industries	$0	$0	$0	$0	$0	$6,000	$0	$0	$0	$0	$0	$0	$0
Thomas Magnete GmbH	$0	$0	$0	$29,910	$0	$0	$0	$0	$0	$38,147	$0	$0	$12,842
Veraphotonics, Mistras	$0	$0	$0	$0	$31,161	$0	$0	$0	$0	$0	$0	$0	$0
WIKA	$0	$0	$0	$0	$0	$300	$0	$0	$0	$0	$0	$0	$0
Total Non-Members	**$769,228**	**$16,000**	**$0**	**$213,805**	**$1,630,942**	**$34,388**	**$502,342**	**$1,000**	**$16,700**	**$168,140**	**$961,098**	**$148,700**	**$592,112**
Total	**$769,228**	**$16,000**	**$0**	**$213,805**	**$1,630,942**	**$34,388**	**$502,342**	**$1,000**	**$16,700**	**$168,140**	**$961,098**	**$148,700**	**$592,112**

Volume II: Project Personnel Data

Project Name	Project Leader	Project Investigator	Project Role	Title	First Name	Middle Initial	Last Name	Suffix	Institution	Title Within Institution	Department Within Institution	Personnel Types Within Institution
1B.1: Next Steps towards Virtual Prototyping of Pumps and Motors	No	No			Daniel		Mizell		Purdue University	Doctoral Student		Research - Doctoral Student
1B.1: Next Steps towards Virtual Prototyping of Pumps and Motors	Yes	Yes			Monika	M	Ivantysynova		Purdue University	Senior Faculty		Curriculum - Senior Faculty Research - Senior Faculty Leadership/Administration - Thrust Leader
1B.1: Next Steps towards Virtual Prototyping of Pumps and Motors	No	No			Ashley	M	Wondergem		Purdue University	Doctoral Student	Mechanical Engineering	Research - Doctoral Student
1B.1: Next Steps towards Virtual Prototyping of Pumps and Motors	No	No			Natalie		Spencer		Purdue University	Master's Student	Mechanical Engineering	Research - Master's Student
1E.3: Actively Controlled Digital Pump Motor	Yes	Yes			John	H	Lumkes		Purdue University			Curriculum - Senior Faculty Research - Senior Faculty
1E.6: High Performance Valve Actuation Systems	Yes	Yes			John	H	Lumkes		Purdue University			Curriculum - Senior Faculty Research - Senior Faculty
1E.6: High Performance Valve Actuation Systems	No	No			Jordan		Garrity		Purdue University	Master's Student		Research - Master's Student
1F.1: Variable Displacement External Gear Machine	Yes	Yes			Andrea		Vacca	PhD	Purdue University	Junior Faculty		Research - Junior Faculty Curriculum - Junior Faculty
1F.1: Variable Displacement External Gear Machine	No	No			Srinath		Tankasala		Purdue University	Master's Student		Research - Master's Student
1F.1: Variable Displacement External Gear Machine	No	No			Sidhant		Gulati	MS	Purdue University	Master's Student		Research - Master's Student
1G.1: Energy Efficient Fluids	No	No			Thomas	R	Chase		University of Minnesota	Senior Faculty		Curriculum - Senior Faculty Research - Senior Faculty
1G.1: Energy Efficient Fluids	Yes	Yes	PI		Paul	W	Michael		Milwaukee School of Engineering	Research Staff	Fluid Power Institute	Research - Research Staff
