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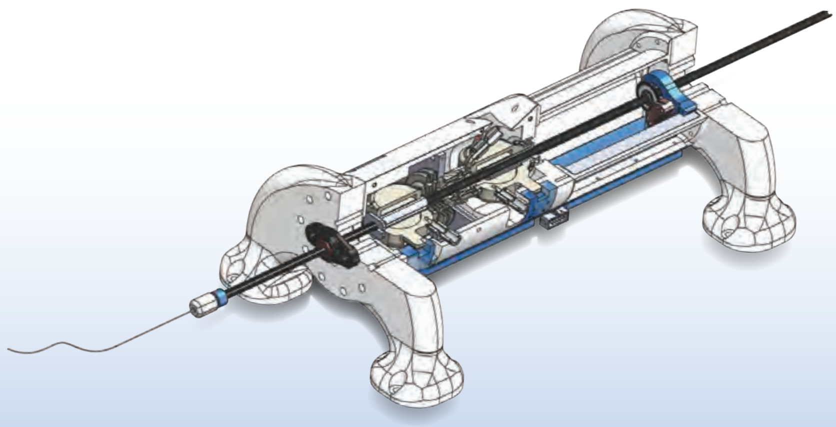
9th ANNUAL REPORT

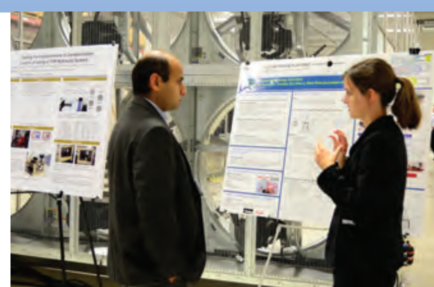
VOLUME 1

COOPERATIVE AGREEMENT #EEC 0540834 / DUE DATE: MARCH 3, 2015



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

COVER SHEET FOR PROPOSAL TO THE NATIONAL SCIENCE FOUNDATION

PROGRAM ANNOUNCEMENT/SOLICITATION NO./CLOSING DATE/If not in response to a program announcement/solicitation enter NSF 00-2 NSF 04-570	**FOR NSF USE ONLY** NSF PROPOSAL NUMBER
FOR CONSIDERATION BY NSF ORGANIZATIONAL UNIT(S) (Indicate the most specific unit known, i.e., program, division, etc.) ERC – Engineering Research Center	

DATE RECEIVED	NUMBER OF COPIES	DIVISION ASSIGNED	FUND CODE	DUNS # (Data Universal Numbering System)	FILE LOCATION
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41-6007513	☐ A RENEWAL ☐ AN ACCOMPLISHMENT-BASED RENEWAL	YES ☐ NO ☒ IF YES, LIST ACRONYM(S)

NAME OF ORGANIZATION TO WHICH AWARD SHOULD BE MADE	ADDRESS OF AWARDEE ORGANIZATION, INCLUDING 9 DIGIT ZIP CODE
University of Minnesota – Twin Cities	University of Minnesota – Twin Cities 450 McNamara Alumni Center Minneapolis, MN 55455-2070
AWARDEE ORGANIZATION CODE (IF KNOWN) 0023879000	
NAME OF PERFORMING ORGANIZATION, IF DIFFERENT FROM ABOVE	ADDRESS OF PERFORMING ORGANIZATION, IF DIFFERENT, INCLUDING 9 DIGIT ZIP CODE
PERFORMING ORGANIZATION CODE (IF KNOWN)	

IS AWARDEE ORGANIZATION (Check All That Apply)
(See GPG II.D.1 For Definitions) ☐ FOR-PROFIT ORGANIZATION ☐ SMALL BUSINESS ☐ MINORITY BUSINESS ☐ WOMAN-OWNED BUSINESS

TITLE OF PROPOSED PROJECT

REQUESTED AMOUNT	PROPOSED DURATION (1-60 MONTHS)	REQUESTED STARTING DATE	SHOW RELATED PREPROPOSAL NO., IF APPLICABLE
$ 1795000	12 months	06/01/2015	

CHECK APPROPRIATE BOX(ES) IF THIS PROPOSAL INCLUDES ANY OF THE ITEMS LISTED BELOW

- ☐ BEGINNING INVESTIGATOR (GPG I.A.3)
- ☐ DISCLOSURE OF LOBBYING ACTIVITIES (GPG II.D.1)
- ☐ PROPRIETARY & PRIVILEGED INFORMATION (GPG I.B, II.D.7)
- ☐ NATIONAL ENVIRONMENTAL POLICY ACT (GPG II.D.10)
- ☐ HISTORIC PLACES (GPG II.D.10)
- ☐ SMALL GRANT FOR EXPLOR. RESEARCH (SGER) (GPG II.D.12)
- ☐ VERTEBRATE ANIMALS (GPG II.D.12) IACUC App. Date ______
- ☒ HUMAN SUBJECTS (GPG II.D.12)
  Exemption Subsection____or IRB App. Date 07/16/2014
- ☐ INTERNATIONAL COOPERATIVE ACTIVITIES: COUNTRY/COUNTRIES ______
- ☐ FACILITATION FOR SCIENTISTS/ENGINEERS WITH DISABILITIES (GPG V.G.)
- ☐ RESEARCH OPPORTUNITY AWARD (GPG V.H)

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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 54 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.

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1. Executive Summary

A. Achievements in the Reporting Year

Additional information on all achievements cited below can be found in Section 1.3 of this report.

i. Three-plane chart's top plane – integrated systems

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.

Pneumatic Control of Voluntary and Involuntary Nerve Impulses for Hemiparesis Rehabilitation and fMRI Study

This project is designed to understand the neuro-mechanical mechanisms associated with repetitive facilitation exercise (RFE) for stroke survivors to gain functional recovery of their hemi-paretic limbs.

ii. Three-plane chart's middle plane – enabling technologies and crosscutting activities

Controlled Stirling Fluid Power Unit

The Controlled Stirling Fluid Power Unit presents a potential solution to the problem of powering portable devices by creating a highly energetic and efficient source of fluid power for such applications.

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.

Two-Degree-of-Freedom, Magnetic-Resonance-Compatible Pneumatic Stepper Module

This project helps overcome the technical barrier of the absence of commercial, off-the-shelf fluid power actuators that are sterilizable and intrinsically safe for use in MRI-guided surgical systems.

iii. Three-plane chart's bottom plane – fundamental science and engineering

The first confirmation of the equivalence of frequency and shear-rate in shear thinning of lubricating oils

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. This research has made the first successful use of the Cox-Merz rule in predicting friction.

Measurement of normal forces due to asymmetric surface textures

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 results show that asymmetric textures produce normal forces that are well above those of symmetric textures.

First numerical model of rod seal operation under starved lubrication conditions with concurrent mixed lubrication

CCEFP research over many years has developed comprehensive numerical models of rod seals, a critical element in hydraulic systems preventing the leakage of hydraulic fluid into the environment. Our most recent models take account of starvation, showing that it leads to significantly higher friction forces.

iv. University education

Fluid Power Fundamentals MOOC Offered Through Coursera

For the first time in the fall of 2014, “Fundamentals of Fluid Power” was offered as a Massive Online Open Course (MOOC). The course attracted 8,399 students from 149 countries. The target audience for the course is entry-level engineers, senior-level undergraduate students, and entry-level graduate students.

Parker Hannifin Chainless Challenge

The Parker Hannifin Chainless Challenge is a design competition for undergraduate college students to design and build a human powered vehicle where the chain is replaced by a hydraulic transmission. 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.

v. Pre-college education

CCEFP Hosts Four NFPA Fluid Power Challenges -- An Engineering Design Competition for 8th Graders

Over 375 8^{th} 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.

vi. General Outreach

Inaugural Fluid Power Innovation and Research Conference (FPIRC)-- A Legacy of the CCEFP

The CCEFP hosted its first annual FPIRC event at Vanderbilt University, October 2014. 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 Chicago, IL in October 2015 and Minneapolis, MN in October 16. Both events are co-located with other academic conferences for increased visibility within the research community.

CCEFP Wins Runner-Up 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.

Additive Manufacturing Excavator Demonstration at IFPE 2017

The CCEFP Industry Engagement Committee (IEC) is leading a collaborative effort with Oak Ridge National Lab’s (ORNL) Manufacturing Demonstration Facility to produce a 3D printed excavator. The excavator will be prominently displayed at the upcoming 2017 CONEXPO-CON/AGG IFPE show in Las Vegas, the largest trade show in North America. The goal of the display is to demonstrate the disruptive impact of 3D manufacturing on how fluid power components and systems are made and to illustrate the role that the CCEFP has played in advancing fluid power research in America.

vii. Diversity Advancements in the Center

NSF Adopts CCEFP's Innovative Approach to Recruitment of Underrepresented Students in Engineering through the National GEM Consortium

The GEM-ERC Fellows Program overcomes barriers to ERC student recruitment of underrepresented students in engineering. 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.

viii. Innovation achievements

Commercialization of an Adjustable Linkage Pump

A novel variable displacement pump was invented, driven by an adjustable linkage. 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.

Novel Energy Recovery Architecture for Use in Hydraulic Elevators

We have conceived a novel hydraulic system that requires minimal electromechanical energy conversion and entirely bypasses throttling to create a more efficient and cost-effective hydraulic elevator. A patent is pending.

ix. New international partnerships/collaborations formed.

None.

High-Level Response and Status to SWOT Findings of Previous Year Site Report

SVT: Not clear how the educational programs will be assessed.

<u>CCEFP Response</u>: The assessment framework outlined QED's annual report will provide valuable insights that address program outcomes that have been deemed important by leaders at NSF, CCEFP, and NFPA. The overarching goal of the QED evaluation is to provide coherence and accountability across E&O programs, projects, and activities, and this is being achieved. Working with CCEFP and NFPA leaders, QED's evaluation research into the pathways by which CCEFP-affiliated community college, undergraduate, and graduate students find their way into fluid power study, jobs, and careers, will convert a theoretical workforce developed via CCEFP programs and courses into an actual applicant pool of potential fluid power employees. This work has substantial implications for sustainability of CCEFP and E&O specifically after ERC graduation.

SVT: Lack of commitment to the test bed projects.