1G.1: Energy Efficient Fluids	No	No			Shima	s	Shahahmadi		Milwaukee School of Engineering	Master's Student	Fluid Power Institute	Research - Master's Student
1G.1: Energy Efficient Fluids	No	No			Shreya		Mettakadapa		Milwaukee School of Engineering	Master's Student	Fluid Power Institute	Research - Master's Student
1G.1: Energy Efficient Fluids	No	No			Russell	J	Steinmetz		Milwaukee School of Engineering	Staff	Fluid Power Institute	Research - Research Staff
1G.1: Energy Efficient Fluids	No	No			Scott	S	Bair		Georgia Institute of Technology	Senior Faculty	School of Mechanical Engineering	Curriculum - Senior Faculty Research - Senior Faculty
1G.3: Rheological Design for Efficient Fluid Power	Yes	Yes			Randy	H	Ewoldt		University of Illinois at Urbana-Champaign	Junior Faculty	Department of Mechanical Science and Engineering	Research - Junior Faculty Curriculum - Junior Faculty
1G.3: Rheological Design for Efficient Fluid Power	No	No			James	T	Allison	Ph.D.	University of Illinois at Urbana-Champaign	Junior Faculty	Industrial and Enterprise Systems Engineering	Research - Junior Faculty Curriculum - Junior Faculty
1G.3: Rheological Design for Efficient Fluid Power	No	No			William		King		University of Illinois at Urbana-Champaign	Senior Faculty	Mechanical Science and Engineering	Curriculum - Senior Faculty Research - Senior Faculty
1G.3: Rheological Design for Efficient Fluid Power	No	No			Lakshmi	G	Rao		University of Illinois at Urbana-Champaign	Master's Student		Research - Master's Student
1G.3: Rheological Design for Efficient Fluid Power	No	No			Jonathon	K	Schuh		University of Illinois at Urbana-Champaign	Master's Student		Research - Master's Student
1G.3: Rheological Design for Efficient Fluid Power	No	No			Yong Hoon		Lee		University of Illinois at Urbana-Champaign	Doctoral Student		Research - Doctoral Student
1J.2: A Novel Pressure-controlled Hydro-Mechanical Transmission	No	No			Biswaranjan		Mohanty		University of Minnesota	Doctoral Student		Research - Doctoral Student
1J.2: A Novel Pressure-controlled Hydro-Mechanical Transmission	Yes	Yes			Kim	A	Stelson		University of Minnesota	Senior Faculty	Mechanical Engineering	Leadership/Administration - Director Curriculum - Senior Faculty Research - Senior Faculty
1J.2: A Novel Pressure-controlled Hydro-Mechanical Transmission	No	No			Emma		Frosina		University of Minnesota			Research - Other Visiting College Student
2B.3: Free Piston Engine Hydraulic Pump	Yes	Yes			Zongxuan		Sun		University of Minnesota	Junior Faculty		Research - Junior Faculty Curriculum - Junior Faculty Leadership/Administration - Research Thrust Management and Strategic Planning