<u>CCEFP Response</u>: CCEFP is fully committed to the ERC systems engineering approach to research planning for all projects and test beds. Hardware demonstrations of concepts provide valuable experiences that our industry members seek in new employees, and we will continue to seek industry help with hardware demonstrations as much as is practical. When is completely supported by non-NSF funds, test beds will be funded as part of the overall research portfolio through a competitive proposal process.

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

<u>CCEFP Response</u>: This comment is a holdover from last year's site visit report making it clear that we have failed to communicate the potential impact of TB4. Our test beds include current applications of on-road and off-road vehicles and machines (TB1 and TB3) and future human-scale applications (TB4 and TB6). TB1 and TB3 are mature applications where the requirements are fairly well defined. TB4 and TB6 are future applications where the requirements are much less well defined. The market potential for TB4 and TB6 could be many billions of dollars annually, but it is much more in the future.

To address the challenge of patient handling, a well-defined process of identifying needs and created system design specifications has been undertaken. Some of the challenges in systems engineering for this application are the need for fluid power components that are smaller, quieter and more environmentally benign than any currently available. The complex requirements of patient and caregiver interaction with the device create design and controls challenges. The control must be responsive, intuitive and safe. Passivity-based controls and small-scale transformers are being demonstrated on the patient handling test bed. These cutting edge design and control approaches have the potential of creating a system that is compact, efficient and intuitive to use.

SVT: It is not clear how students will learn hardware integration with decreased emphasis on test beds after graduation.

<u>CCEFP Response</u>: CCEFP intends to continue with hardware integration within the allowable constraints of available resources.

SVT: It is not clear that the sustainability strategy has been broadly discussed among Center participants.

<u>CCEFP Response</u>: For the last two years, CCEFP and NFPA have been engaged in negotiations that have gradually evolved from being contentious to being cooperative. Many open-ended issues have been addressed in closed-door discussions. The CCEFP staff and CCEFP Management Committee have been closely involved in this process, but the details have not been widely communicated, as is appropriate at the sensitive stage of negotiation. Students, faculty and staff are aware of the general

outlines of the sustainability strategy through CCEFP wide presentations by the Director and will become aware of the details of the strategy as these details become finalized.

SVT: The NFPA is a single point of failure.

<u>*CCEFP Response*</u>: A more relevant question is: How robust is the sustainability strategy? We have carefully considered all options and have come to believe that the collaborative model with NFPA has the highest probability of success. Collaboration between universities and industry is challenging because of cultural differences, but as the collaboration and trust between CCEFP and NFPA improves, we have become increasingly confident of the superiority of the collaborative approach.

SVT: Potential for diverging priorities among researchers and universities.

<u>*CCEFP Response*</u>: This is an ongoing challenge that we expect to be little different under our non-NSF funded model. The key is to have an overall strategy with sufficient funding for pre-competitive research to support the strategy. We expect to have strong leadership in the CCEFP to set the high-level research strategy. A pooled industry fund of $2 million with small university indirect charges can fund somewhere between ten and twenty projects to support this strategy. Additional support from multi-institution large government grants and associated projects will add to the impact.

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

<u>*CCEFP Response*</u>: *T*he site visit team is correct in identifying insufficient industry funding as a threat, but recent experience has been encouraging. In phase I, fifty companies with a commitment of more $800,000 annually have joined the Pascal Society. In phase II, a much broader campaign will recruit additional members. The incremental funding model predicts that Pascal Society funding will increase by $200,000 a year so that the $2 million goal will be reached in six years.

SVT: Technologies that are competitive with fluid power may prevail if fluid power advances do not come to market in a timely fashion.

<u>*CCEFP Response*</u>: Electro-mechanical actuation continues to compete with hydraulic and pneumatic solutions. One notable example is hybrid vehicles. Government research support has almost exclusively gone to electric hybrids with hydraulic hybrids being neglected in spite of the potential especially for larger vehicles. The DOE has invested billions of dollars in new battery technology while investing almost nothing in fluid power.

To correct this imbalance, leadership from CCEFP and NFPA has actively networked with appropriate parts of DOE. Results include an energy study that validates the potential of large energy savings in existing markets and initiating of an active discussion between the fluid power community and the Energy Efficiency and Renewable Energy (EERE) office of DOE on future research activities. ITECS, a government research consulting firm has been engaged by CCEFP to help identify and pursue other opportunities. Efforts to receive large multi-university government grants for CCEFP are being spearheaded by the Government Relations Committee that was formed in early 2014.

The timely commercialization of CCEFP research results is another area of focus. In early 2014 an Industrial Relations Committee was formed whose primary mission was to develop a structured process for commercialization of Center research findings. This committee's mission has been expanded to include growing industry sponsored research within the Center to further enable commercialization. Efforts to commercialize research results through CCEFP member companies are being augmented in parallel by renewed focus on start-up activities. Many start-up opportunities are available at our member universities. For example, the University of Minnesota was recently awarded an I-Corps site as was the University of Illinois at Urbana-Champaign. Georgia Tech was previously chosen as one of three designated NSF I-Corps nodes in the country. Two CCEFP projects were awarded MNDRIVE grant awards this year. Many other such examples exist throughout the Center.

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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 Director	Jim Van De Ven	Mechanical Engineering	University of Minnesota
Education Outreach Director	Alyssa Burger	ERC Staff	University of Minnesota
Sustainability Director	Brad Bohlmann	ERC Staff	University of Minnesota
Administrative Director	Lisa Wissbaum	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
Andrew Schenk	SLC President	Agricult. / Biological Eng.	Purdue 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
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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
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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
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Navneet Gulati	Senior Manager - Electro-Hydraulic Controls	CNH
Gary Kassen	Engineering Director - Hydraulic Competency Center	CNH
Bill Durr	Engineering Manager	Caterpillar Inc.
Aleksandar Egelja	Engineering Manager	Caterpillar Inc.
Eric Bretey	Manager, Advanced Systems Engineering	Danfoss
Marcus Royal	Engineering Manager	Deltrol Fluid Products
Marty Barris	Director, Hydraulic Products	Donaldson Company
Gunter Matt	Design Engineer	Doosan
Tom Sagaser	Vice President of Hydraulics Functions	Doosan
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
Rick Hill	Project Development Engineer	Gates Corp.
Jeff Lemonds	Director of Corporate Business Development	HYDAC Technology Corp.
Gordon Shellhaas	Executive Vice President	Hydraquip Distribution
Scott Lane	Engineering Manager	Linde Hydraulics Corp.
Shubhamita Basu	Technology Manager, Industrial	Lubrizol
Cornel Cristea	Director, Engineering Operations	MICO Inc.
Dan Foster	Director of Engineering	Moog Inc.
Eric Lanke	Executive Director	National Fluid Power Assoc.
Paul Gangopadhyay	Vice President, Business Development	Netshape Technologies, Inc.
Paul Paluszewski	Director Product Development - Machinery & Equipment	Pall Corporation
Ray Collett	Manager, Innovation & Technology	Parker Hannifin Corp.
Markus Rauchhaus	Managing Director	Poclain Hydraulics
Paul Spotts	Sales and Marketing Manager	Quality Control Corp. - QCC
Sam Lowry	President	Simerics Inc.
Larry Castleman	Technical Director of Product Development	Trelleborg Sealing Solutions

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1. SYSTEM VISION AND VALUE ADDED 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.

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. By definition, an entity's vision is *a compelling, but realistic future state*. 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, we have decided to change the vision statement 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 completes its ninth 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.

As is the case with CCEFP's vision, the Center's strategy has continued to evolve and mature. Through 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 industry we gain an ever-improving understanding of the critical needs in fluid power. The relevance of the Center's strategy and research agenda is validated by the strong industry support it enjoys and by the adoption of similar ideas in the international fluid power research community.

The CCEFP has made sustainability its top priority. We envision revenues coming from three major sources: pooled industry funds from the NFPA Foundation, associated projects from both industry and government sources and large, multi-university grants from federal agencies. The NFPA Foundation support model is described in section 5.3. Government Relations and Industry Relations committees have been active focusing on the other major elements of the Center sustainability plan. The progress of these committees is also described in section 5.3.

1.1 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". In order 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 in order 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 CCEFP strategic planning process has identified the following transformational goals necessary to realize our vision:

1. Doubling fluid power system efficiency in current applications and in new transportation applications.
2. Increasing fluid power energy storage density by an order of magnitude.
3. Developing new miniature fluid power components and systems including power supplies that are one to two orders of magnitude smaller than anything currently available.
4. Making fluid power ubiquitous meaning able to be used in any environment. This requires fluid power that is clean, quiet, safe and easy to use.

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 three are transformational.

Table 1-1: Fluid Power Technical Barriers

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	

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. Three of the Center's four test beds focus on mobile hydraulics and the fourth, the ankle-foot orthosis, has researchers working on both hydraulic and pneumatic solutions.

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 are carefully selected and representative members of the following six families.

1. Large Stationary Equipment (500 kW and greater): Wind Power Generator (Test Bed Alpha)
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 Beta)

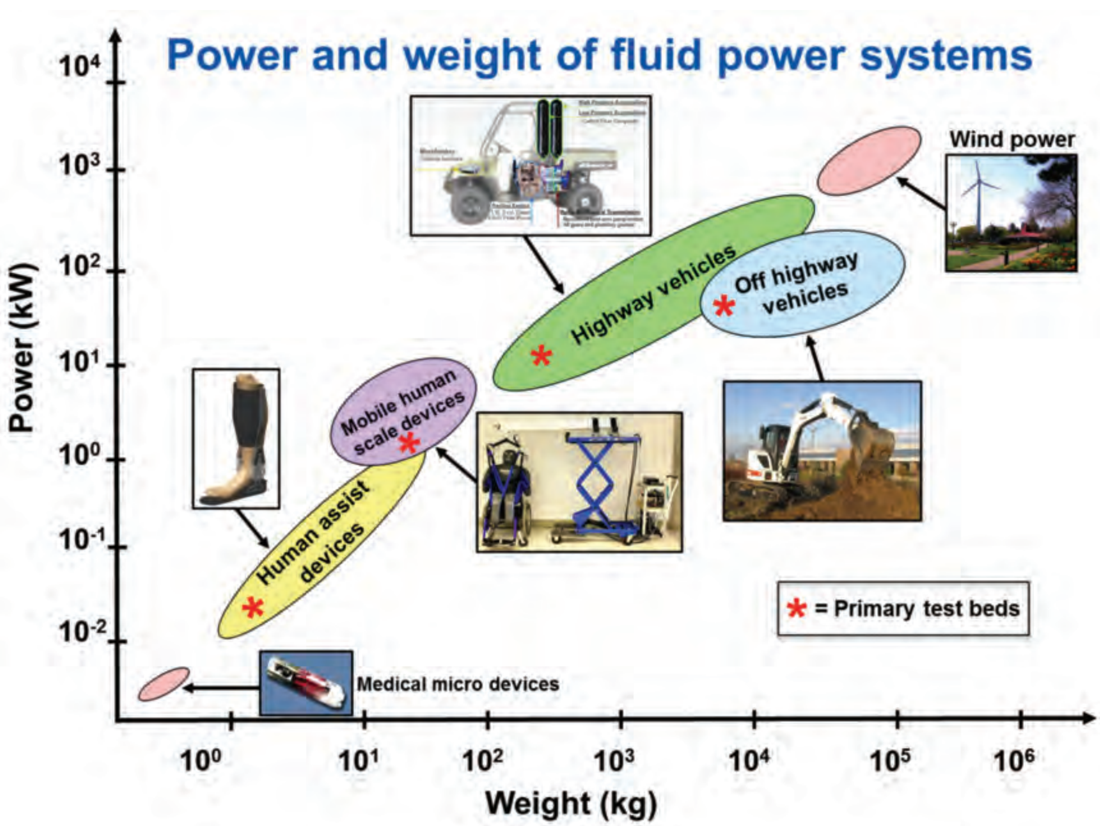

Figure 1-1: Range of CCEFP Test Beds

Fluid Power Is Transformational

CCEFP is performing transformational research that can 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[1] 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. One important emerging market is transportation. Using fluid power more widely in transportation through the development of hydraulic hybrid vehicles will save an additional $50 billion per year in energy.

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. Using the technology more widely in transportation through the development of hydraulic hybrid personal use vehicles could save an additional $50 billion per year in energy and eliminates millions of tons of exhaust emissions. In 2013, Peugeot announced its intent to commercialize the first hydraulic hybrid passenger car. This is very exciting news as it will be the first implementation of hydraulic hybrid technology in personal use vehicles. Peugeot is working with CCEFP member Bosch Rexroth to develop the hybrid hydromechanical (hybrid HMT) system. The first hybrid HMT commercialized was by Parker Hannifin, another CCEFP member, who developed the system in collaboration with CCEFP researchers at Purdue University.

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.

Doubling the efficiency in current off-road applications has been demonstrated on the Caterpillar hydraulic hybrid excavator, a 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 40% since 2007 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 Alpha is a hydrostatic wind turbine and Test Bed Beta is precision pneumatics for MRI guided surgery. This extends the range of power and weight to both larger and smaller sizes. The beta test bed is particularly well suited for demonstrating fluid power ubiquity due to the challenging requirements of a hospital environment.

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[1] 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).

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, Test Bed α, 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. This new test bed 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, equipment takes highly varied forms. 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. Excluded applications 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 nearly 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 solves the energy storage problem for the hydraulic hybrid vehicle indirectly. 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 and is now being funded with CCEFP matching funds from the University of Minnesota.

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 major 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 more 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 instantaneous on-off capability, meaning it has no need to idle. The design is modular, so several engines 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 need for energy storage.

The evolution of test beds is an ongoing challenge that has been carefully guided by the Center. The test beds supported by core funding were reduced from six to four by the Center's third year. Through roadmapping of the industry's major challenges we found that the stationary manufacturing machine and portable power tool test beds were not well-aligned with industry's needs. In year 6, we added two research projects which by their nature are test beds. Test bed α, large stationary equipment, is focused on bringing the benefits of fluid power to wind energy. The researchers working on test bed β, micro-medical devices, have built a functional MRI-compatible surgical tool. In addition to the new test beds, test bed 4 was redirected from a rescue robot to a patient transfer device (PTD). This change has several advantages at a strategic level. It is a better match to our industry's interest, is contributing to developing critical mass in medical systems, and has enabled collaboration with another ERC. The core funded test beds have been augmented by associated test beds with other funding. CCEFP's test beds have evolved and have been augmented over the life of the Center. We believe they will position the Center for a sustainable future.

Response to the Site Visit Team SWOT Report

SVT: Not clear how the educational programs will be assessed.

CCEFP Response: Quality Evaluation Designs (QED) acknowledges the site visit team's concerns. In response, QED sent Dr. Jenifer Helms, our lead consultant on the project, to Minneapolis in early June to meet with Alyssa Burger (E&O Director) and Dr. Jim Van de Ven (CCEFP Education Director) to discuss the evaluation design and implementation of this year's evaluation activities. The assessment framework outlined QED's annual report will provide valuable insights that address program outcomes that have been deemed important by leaders at NSF, CCEFP, and NFPA. Early implementation of surveys will ensure sufficient student-level data are collected to document and assess these important outcomes.

The overarching goal of the QED evaluation is to provide coherence and accountability across E&O programs, projects, and activities, and this is being achieved. Working with CCEFP and NFPA leaders, QED's evaluation research into the pathways by which CCEFP-affiliated community college, undergraduate, and graduate students find their way into fluid power study, jobs, and careers, will convert a theoretical workforce developed via CCEFP programs and courses into an actual applicant pool of potential fluid power employees. This work has substantial implications for sustainability of CCEFP and E&O specifically after ERC graduation.

QED is committed to the evaluation goals and design we have contracted with CCEFP to execute. We take seriously the site visit team's strong recommendation for greater interaction with CCEFP. We have already had one face-to-face meeting with E&O leaders. Another scheduled in mid-June between QED, E&O and NFPA leaders was postponed due to a family emergency, but that will be rescheduled in the next two weeks. QED assures the site visit team that the evaluation will be executed conscientiously, resulting in substantive formative and summative data in 2014-15.

A miscommunication during the site visit presentation is worth noting. QED defines "student" broadly to include the anticipated survey participants of all E&O programs and activities. CCEFP has sufficient and accurate data of its "own" students, meaning, those engaged in CCEFP research and educational programming. CCEFP does not currently collect data on students impacted by new and/or course modules and curriculum based on CCEFP work. CCEFP reports the number of students impacted by courses and curriculum, but does not, and in most cases, cannot collect data on the actual students enrolled in courses. QED and the E&O team have identified undergraduate and graduate students taking courses as an opportunity in assessing CCEFP educational impact. Work in Y9 includes capturing data from students in courses influenced by CCEFP work. This work will contribute to the fluid power pathways study, previously mentioned.

SVT: Lack of commitment to the test bed projects.

CCEFP Response: CCEFP is fully committed to the ERC strategic systems engineering approach to research planning for all projects and test beds. Hardware demonstrations of concepts provide valuable experiences that our industry members seek in new employees, and we will continue to seek industry help with hardware demonstrations as much as is practical. Additionally, CCEFP will implement a two-pronged approach to improvement. In the next two years, we will provide research supplements to demonstrate research results from projects on test beds. These will be allocated in a competitive process in response to a call for proposals. After that, when we are completely supported by non-NSF funds, test beds will be funded as part of the overall research portfolio. In contrast to the current practice, funding for these test beds will be determined through a competitive proposal process.

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

CCEFP Response: This comment is a holdover from last year's site visit report making it clear that we have failed to communicate the potential impact of TB4. Our test beds include current applications of on-road and off-road vehicles and machines (TB1 and TB3) and future human-scale applications (TB4 and

TB6). TB1 and TB3 are mature applications where the requirements are fairly well defined. TB4 and TB6 are future applications where the requirements are much less well defined. The market potential for TB4 and TB6 could be many billions of dollars annually, but it is much more in the future.

To address the challenge of patient handling, a well-defined process of identifying needs and created system design specifications has been undertaken. Some of the challenges in systems engineering for this application are the need for fluid power components that are smaller, quieter and more environmentally benign than any currently available. The complex requirements of patient and caregiver interaction with the device create design and controls challenges. The control must be responsive, intuitive and safe. Passivity based controls and small-scale transformers are being demonstrated on the patient handling test bed. These cutting edge design and control approaches have the potential of creating a system that is compact, efficient and intuitive to use.

SVT: Not clear how students will learn hardware integration with decreased emphasis on test beds after graduation.

CCEFP Response: CCEFP intends to continue with hardware integration within the allowable constraints of available resources.

SVT: It is not clear that the sustainability strategy has been broadly discussed among Center participants.

CCEFP Response: For the last two years, CCEFP and NFPA have been engaged in negotiations that have gradually evolved from being contentious to being cooperative. Many open-ended issues have been addressed in closed-door discussions. The CCEFP staff and CCEFP Management Committee have been closely involved in this process, but the details have not been widely communicated, as is appropriate at the sensitive stage of negotiation. Students, faculty and staff are aware of the general outlines of the sustainability strategy through CCEFP wide presentations by the Director and will become aware of the details of the strategy as these details become finalized.

SVT: The NFPA is a single point of failure.

CCEFP Response: A more relevant question is: How robust is the sustainability strategy? We have carefully considered all options and have come to believe that the collaborative model with NFPA has the highest probability of success. Collaboration between universities and industry is challenging because of cultural differences, but as the collaboration and trust between CCEFP and NFPA improves, we have become increasingly confident of the superiority of the collaborative approach.

SVT: Potential for diverging priorities among researchers and universities.

CCEFP Response: This is an ongoing challenge that we expect to be little different under our non-NSF funded model. The key is to have an overall strategy with sufficient funding for pre-competitive research to support the strategy. We expect to have strong leadership in the CCEFP to set the high-level research strategy. A pooled industry fund of $2 million with small university indirect charges can fund somewhere between ten and twenty projects to support this strategy. Additional support from multi-institution large government grants and associated projects will add to the impact.

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

CCEFP Response: The site visit team is correct in identifying insufficient industry funding as a threat, but recent experience has been encouraging. Sixty-two companies have been invited to join the Pascal Society since mid-April. To date, thirty companies have accepted the invitation, four have declined, and twenty-eight are undecided. The total commitments of these thirty companies exceed $500,000 per year. We anticipate that at least fifty of the invited companies will accept the Pascal invitation with an annual commitment of around $800,000. The incremental funding model predicts that this funding will increase by $200,000 a year so that the $2 million goal will be reached in six years.

SVT: Technologies that are competitive with fluid power may prevail if fluid power advances do not come to market in a timely fashion.