Volume II: Project Personnel Data

Project Name	Project Leader	Project Investigator	Project Role	Title	First Name	Middle Initial	Last Name	Suffix	Institution	Title Within Institution	Department Within Institution	Personnel Types Within Institution
2B.3: Free Piston Engine Hydraulic Pump	No	No			Chen		Zhang	PhD	University of Minnesota	Doctoral Student	Mechanical engineering	Research - Doctoral Student
2B.4: Controlled Stirling Thermocompressors	No	No			Justin		Paldowic		University of Michigan- Ann Arbor	Undergraduate Student		REU Student - NSF REU Site Award
2B.4: Controlled Stirling Thermocompressors	Yes	Yes			Eric	J	Barth		Vanderbilt University	Senior Faculty		Curriculum - Senior Faculty Leadership/Administration - Research Thrust Management and Strategic Planning Research - Senior Faculty
2B.4: Controlled Stirling Thermocompressors	No	No			Justin		Paldowic		Vanderbilt University			Curriculum - Undergraduate Student
2C.2: Advanced Strain Energy Accumulator	No	No			Josh		Cummins		Vanderbilt University	Doctoral Student		Research - Doctoral Student
2C.2: Advanced Strain Energy Accumulator	Yes	Yes			Eric	J	Barth		Vanderbilt University	Senior Faculty		Curriculum - Senior Faculty Leadership/Administration - Research Thrust Management and Strategic Planning Research - Senior Faculty
2C.2: Advanced Strain Energy Accumulator	No	No			Doug	E	Adams		Vanderbilt University	Senior Faculty		Curriculum - Senior Faculty Research - Senior Faculty
2C.2: Advanced Strain Energy Accumulator	No	No			Vito	R	Gervasi		Milwaukee School of Engineering	Research Staff		Research - Research Staff
2F.1 Soft Pneumatic Actuator for Arm Orthosis	No	No			Brooke	A	Slavens		University of Wisconsin- Madison	Junior Faculty		Curriculum - Junior Faculty
2F.1 Soft Pneumatic Actuator for Arm Orthosis	No	No			Deen		Farooq		University of Illinois at Urbana-Champaign	Master's Student		Research - Master's Student
2F.1 Soft Pneumatic Actuator for Arm Orthosis	Yes	Yes			Elizabeth	T	Hsiao-Wecksler	PhD	University of Illinois at Urbana-Champaign	Senior Faculty	Department of Mechanical Science & Engineering	Curriculum - Senior Faculty Research - Senior Faculty
2F.1 Soft Pneumatic Actuator for Arm Orthosis	No	No			Gaurav		Singh		University of Illinois at Urbana-Champaign	Doctoral Student		Research - Doctoral Student
2F.1 Soft Pneumatic Actuator for Arm Orthosis	No	No			Girish		Krishnan	PhD	University of Illinois at Urbana-Champaign	Junior Faculty		Research - Junior Faculty Curriculum - Junior Faculty
2F.1 Soft Pneumatic Actuator for Arm Orthosis	No	No			Placid		Ferreira		University of Illinois at Urbana-Champaign	Senior Faculty		Curriculum - Senior Faculty Research - Senior Faculty
2F.1 Soft Pneumatic Actuator for Arm Orthosis	No	No			Sameh		Tawfick	PhD	University of Illinois at Urbana-Champaign	Junior Faculty	Mechanical Science and Engineering	Research - Junior Faculty Curriculum - Junior Faculty
2F: MEMS Proportional Pneumatic Valve	Yes	Yes			Thomas	R	Chase		University of Minnesota	Senior Faculty		Curriculum - Senior Faculty Research - Senior Faculty
2F: MEMS Proportional Pneumatic Valve	No	No			Erik		Hemstad		University of Minnesota	Master's Student		Research - Master's Student
2F: MEMS Proportional Pneumatic Valve	No	No			Alex		Hargus		University of Minnesota	Master's Student	Mechanical Engineering	Research - Master's Student
2G: Fluid Powered Surgery and Rehabilitation via Compact Integrated Systems	No	No			Euisun		Kim		Georgia Institute of Technology	Doctoral Student	Mechanical Engineering	Research - Doctoral Student
2G: Fluid Powered Surgery and Rehabilitation via Compact Integrated Systems	No	No			Angelica	V	Price		Vanderbilt University			Curriculum - Undergraduate Student
2G: Fluid Powered Surgery and Rehabilitation via Compact Integrated Systems	No	No			Yue		Chen		Vanderbilt University	Doctoral Student	Mechanical Engineering	Research - Doctoral Student
2G: Fluid Powered Surgery and Rehabilitation via Compact Integrated Systems	No	No			Bryn		Pitt		Vanderbilt University	Doctoral Student	Mechanical Engineering	Research - Doctoral Student
2G: Fluid Powered Surgery and Rehabilitation via Compact Integrated Systems	No	No			Angelica	V	Price		The College of Idaho	Undergraduate Student		REU Student - NSF REU Site Award
2G: Fluid Powered Surgery and Rehabilitation via Compact Integrated Systems	No	No			Jun		Ueda		Georgia Institute of Technology	Senior Faculty		Curriculum - Senior Faculty Research - Senior Faculty
2G: Fluid Powered Surgery and Rehabilitation via Compact Integrated Systems	Yes	Yes			Robert	J	Webster	III	Vanderbilt University	Junior Faculty		Research - Junior Faculty Curriculum - Junior Faculty
2G: Fluid Powered Surgery and Rehabilitation via Compact Integrated Systems	No	No			Charles		Williams		Milwaukee School of Engineering	Master's Student		Research - Master's Student