CCEFP Response: Electro-mechanical actuation continues to compete and in some markets displace hydraulic and pneumatic solutions. One notable example is hybrid vehicles. Government research support has almost exclusively gone to electric hybrids with hydraulic hybrids being neglected in spite of the promise especially for larger vehicles. The DOE has invested billions of dollars in new battery technology while investing almost nothing in fluid power.

To correct this imbalance, leadership from CCEFP and NFPA has actively networked with appropriate parts of DOE. Results include an energy study that validates the potential of large energy savings in existing markets and initiating of an active discussion between the fluid power community and the Energy Efficiency and Renewable Energy (EERE) office of DOE on future research activities. ITECS, a government research consulting firm has been engaged by CCEFP to help identify and pursue other opportunities. Efforts to receive large multi-university government grants for CCEFP are being spearheaded by the Government Relations Committee that was formed in early 2014.

The timely commercialization of CCEFP research results is another area of focus. In early 2014 an Industrial Relations Committee was formed whose primary mission was to develop a structured process for commercialization of Center research findings. This process is now being implemented. This committee's mission has been expanded to include growing industry sponsored research within the Center to further enable commercialization. Efforts to commercialize research results through CCEFP member companies are being augmented in parallel by renewed focus on start-up activities. Many opportunities for leverage existing programs are available at our member universities. For example, the University of Minnesota was recently awarded an I-Corps site as was the University of Illinois at Urbana-Champaign. Georgia Tech was previously chosen as one of three designated NSF I-Corps nodes in the country. Two CCEFP projects were awarded MNDRIVE grant awards this year. Many other such examples exist throughout the Center.

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1.2 VALUE ADDED AND BROADER IMPACTS

Research

The four 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.

<u>Test Bed 1</u>

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).

Considerable progress has been demonstrated in the Test Bed 1 in the last year. Since the introduction of secondary-controlled drives, many advances in the control of the actuator position, velocity and torque have been developed. However, every approach to date assumes a constant pressure at the working port of the secondary unit. A robust controller which achieves maximum actuator performance (good tracking of the cab velocity) while minimizing losses by actively controlling the secondary unit working pressure was developed, implemented and tested on Test Bed 1. It was demonstrated that pressure tracking improved greatly over a range of inertia loads and commanded speeds. Using the developments from project 1A.2, the concept of pump switching was realized in Test Bed 1. Pump switching has the potential to minimize the number of pumps in a DC hydraulic system. Measurements of pump switching for the excavator boom actuator under a large load to show the ability of the control algorithms to prevent undesired actuator transients. One of the often overlooked challenges of fluid power systems is that in most cases hydraulic drives are extremely powerful relative to their primary movers. If not addressed properly, this condition can degrade performance, controllability, efficiency and even lead to complete system shutdown. To prevent engine overloading and its undesired effects, several hydraulic and electro-hydraulic anti-stall system have been proposed and commercialized. The main challenge for DC actuation is the one pump per actuator requirement. This condition complicates the conception and implementation of an anti-stall apparatus. For this reason, an electronic anti-stall control for DC actuation was proposed. To show the validity of the controller approach, the strategy was implemented and tested in Test Bed 1. An aggressive cycle was used to show the controller working at extreme operating conditions and the resulting engine speed error is relatively small.

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 order to focus resources, the CCEFP has concentrated its effort on the Gen 1 vehicle with the Gen 2 vehicle becoming an industry led test bed on which the CCEFP provided control support. Progress on the Gen 1 vehicle includes a new clutch design. The old clutch was only able to transmit torque in one direction and instances of reverse torque transmission, though infrequent and brief, would damage the clutch. A new hydraulic clutch, with two way torque transmission capability, was purchased and installed. The new clutch system now enables us to simulate complete drive cycles. In addition, the vehicles sensors were upgraded. A wireless torque sensor was installed on the transmission input shaft to directly measure engine torque. At the suggestion of one of our industry mentors, pressure and temperature sensors were installed at the inlet and outlet ports of the two hydraulic pump motors to improve the assessment of their efficiency, particularly while experimenting with alternative hydraulic fluids. Also, improvements were made to the dynamometer controller that increased its bandwidth from 6 rad/s to about 15 rad/s. Additionally, a new energy management strategy was implemented. The top level of the three level vehicle controller was programmed to implement a rule based energy management algorithm developed in related Project 1A.1. The vehicle was tested on the dynamometer using the urban and highway drive cycles. This is the first time that test bed 1 was tested in hybrid mode using an urban drive cycle. Unfortunately, the results showed little improvement in fuel economy over CVT mode. The likely reason is that the algorithm used was not designed to fit the Generation I vehicle. Improvement is expected for future hybrid algorithms such as Mild Hybrid and Lagrange multiplier.

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.

Substantial work was done in the past year on systems integration and hardware improvements. Two additional degrees of freedom were added, the differential drive wheels. The cart is fully functional and ready for testing of more advanced control architectures, such as obstacle avoidance. Additional updates have also been made to the overall electrical system, including addition of a breakout board and electrical box to handle all sensing, including pressures on each side of each actuator, motor currents, actuator positions, operator input forces, and other system forces. Also, a model was created to simulate the mechanical dynamics of the main lifting scissor mechanism, boom extension, and actuation mechanisms, as well as a variable patient payload. A gray box model based on system identification by spectral analysis, roughly based on the form of a first principles based model, has been developed for the actuation systems, with input reference motor current and output actuator motion. In addition, research on the control and operator interface was undertaken. In order to allow for this powerful machine to operate safely in a relatively delicate environment with humans in the workspace, and to reduce the caretaker mental workload, it is desirable to manage any undesirable interaction forces. For the main lifting and boom extension, some interaction with the caretaker and patient is necessary. Therefore, it is desirable to develop controllers which manage both force and motion. A substantial literature study has been performed on various types of interaction controllers, particularly those that are well-suited for hydraulic actuation. Several forms of interaction control will be tested on the boom extension.

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: CCEFP researchers began a collaboration with researchers at the Rehabilitation Institute of Chicago to begin testing the Gen 2.0 PPAFO compared to tibial stimulators and passive AFOs in post-stroke and multiple sclerosis (MS) subjects. By the end of reporting period a 20-person study on MS participants was near completion. Results suggest that walking with the PPAFO reduces stride length and velocity, but improves joint kinematics perhaps leading to less stress on compensating joints for ankle impairment. In an associated project with the Movement Disorders Center at the University of Minnesota, we are investigating the use of the PPAFO as a gait initiation device for people with Parkinson's disease (PD). A pilot study on healthy young adults provided insight into the feasibility of this application and an on-going study with people with PD began in 2013 and continued in the reporting period. Preliminary results suggest that modest mechanical assistance at the ankle could enhance diminished or absent force production and lateral weight shift while preparing for the start of a step in people with PD and symptoms of freezing of gait.

Hydraulic AFO: The research objective for the HAFO test bed is to understand the limits of small-scale hydraulics in the 10-100W range. The motivation is the need for small, untethered wearable robots. The rationale for using hydraulics is that the higher pressures that can be attained with hydraulics enables high-torque exoskeletons. From an analysis of small-scale system, we determined that the hydraulic pressure must be over 500 psi for high power-to-weight and chose 2,000 psi as the nominal pressure for the HAFO. The key design requirements driving the test bed HAFO are:

(1) 90 Nm torque

(2) 70 deg range of motion

(3) 100 deg/sec angular velocity

(4) Fits under the wearer's pants

(5) Less than 1 kg mass at the ankle

(6) 3,000 steps between recharge

(7) No tether

The configuration of the current HAFO test bed is: Battery → DC Motor → Pump → Hose → Cylinder. In the reporting period, we completed the design and assembly of a wearable HAFO and met all of the key design requirements except requirement 6 which is yet to be tested.

Education Outcomes

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

The objective 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 the goal: (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, (3) Provide advanced students with the opportunity to learn cutting edge curricular material based on the latest CCEFP research. Important activities in the university education include the REU program, the Fluid Power Scholars program, the SLC Travel and Grants program, capstone design projects and integration of fluid power into the core curriculum of mechanical engineering and related disciplines.

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. These outcomes are also served by the CCEFP outreach programs that are STEM-oriented but without a core fluid power focus. The Center believes that increasing interests in STEM fields among young students is an important first step in increasing the number of students later pursuing engineering studies, some of them in fluid power. Important activities in the pre-college outreach program include the Fluid Power Challenge, the gidaa robotics program and the RET program.

Industry is an essential component of the CCEFP. Over 50 fluid power manufacturers and distributors are CCEFP supporters through the NFPA Pascal Society. They have stated many times that the education outcomes (i.e. intellectual capital) of the Center are as important to them as the research outcomes. These Center partners share in a common goal - to foster deep understandings of fluid power technology and its applications among its students. To that end, the Center is striving to provide students with specialized, research-driven education while striving to implement ways to connect students with industry.

The CCEFP is responsible for providing its students with opportunities to network with industry representatives through a variety of channels. In doing so, there are multiple benefits: all students will better understand the fluid power industry's needs and its markets; interested students will be able to find internships and later job opportunities upon graduating; and companies will be able to meet, interact, and discuss potential employment opportunities with students. Channels utilized in this project include company tours, poster sessions, and resume exchanges as well as additional opportunities that extend the Center's outreach to more students and companies. This program leverages the existing events and activities of the CCEFP and engages students in the fluid power industry, often offering them opportunities to stay in this industry so they can have an impact in fluid power research and applications. Important CCEFP programs that foster industrial engagement include capstone design course projects, the Fluid Power Scholars program, the CCEFP webcast series, and CCEFP student retreats hosted by industry, IEC Summits, CCEFP Fluid Power Innovation & Research Conference (FPIRC) and the recently initiated CCEFP-Industry GEM Fellowship program.

Highlights of the Y9 CCEFP Education and Outreach Program include:

- CCEFP hosts a variety of networking opportunities between industry and students at events like FPIRC and IEC Summits.
- The Fluid Power Scholars program continues to be a success by educating undergraduate interns before they enter the fluid power industry. This program is changing and expanding.
- CCEFP received funding from NFPA to host two additional Fluid Power Challenge events, meanwhile, UMN and MSOE regularly offer the program.
- The first fluid power Massive Open Online Course (MOOC), was offered Fall 2014, through Coursera, approved by the University of Minnesota.
- CCEFP is granted an NSF REU Site Award for three years.
- Over 175 REU students have participated in CCEFP research.
- A thorough evaluation of E&O programs meeting six approved objectives have shown extremely positive results and data to help drive innovative workforce programming.
- Recent CCEFP longitudinal survey shows that: 45% of all former CCEFP students are working in fluid power in some way; 51% of all former CCEFP students are working in some industry; 13% of all former CCEFP students are employees of CCEFP fluid power industry member companies, 57% of all former CCEFP undergraduate researchers enter graduate school; and 25% of those are PhD candidates
- GEM-ERC-Industry Fellowship program has a bright future, support and buy-in from NSF leadership.

- Fluid Power Exhibits are now on permanent display at the Science Museum of Minnesota.

Industrial Collaboration and Tech Transfer Interactions

The CCEFP implemented a major change in its sustainability strategy in this reporting year. The key aspect of this change from an industry perspective was a switch from our existing industry membership agreement organizational format to an industry gifting structure called the Pascal Society. All changes were discussed extensively with NSF at last year's site visit. The successful implementation was made possible in large part by an even closer collaboration with the National Fluid Power Association (NFPA), an industry consortium alliance which represents much of the fluid power industry. While the NFPA has always been active in the CCEFP, during the past year they became committed to helping the Center achieve sustainability. As an outcome our two organizations have reached a formal agreement to collaborate much more closely in the areas of fund raising and sharing of administrative costs through synergistic leveraging of each organization's strengths. Greater detail of the new Pascal Society and the increased industry collaboration through NFPA will be described in sections 4 and 5.3.

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 implements its new sustainability strategy. However, because the CCEFP enjoys such broad industry representation, it can be challenging to achieve the necessary level of engagement to ensure each member's continued, long-term commitment. To improve this engagement we have initiated efforts that leverage the already well-established industry communications network and numerous media outlets of the NFPA. A mutually developed Engagement Strategy with the NFPA is currently underway. In addition to the obvious industry engagement avenues, this strategy will include programs that will engage all critical stakeholders of the Center (Industry, PIs, Students, general public, etc.).

With the introduction of the Pascal Society, the Industrial Advisory Board (IAB) has been 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 listed in Appendix III. 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 is a monthly IEC conference call 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 IEC meetings are held on site 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 are held during the evenings and are an excellent venue to get to know one another better. All 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. A recent improvement has been to include industry feedback via an electronic survey that is completed by attendees after each research project presentation.

With the CCEFP in its ninth year, some of our most successful pre-competitive research projects are at or approaching technology readiness level 4. At this level the research is ready for direct industry involvement and commercialization. The Center uses a number of ways to facilitate the translation of its research findings into industry. Chief among these is through industry sponsored research. At our last NSF Site Visit, there was a show of hands that indicated nearly every IAB member company has sponsored research during the Center's lifespan. Recently we established an Industry Relations Committee whose primary objective is to increase the level of industry sponsored research associated with the CCEFP. Another major translational activity is through industry sponsored internships and direct hiring of our students. Surveys of our industry members consistently point to highly trained students as the number one value they associated with the Center. Faculty consulting to industry has picked up over the life of the Center as well. In the past year we have placed our focus on securing joint government research between our industry members and Center faculty as well as supporting entrepreneurial startups. The PFI:AIR and I-Corps grant opportunities are particularly well suited for these activities.

A list of test beds and projects that we feel have commercial potential are listed below. We continue to work closely with our industry members to identify interested partners for collaboration to move these projects toward commercialization.

- Test Bed 1: High Efficiency Excavator
- Test Bed 6: Fluid Power Ankle-Foot Orthosis
- Project 1A.1: Technology Transfer Process for Energy Management Systems
- Project 1A.2: Multi Actuator Hydraulic Hybrid Machine Systems
- Project 1B.1: New Material Combinations/Surface Shapes for the Main Tribo-systems of Piston Machines
- Project 1E.4: Piston-by-Piston Control of Pumps and Motors using Mechanical Methods
- Project 1F.1: Variable Displacement Gear Machine
- Project 2B1: Free Piston Engine Compressor
- Project 2B.3: Free Piston Engine Hydraulic Pump
- Project 2C2: Advanced Strain Energy Accumulator
- Project 2F: MEMS Proportional Pneumatic Valve
- Project 2G: Fluid Powered Surgery and Rehabilitation via Compact, Integrated Systems
- Project 3B.1: Passive Noise Control in Fluid Power
- Project 3E.1: Pressure Ripple Energy Harvester
- Associated project: Open Accumulator Compressed Air Storage Concept for Wind Power
- Associated project: Non-contacting Magnetic Position Sensor
- Supplemental project: Variable Displacement, Adjustable Linkage Pump

Each year the Industrial Advisory Board refreshes their SWOT assessment of the Center. This continues to be a valuable communication tool for providing industry feedback to the CCEFP. Throughout the Center's history areas once deemed as "weaknesses" by industry have grown to become strengths. This transformation continues to occur with the IAB providing feedback not only on the urgency of sustainability planning but how to structure the plan so it will be well received by industry. A special session was dedicated to sustainability at the last Industry Annual Conference. The feedback from this session drove significant changes to our post NSF sustainability plan described briefly below and in in greater detail in Section 4. This willingness to change is indicative of an organization that listens to its customers. New areas for improvement will continue to take the place of previous ones as they are satisfactorily addressed.

The Center is aggressively pursuing long-term sustainability. Our plan calls for a balanced funding model from three key areas 1) industry fund raising in the form of a "gift" for pre-competitive research 2) additional large, multi-site government grants and 3) sponsored research. Of these, we feel that industry fund raising and government grants are where we must initially focus. These areas provide the pre-competitive research engine for the Center that will inevitably attract additional sponsored research. The Center has formed two committees - Industry Relations and Government Relations - to champion these initial efforts. The CCEFP is actively working with the NFPA to improve industry relations and fund raising. The approach we are pursuing involves sharing CCEFP administrative activities (and associated costs) with the NFPA where it makes sense. One obvious area is the ILO position. Education and Workforce Development is another. The NFPA already enjoys a well-established communications and event planning infrastructure that can assist the Center in future such activities. Most importantly, however, is the NFPA's offer to take over all industry fund raising activities for pre-competitive research. This activity will take the place of our current industry membership structure. This change in responsibilities will allow the Center to focus on its core strength of pursuing government funding. Of course there will be close cooperation and communication between both organizations efforts.

Industry surveys have indicated that the most important output of the CCEFP is its future workforce talent pool. We are always looking for opportunities to facilitate student exposure to industry. Some key activities include industry hosted student retreats, IAB/IEC summits at member universities, Fluid Power Scholar internships and, of course, the ever popular student-led biweekly research webinar updates.

Team and Diversity

Diversity statistics for ERC faculty and students are given in Table 7a. The largest representation in the table is for U.S. citizens and permanents residents being 82% of the respondents. For this group, the representation of women was near or exceeding the national averages in all groups. This is a significant in demonstrating the Center's ability to attract women, in a traditionally male-dominated field of mechanical engineering. Comparing CCEFP with national averages, 34% of doctoral students are female, absolutely remarkable in such a male-dominated field. 24% of non-REU undergraduates and 27% of REU students are women as compared to 19% nationally. 14% of Center faculty are women, while 22% of the Center's Leadership Team is female, both up from the previous reporting year. Underrepresented racial minorities are near or exceeding national averages, retaining the representation in this area. The percentage for underrepresented racial minorities was 10% for faculty compared to 3% nationally, 12% for doctoral students compared to 4.7% nationally, and 12% for non-REU students and 23% for REU students compared to 6.4% for undergraduates nationally. Hispanics/Latino/a are represented within the CCEFP, both domestically and internationally, however the data seems to diminish the personnel representation based on national averages. Hispanic/Latino persons represent 9% of our REU and 10% of undergraduate researchers, 4% of our graduate students and 7% of our faculty. These numbers are incremental improvements in the recruitment of ethnically diverse participants. Those who identify themselves as persons with disabilities is lower than national averages, and additional efforts will be needed to recruit members of these groups.

Quantifiable Outputs

Table 1, "Quantifiable Outputs", and Table 1a, "Average Metrics Benchmarked Against All Active ERCs and the Center's Tech Sector" give a snapshot comparison of CCEFP compared to other ERCs. They can be found in Appendix I. The most important metrics and comparisons are given below.

The number of publications in peer-reviewed technical journals decreased from 24 from 17. Additional efforts in this area are still needed, since the average for this figure is 37 among all active ERCs.