Volume II: Project Personnel Data

Project Name	Project Leader	Project Investigator	Project Role	Title	First Name	Middle Initial	Last Name	Suffix	Institution	Title Within Institution	Department Within Institution	Personnel Types Within Institution
3A.1: Operator Interface Design Principles for Hydraulics	No	No			Eui	H	Park		North Carolina Agriculture and Technical State University	Senior Faculty		Curriculum - Senior Faculty Research - Senior Faculty
3A.1: Operator Interface Design Principles for Hydraulics	Yes	Yes			Wayne	J	Book		Georgia Institute of Technology	Senior Faculty		Curriculum - Senior Faculty Research - Senior Faculty Leadership/Administration - Thrust Leader
3A.1: Operator Interface Design Principles for Hydraulics	No	No			Beau		Domingue		Georgia Institute of Technology	Master's Student	Mechanical Engineering	Research - Master's Student
3A.1: Operator Interface Design Principles for Hydraulics	No	No			Heather	C	Humphreys		Georgia Institute of Technology	Doctoral Student	Mechanical Engineering	Research - Doctoral Student
3A.1: Operator Interface Design Principles for Hydraulics	No	No			James	D	Huggins		Georgia Institute of Technology	Research Staff		Research - Research Staff
3A.3: Human Performance Modeling and User Centered Design	No	No			Dorian		Davis		North Carolina Agriculture and Technical State University	Doctoral Student		Research - Doctoral Student
3A.3: Human Performance Modeling and User Centered Design	Yes	Yes			Steven	X	Jiang		North Carolina Agriculture and Technical State University	Senior Faculty	Industrial and Systems Engineering	Curriculum - Senior Faculty Research - Senior Faculty
3D Excavator	No	Yes			Jane		Davidson		University of Minnesota	Faculty		Curriculum - Senior Faculty Research - Senior Faculty
3D Excavator	No	No			Susan		Mantell		University of Minnesota	Faculty		Curriculum - Senior Faculty Research - Senior Faculty
3D Excavator	No	No			Tom		Kurfess		Georgia Institute of Technology	Senior Faculty		Curriculum - Senior Faculty Research - Senior Faculty
3D Excavator	No	No			Michael	J	Gust		University of Minnesota	Staff		Leadership/Administration - Industrial Liaison Officer (ILO)
3D Excavator	Yes	Yes			Kim	A	Stelson		University of Minnesota	Senior Faculty	Mechanical Engineering	Leadership/Administration - Director Curriculum - Senior Faculty Research - Senior Faculty
3D.2: New Directions in Elastohydrodynamic Lubrication to Solve Fluid Power Problems	Yes	Yes			Scott	S	Bair		Georgia Institute of Technology	Senior Faculty	School of Mechanical Engineering	Curriculum - Senior Faculty Research - Senior Faculty
3E.1: Pressure Ripple Energy Harvester	No	No			Zack		Koontz		Georgia Institute of Technology	Undergraduate Student		Curriculum - Undergraduate Student
3E.1: Pressure Ripple Energy Harvester	No	No			Ellen		Skow		Georgia Institute of Technology	Doctoral Student		Research - Doctoral Student
3E.1: Pressure Ripple Energy Harvester	Yes	Yes			Kenneth	A	Cunefare	Ph.D.	Georgia Institute of Technology	Senior Faculty		Curriculum - Senior Faculty Research - Senior Faculty
Adjustable Linkage Pump	No	No			Anirudh Reddy		Ravula		University of Minnesota	Master's Student		Research - Master's Student
Adjustable Linkage Pump	Yes	Yes			James	D	Van de Ven		University of Minnesota	Junior Faculty	Mechanical Engineering	Research - Junior Faculty Curriculum - Junior Faculty Leadership/Administration - Education Program Leader
Adjustable Linkage Pump	No	No			Anthony		Knutson		University of Minnesota	Doctoral Student		Research - Doctoral Student
Advanced Hydraulic Systems for Next Generation of Skid Steer Loaders	Yes	Yes			Monika	M	Ivantysynova		Purdue University	Senior Faculty		Curriculum - Senior Faculty Research - Senior Faculty Leadership/Administration - Thrust Leader
Advanced Hydraulic Systems for Next Generation of Skid Steer Loaders	No	No			Mrudula		Orpe		Purdue University	Master's Student		Research - Master's Student
Aeration and Fluid Efficiency 060	Yes	Yes			Paul	W	Michael		Milwaukee School of Engineering	Research Staff	Fluid Power Institute	Research - Research Staff
Building a Hardware-in-the-loop Simulation Testbed and a Living Laboratory for Evaluating Connected Vehicle-Highway Systems	Yes	Yes			Zongxuan		Sun		University of Minnesota	Junior Faculty		Research - Junior Faculty Curriculum - Junior Faculty Leadership/Administration - Research Thrust Management and Strategic Planning
CAREER: Control of Mechatronic Automotive Propulsion Systems	Yes	Yes			Zongxuan		Sun		University of Minnesota	Junior Faculty		Research - Junior Faculty Curriculum - Junior Faculty Leadership/Administration - Research Thrust Management and Strategic Planning
Controllable Hydraulic Ankle Prosthesis	No	No			John		Skelton		University of Minnesota	Master's Student		Research - Master's Student
Controllable Hydraulic Ankle Prosthesis	Yes	Yes			William		Durfee		University of Minnesota	Senior Faculty	Mechanical Engineering	Curriculum - Senior Faculty Research - Senior Faculty