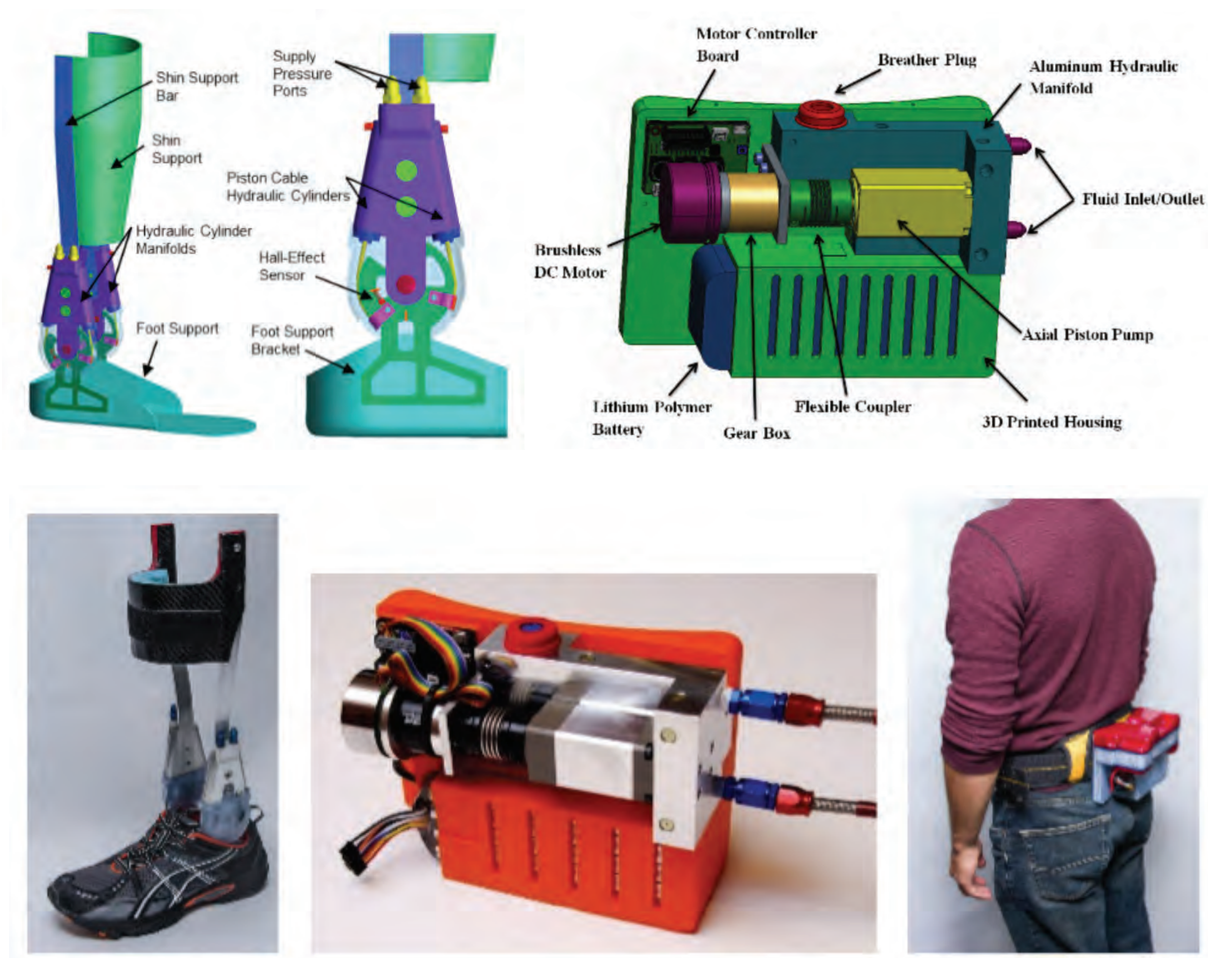
Doctoral degrees granted increased slightly from 11 to 12. Masters degrees granted increased from 7 to 12. The continued high number of doctoral students shows that they are completing their degrees in a timely manner. Education impact is noteworthy with 31 courses offered containing ERC content, compared to the average of 19 among all active ERCs. CCEFP's extensive K-12 education and outreach activities help the Center to exceed most norms in these categories.

1.3 HIGHLIGHTS OF SIGNIFICANT ACHIEVEMENT AND IMPACT

RESEARCH / TECHNOLOGY ADVANCEMENT HIGHLIGHTS

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 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 just 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 deg/s, weighs less than 1 kg at the ankle and fits under a pair of loose-fitting pants.

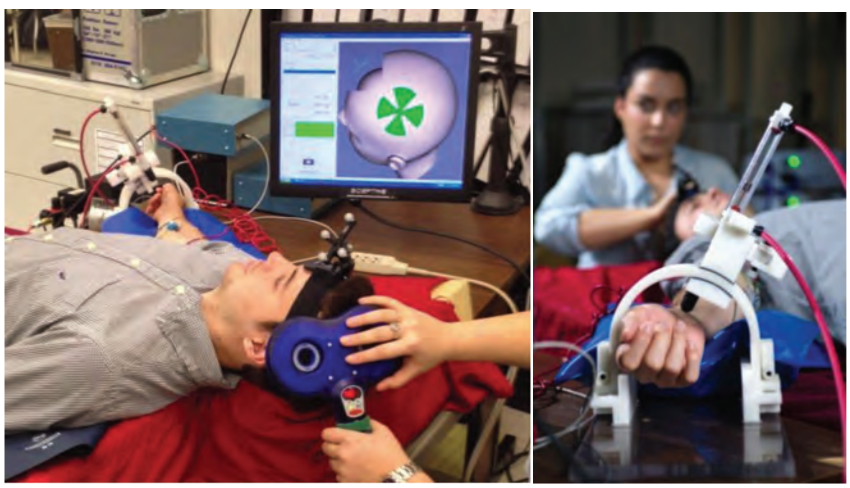


HAFO layout (top) and prototype (bottom)

Pneumatic Control of Voluntary and Involuntary Nerve Impulses for Hemiparesis Rehabilitation and fMRI Study

This project is designed to understand the neuromechanical mechanisms associated with repetitive facilitation exercise (RFE) for stroke survivors to gain functional recovery of their hemiparetic limbs. RFE, the facilitation technique of interest, was proposed by Dr.Kawahira as a new effective method for stroke patients. RFE consists of mechanical stimulation to dysfunctional muscle by a gentle tap at the muscle and this induces a stretch reflex response at the brain. This exercise is believed to facilitate the reorganization of neural pathways by overlapping the stretch reflex response with a voluntary motor command signal by the patient, which leads to muscle response. Although the outcomes of RFE treatment obtained so far are all promising, the hypothesized mechanism under RFE still needs more neurological data to verify. Functional magnetic resonance imaging (fMRI) technology can be used on the brain regions for clarifying the effects of RFE therapy and underlying mechanism

To achieve the goal of this project, the first prototype of RFE rehabilitation device that replicates the RFE procedure was built and tested with transcranial magnetic stimulation (TMS) that simulates 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 for later fMRI research. Mechanical stimulation given by the medical hammer evokes the stretch reflex response at the tendon interested. Subject received this mechanical stimulation and TMS with various time intervals between two in order to observe temporal dynamics of RFE. Human subject data shows that there is a time window, or certain range of time intervals between two signals that evokes muscle response. It shows potential that this response could be an element that contributes to regaining neural functionality by RFE.



Experimental Setup

Controlled Stirling Fluid Power Unit

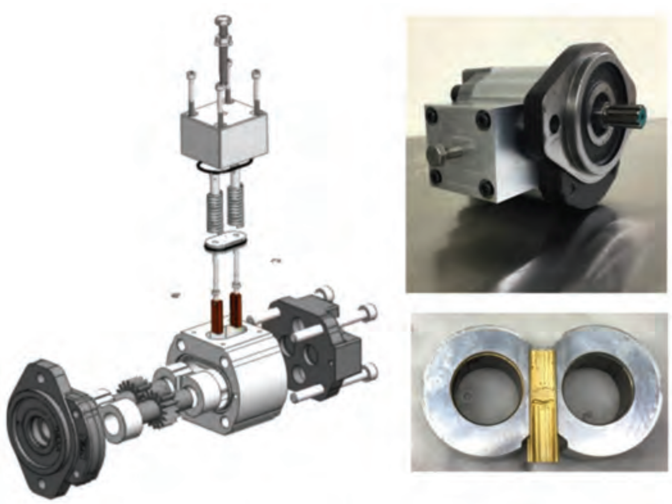
Controlled Stirling power unit prototype

Current sources of energy are extremely limiting for 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 the method of actuation 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 presents a potential solution to this problem by availing a highly energetic and efficient source of fluid power to such applications. This power unit is a Stirling engine that either pumps hydraulic fluid or compresses air, depending on the application. The power unit pictured below uses hydrocarbon fuel as its primary energy source and 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 and results 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 put the device on track to achieve a target hydraulic output pressure of 70 bar with power output ranging from 50-200 W. The target energy density is four times that of batteries and the target power density when coupled with highly power dense fluid power actuators 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.

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 at the Maha Fluid Power Research Center at Purdue. The figure below shows some details of the prototype realized by researchers under Dr. Vacca's supervision. The new machine encompasses the well-known advantages of traditional external gear machines such as low cost, compact units, good reliability and reasonable efficiency. Additionally, the proposed design allows for a 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 at Purdue, the prototype used for the experiments offers displacement variation in the range of 35%.

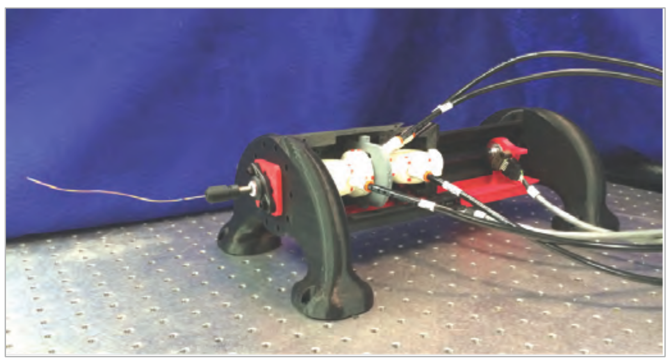
The proposal of this new concept for low cost variable displacement units has the potential to substitute current fixed displacement units in many applications such as charge pumps in hydrostatic transmissions, or hydraulic fan drives, with significant reduction of fuel consumption.



Exploded view of the proposed variable displacement external gear machine as well as the prototype produced as an outcome of project 1F.1

Two-Degree-of-Freedom, Magnetic-Resonance-Compatible Pneumatic Stepper Module

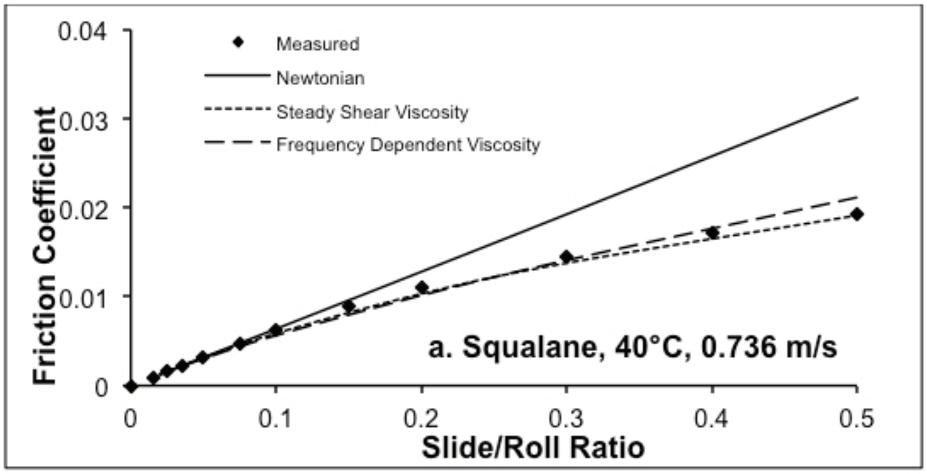
Fluid power actuators (hydraulic and pneumatic) are well suited for electromagnetically sensitive environments like magnetic resonance imaging (MRI) machines. Such actuators would enable intraoperative MRI guidance of robotically steerable needles. Yet, a technical barrier to using fluid power in MRI-guided surgical systems is the absence of commercial, off-the-shelf fluid power actuators that are sterilizable and intrinsically safe. Towards filling this technology gap, researchers at Vanderbilt University and Milwaukee School of Engineering have designed and built an additively manufactured pneumatic stepper actuator. Designed using corrugated diaphragm theory, one helix-shaped bellows and one toroid-shaped bellows provide pure rotation and pure translation, respectively. The entire 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 of these modules can be cascaded together as a complete actuation unit for steerable needles comprising 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 by laser sintering of nylon powder, the prototype device is compact and hermetically sealed for sterilizability. The linear bellows produced peak forces of 7.4 lbf and -6.0 lbf for needle insertion and retraction, respectively. The rotary bellows produced peak torques of ±0.60 lbf-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.