Volume II: Project Personnel Data

Project Name	Project Leader	Project Investigator	Project Role	Title	First Name	Middle Initial	Last Name	Suffix	Institution	Title Within Institution	Department Within Institution	Personnel Types Within Institution
CPS: Synergy: Integrated Modeling Analysis and Synthesis of Miniature Medical Devices	Yes	Yes		Dr.	Pietro		Valdastri		Vanderbilt University			Curriculum - Senior Faculty Research - Senior Faculty
Detailed modeling of Gerotor units	Yes	Yes			Andrea		Vacca	PhD	Purdue University	Junior Faculty		Research - Junior Faculty Curriculum - Junior Faculty
Detailed modeling of Gerotor units	No	No			Andrew		Robison		Purdue University	Doctoral Student		Research - Doctoral Student
Development of a Forearm Simulator to Recreate Abnormal Muscle Tone Due to Brain Lesions	Yes	Yes			Elizabeth	T	Hsiao-Wecksler	PhD	University of Illinois at Urbana-Champaign	Senior Faculty	Department of Mechanical Science & Engineering	Curriculum - Senior Faculty Research - Senior Faculty
Development of a Gasoline Engine Driven Ultra High Pressure Hydraulic Pump	Yes	Yes			Andrea		Vacca	PhD	Purdue University	Junior Faculty		Research - Junior Faculty Curriculum - Junior Faculty
EFRI-RESTOR: Novel Compressed Air Approach for Off-Shore Wind Energy Storage	Yes	Yes			Perry	Y	Li		University of Minnesota	Senior Faculty		Curriculum - Senior Faculty Research - Senior Faculty
EFRI-RESTOR: Novel Compressed Air Approach for Off-Shore Wind Energy Storage	No	No			Terrence	W	Simon		University of Minnesota	Senior Faculty		Curriculum - Senior Faculty Research - Senior Faculty
Electrohydraulic Braking System	No	No			Riccardo		Bianchi		Purdue University	Doctoral Student		Research - Doctoral Student
Electrohydraulic Braking System	Yes	Yes			Andrea		Vacca	PhD	Purdue University	Junior Faculty		Research - Junior Faculty Curriculum - Junior Faculty
Energy Efficienct Fluid Field Trial 061	Yes	Yes			Paul	W	Michael		Milwaukee School of Engineering	Research Staff	Fluid Power Institute	Research - Research Staff
Energy Efficient Fluids	Yes	Yes			Paul	W	Michael		Milwaukee School of Engineering	Research Staff	Fluid Power Institute	Research - Research Staff
Energy saving hydraulic system architecture for next generation of combines utilizing displacement control	No	No			Damiano		Padovani		Purdue University	Master's Student		Research - Master's Student
Energy saving hydraulic system architecture for next generation of combines utilizing displacement control	Yes	Yes			Monika	M	Ivantysynova		Purdue University	Senior Faculty		Curriculum - Senior Faculty Research - Senior Faculty Leadership/Administration - Thrust Leader
Evaluation And Design Improvements For A Hydraulic Pump	Yes	Yes			Monika	M	Ivantysynova		Purdue University	Senior Faculty		Curriculum - Senior Faculty Research - Senior Faculty Leadership/Administration - Thrust Leader
Evaluation of performance of counterbalance valves	Yes	Yes			Andrea		Vacca	PhD	Purdue University	Junior Faculty		Research - Junior Faculty Curriculum - Junior Faculty
Fluid Power Advanced Manufacturing Technology Consortium	Yes	Yes			Kim	A	Stelson		University of Minnesota	Senior Faculty	Mechanical Engineering	Leadership/Administration - Director Curriculum - Senior Faculty Research - Senior Faculty
High Pressure Compliant Material Development	Yes	Yes			Kenneth	A	Cunefare	Ph.D.	Georgia Institute of Technology	Senior Faculty		Curriculum - Senior Faculty Research - Senior Faculty
Modeling of external gear pumps operating with power law fluids and experimental validation	Yes	Yes			Andrea		Vacca	PhD	Purdue University	Junior Faculty		Research - Junior Faculty Curriculum - Junior Faculty
Modelling and analysis of swash plate axial piston pump	Yes	Yes			Monika	M	Ivantysynova		Purdue University	Senior Faculty		Curriculum - Senior Faculty Research - Senior Faculty Leadership/Administration - Thrust Leader
MRI: Development of a Controlled-Trajectory Rapid Compression and Expansion Machine	Yes	Yes			Zongxuan		Sun		University of Minnesota	Junior Faculty		Research - Junior Faculty Curriculum - Junior Faculty Leadership/Administration - Research Thrust Management and Strategic Planning
New Generation Of Green Highly Efficient Agricultural Machines Powered By High Pressure Water Hydraulic Technology	Yes	Yes			Andrea		Vacca	PhD	Purdue University	Junior Faculty		Research - Junior Faculty Curriculum - Junior Faculty
New Geometries for External Gear Machines towards the reduction of Noise Emissions	Yes	Yes			Andrea		Vacca	PhD	Purdue University	Junior Faculty		Research - Junior Faculty Curriculum - Junior Faculty
Noise measurements and valve plate design to reduce noise and maintain low control effort for tandem pumps.	Yes	Yes			Monika	M	Ivantysynova		Purdue University	Senior Faculty		Curriculum - Senior Faculty Research - Senior Faculty Leadership/Administration - Thrust Leader
Numerical Modeling of GEROTORs unit	Yes	Yes			Andrea		Vacca	PhD	Purdue University	Junior Faculty		Research - Junior Faculty Curriculum - Junior Faculty
Optimal design of a fuel injection pump	Yes	Yes			Andrea		Vacca	PhD	Purdue University	Junior Faculty		Research - Junior Faculty Curriculum - Junior Faculty
Passive hydraulic medical training simulator for mimicking joint spasticity and rigidity	Yes	Yes			Elizabeth	T	Hsiao-Wecksler	PhD	University of Illinois at Urbana-Champaign	Senior Faculty	Department of Mechanical Science & Engineering	Curriculum - Senior Faculty Research - Senior Faculty
Phase 3: Low Cost Compressed Natural Gas	Yes	Yes			Perry	Y	Li		University of Minnesota	Senior Faculty		Curriculum - Senior Faculty Research - Senior Faculty

Volume II: Project Personnel Data

Project Name	Project Leader	Project Investigator	Project Role	Title	First Name	Middle Initial	Last Name	Suffix	Institution	Title Within Institution	Department Within Institution	Personnel Types Within Institution
Test Bed 1: Heavy Mobile Equipment- Excavator	No	No			Sam		Seifert		Georgia Institute of Technology	Master's Student	Mechanical Engineering	Research - Master's Student
Test Bed 1: Heavy Mobile Equipment- Excavator	Yes	Yes			Monika	M	Ivantysynova		Purdue University	Senior Faculty		Curriculum - Senior Faculty Research - Senior Faculty Leadership/Administration - Thrust Leader
Test Bed 4: Patient Transfer Device - Hydraulics at Human Scale	Yes	Yes			Wayne	J	Book		Georgia Institute of Technology	Senior Faculty		Curriculum - Senior Faculty Research - Senior Faculty Leadership/Administration - Thrust Leader
Test Bed 6: Human Assist Devices (Fluid Powered Ankle-Foot-Orthoses)	Yes	Yes			Elizabeth	T	Hsiao-Wecksler	PhD	University of Illinois at Urbana-Champaign	Senior Faculty	Department of Mechanical Science & Engineering	Curriculum - Senior Faculty Research - Senior Faculty
Test Bed 6: Human Assist Devices (Fluid Powered Ankle-Foot-Orthoses)	No	No			Mazharul		Islam		University of Illinois at Urbana-Champaign	Doctoral Student		Research - Doctoral Student
Test Bed 6: Human Assist Devices (Fluid Powered Ankle-Foot-Orthoses)	No	No			Brett	C	Neubauer		University of Minnesota	Doctoral Student		Research - Doctoral Student
Testbed 3: Highway Vehicles -- Hydraulic Hybrid Passenger Vehicle	No	No			John		Pullar		University of Minnesota	Undergraduate Student		Curriculum - Undergraduate Student
Testbed 3: Highway Vehicles -- Hydraulic Hybrid Passenger Vehicle	Yes	Yes			Perry	Y	Li		University of Minnesota	Senior Faculty		Curriculum - Senior Faculty Research - Senior Faculty
Testbed 3: Highway Vehicles -- Hydraulic Hybrid Passenger Vehicle	No	No			Jenna		McGuire		University of Minnesota	Master's Student		Research - Master's Student
Testbed 3: Highway Vehicles -- Hydraulic Hybrid Passenger Vehicle	No	No			Kai Loon		Cheong		University of Minnesota	Doctoral Student	Mechanical Engineering	Research - Doctoral Student
Viscosity Measurements of Polymer Solutions at Elevated Temperatures and Pressure	Yes	Yes			Scott	S	Bair		Georgia Institute of Technology	Senior Faculty	School of Mechanical Engineering	Curriculum - Senior Faculty Research - Senior Faculty
Wearable eMbots to Induce Recovery of Function	Yes	Yes			William		Durfee		University of Minnesota	Senior Faculty	Mechanical Engineering	Curriculum - Senior Faculty Research - Senior Faculty