Photograph of prototype with helix-shaped concentric tube needle. One half of the device housing is not shown, to expose inner working parts.

The first confirmation of the equivalence of frequency and shear-rate in shear-thinning of lubricating oils

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.



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 in order to determine the texture profile dependence on the friction reduction. Figure 1 shows the experimental set up and the surfaces tested.

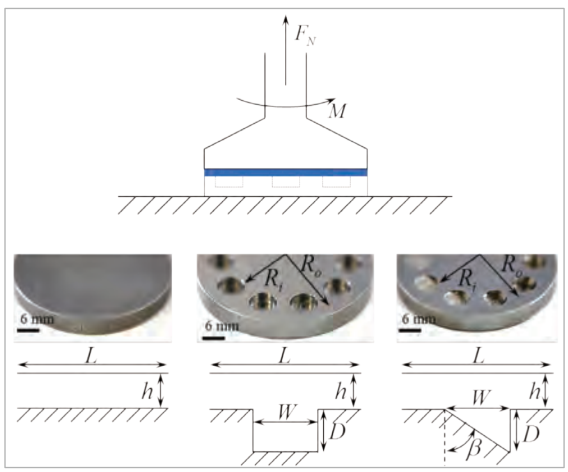


Figure 1: Experimental setup showing the three types of textures tested. FN is the measured normal force, and M is the measured torque. The top plate rotates in both directions in order to determine direction of relative motion effects.

The measured normal forces, after corrections for inertia and surface tension, are given in Figure 2. 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. Figure 2 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.

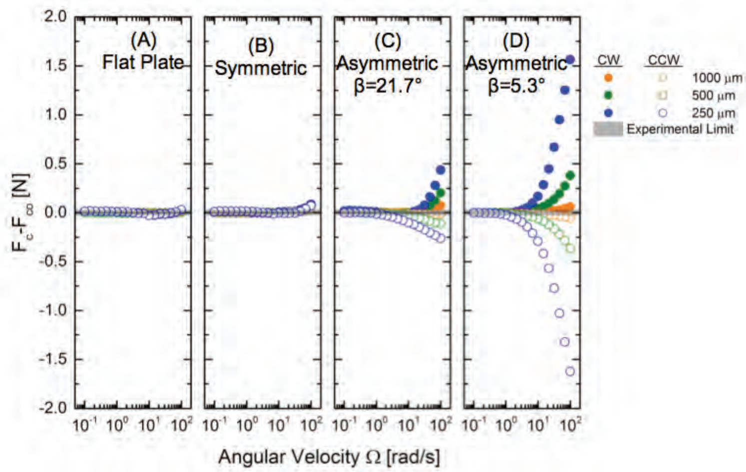
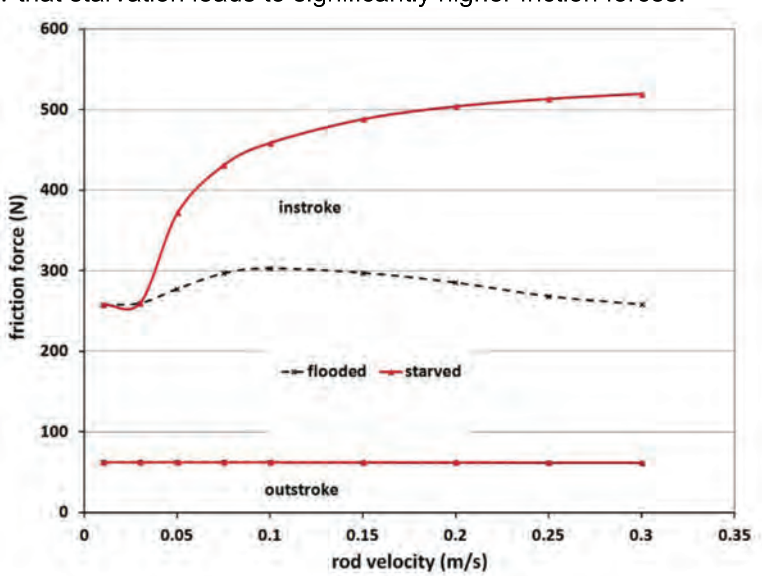


Figure 2: Experimental normal forces measured using high viscosity standard S600. The forces have been corrected for inertia and surface tension effects. Non-parallelism was minimized in the experimental set up. (A) is the flat plate. (B) is the symmetric texture. (C) is the asymmetric texture with α=68.3°. (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.

First numerical model of rod seal operation under starved lubrication conditions with concurrent mixed lubrication

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 directly into the environment. At the CCEFP numerical models of the rod seal have been developed. They are capable of predicting the 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 generally 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.

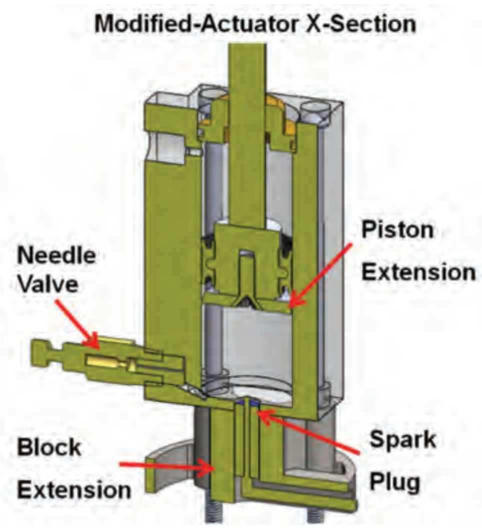


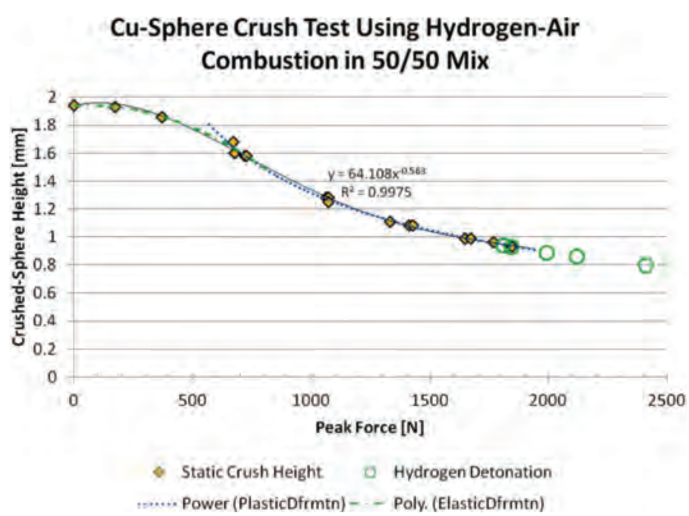
Comparison of starved and flooded lubrication conditions in a rod seal

Demonstration of Combustion-Driven Direct Actuation Using an Off-the-Shelf Pneumatic Actuator

As an associated project to Test Bed 6, MSOE has constructed a combustion test stand to measure the forces that can be generated when employing an off-the-shelf pneumatic actuator as an internal-combustion-driven actuator, and successfully demonstrated that peak forces of 1.8 kN (400 lbf) can be achieved for a 25 mm-diameter piston – capable of generating the targeted 75 Nm of peak torque for ankle-joint actuation, using a 4.2 cm-radius pulley. This is the first successful demonstration of combustion-driven actuation for an active orthosis, and paves the way for the development of a high-efficiency, power-dense, pneumatic, actuation system.

For these latest tests, hydrogen was used as a fuel, because it (1) has high mass-specific energy; (2) is readily available and inexpensive to produce with an electrolyzer; (3) has a vapor pressure above the 20 bar target compression pressure; and, (4) produces only water as a byproduct. Ethylene is another fuel candidate for near-isothermal compression, and can be easily stored as a liquid – good for extended outdoor operation.

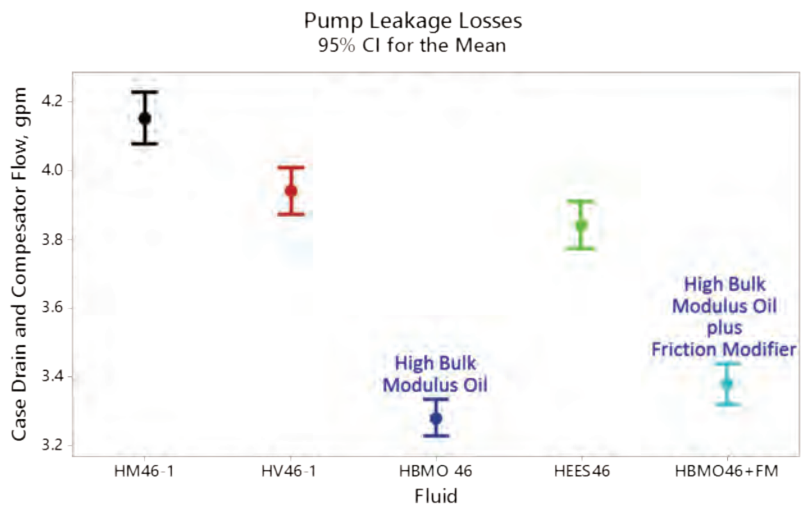




A CCEFP REU student, Donald Kuettel III (UW Madison), worked at MSOE over the summer of 2014 to calculate: the fuel-to-air ratio required for propane combustion; the P-V curve for one cycle of the Walking Engine using an off-the-shelf actuator; and, the optimal pulley geometry to match a human ankle-torque curve.