This page is intentionally left blank

APPENDIX V

Certifications

This page is intentionally left blank

Table 9b - Cost Sharing by Institution						
	Award Year 1 (FY07)		Award Year 2 (FY08)		Award Year 3 (FY09)	
Institution	**Committed**	**Actual**	**Committed**	**Actual**	**Committed**	**Actual**
U. of Minnesota	$180,180	$180,180	$182,000	$182,000	$220,469	$220,469
Georgia Tech	$112,860	$67,584	$129,000	$140,827	$133,000	$83,110
MSOE	$0	$0	$10,800	$18,086	$0	$0
Purdue	$112,860	$112,860	$129,000	$113,321	$133,000	$162,637
UIUC	$112,860	$33,529	$123,200	$78,405	$124,865	$200,516
Vanderbilt	$75,240	$75,240	$76,000	$157,021	$88,666	$112,359
	Award Year 4 (FY10)		Award Year 5 (FY11)		Award Year 6 (FY12)	
Institution	**Committed**	**Actual**	**Committed**	**Actual**	**Committed**	**Actual**
U. of Minnesota	$226,367	$187,032	$242,667	$239,266	$339,537	$446,797
Georgia Tech	$142,995	$267,384	$152,000	$135,564	$130,232	$70,269
MSOE	$0	-	$0	-	$0	$0
Purdue	$142,995	$139,404	$152,000	$287,394	$152,557	$95,526
UIUC	$142,995	$208,339	$119,541	$163,809	$92,093	$185,553
Vanderbilt	$94,648	$69,213	$101,333	$119,717	$85,581	$43,565
	Award Year 7 (FY13)		Award Year 8 (FY14)		Award Year 9 (FY15)	
Institution	**Committed**	**Actual**	**Committed**	**Actual**	**Committed**	**Actual**
U. of Minnesota	$339,537	$602,309	$339,537	$569,662	$226,641	$499,521
Georgia Tech	$130,232	$61,944	$130,232	$69,552	$71,930	$110,071
MSOE	$0	-	$0	-	$0	$0
Purdue	$152,557	$56,262	$152,557	$119,663	$101,832	$78,946
UIUC	$92,093	$84,696	$92,093	($32,346)	$1,377	($11,743)
Vanderbilt	$85,581	$35,335	$85,581	$18,642	$478	$13,987
					Cumulative	
Institution					**Committed**	**Actual**
U. of Minnesota					$2,296,935	$3,127,236
Georgia Tech					$1,132,481	$1,006,305
MSOE					$10,800	$18,086
Purdue					$1,229,358	$1,166,013
UIUC					$901,117	$910,759
Vanderbilt					$693,108	$645,079

Marguerite Webb

This page is intentionally left blank

Table 10a: Unexpended Residual in the Current Award and Proposed Award Year		
	Previous Award Year to Current Award Year	**Current Award Year to Proposed Award Year**
Total Unexpended Residual Funds	$1,044,455	$893,603
Committed, Encumbered, Obligated funds (obligated = planned for)	$1,044,455	$893,603
Residual Funds Without Specified Use	$0	$0

Margaret Webb

This page is intentionally left blank

CCEFP CONTRIBUTOR LIST
Private Sector Firms (formerly "member" list)

National Fluid Power Association (NFPA) Education and Technology Foundation

This page is intentionally left blank