High Bulk Modulus Oil Research Collaboration

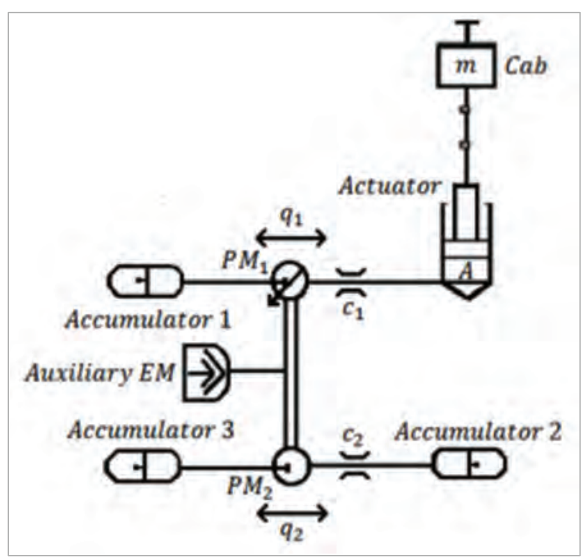
A prototype high-bulk modulus hydraulic fluid was developed, characterized and evaluated in collaboration including Paul Michael at MSOE, Dr. Hideto Kamimura of Idemitsu Lubricants America and Dr. Scott Bair or Georgia Tech. Testing in a dynamometer at the MSOE Fluid Power Institute revealed a 20% reduction in pump case and pressure compensator (PC) 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 PC control valve flow rates are affected by the bulk modulus, density, and viscosity properties of fluids. In addition, 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.

Novel Energy Recovery Architecture for Use in Hydraulic Elevators

Hydraulic elevators suffer from high inefficiencies due to fluid throttling and/or 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 the electromechanical energy conversions would make for a significant improvement in system efficiency as compared to the state-of-the-art. We have conceived a novel hydraulic system (pictured below) using a hydraulic transformer which requires minimal electromechanical energy conversion and entirely bypasses throttling. Simulation results of the novel system show promising efficiency improvements when compared to the same operation of existing systems (manuscript in preparation). Algorithms for effectively controlling the architecture have also been developed.

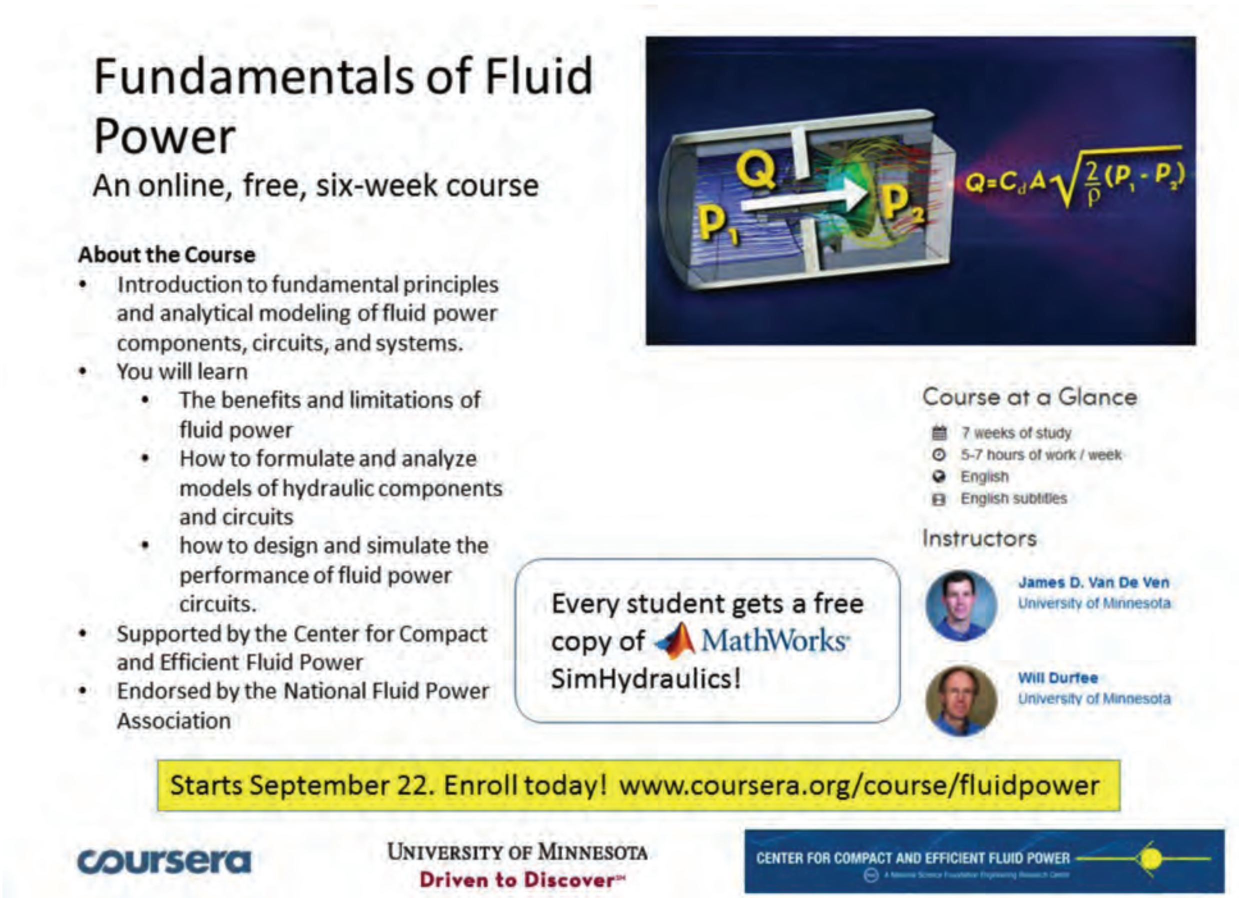


Schematic of Energy Recapture System for Hydraulic Elevators

EDUCATION HIGHLIGHTS

Fluid Power Fundamentals MOOC Offered Through Coursera

In the fall of 2014, University of Minnesota Professors James Van de Ven and William Durfee taught a Massive Online Open Course (MOOC) on Coursera titled "Fundamentals of Fluid Power." The course attracted 8,399 students from 149 countries, with the following continental breakdowns: 40% Asia, 29% North America, 22% Europe, 9% Africa, and 8% South America. The course consisted of 34 on-location and in-studio video lectures 5-12 minutes in length, weekly homework assignments, weekly quizzes, and an active discussion forum. MathWorks gave each student a limited time license to SimHydraulics, which was used in lectures and homework assignments to simulate the behavior and performance of circuits. Of the large group of students enrolled in the course, 13.5% watched all of the videos and 6.7% completed all of the quizzes. In the course students learned: 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 target audience for the course is entry-level engineers, senior-level undergraduate students, and entry-level graduate students.



Fundamentals of Fluid Power MOOC web page

Parker Hannifin 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. A team of 5-6 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, 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 about a dozen teams in the competition. In 2011-12, CCEFP was represented by Illinois, Illinois Tech, Minnesota and Purdue. 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, CCEFP was represented by teams 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.

Inaugural "Fluid Power Innovation and Research Conference" (FPIRC) – Creating a Legacy for the CCEFP

The CCEFP hosted its first annual FPIRC event at Vanderbilt University, October 2014. 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. Over 200 participants attended FPIRC14, half being industry representatives. Highlights from the event included a high caliber panel on public-private partnerships in innovation, over 60 fluid power research posters and presentations, tours of Vanderbilt laboratories and a special visit to Oak Ridge National Laboratory. Upcoming FPIRC events include Chicago, IL in October 2015 and Minneapolis, MN in October 16. Both events are co-located with other academic conferences for increased visibility within the research community. It is anticipated that half the research program would be presentations from industry and invited academics outside the CCEFP research community.

CCEFP Joins NFPA as an Exhibitor at the International Manufacturing Technology Show in Chicago

The CCEFP and the National Fluid Power Association (NFPA) co-exhibited at the Smartforce Student Summit during the International Manufacturing Technology (IMTS) Show 2014 in Chicago, IL, September 8 - 13. The IMTS supports the next generation "smartforce" entering the manufacturing technology industry who will keep the U.S. in its global manufacturing leadership position. The CCEFP and NFPA will become partners in workforce development and will leverage opportunities to exhibit and promote fluid power to the K12 and undergraduate science and engineering student audience.

CCEFP Wins Runner-Up 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.

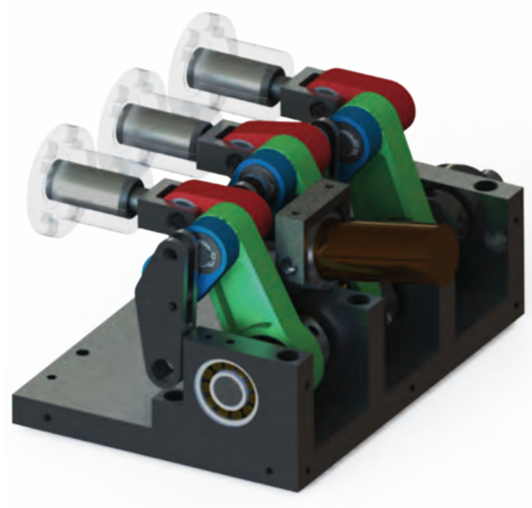
CCEFP Hosts Four NFPA Fluid Power Challenges - An Engineering Design Competition for 8th Graders

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.

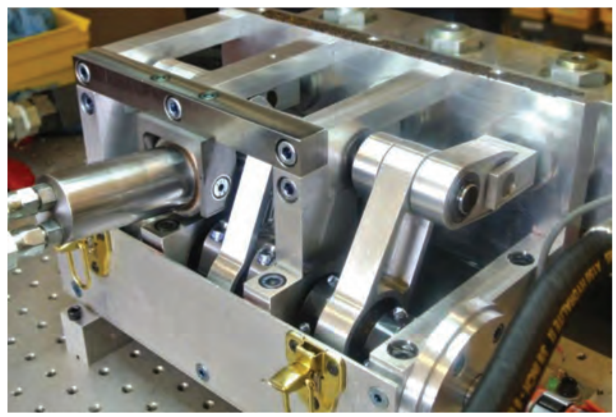
TECHNOLOGY TRANSFER HIGHLIGHTS

Commercialization of an Adjustable Linkage Pump

In an affiliated research project on compressed air energy storage, a novel variable displacement pump was invented, that is driven by an adjustable linkage. 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 will result 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, when compared to market leading variable displacement hydraulic pumps. This project addresses the following technology gaps as it translates from research discovery toward 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

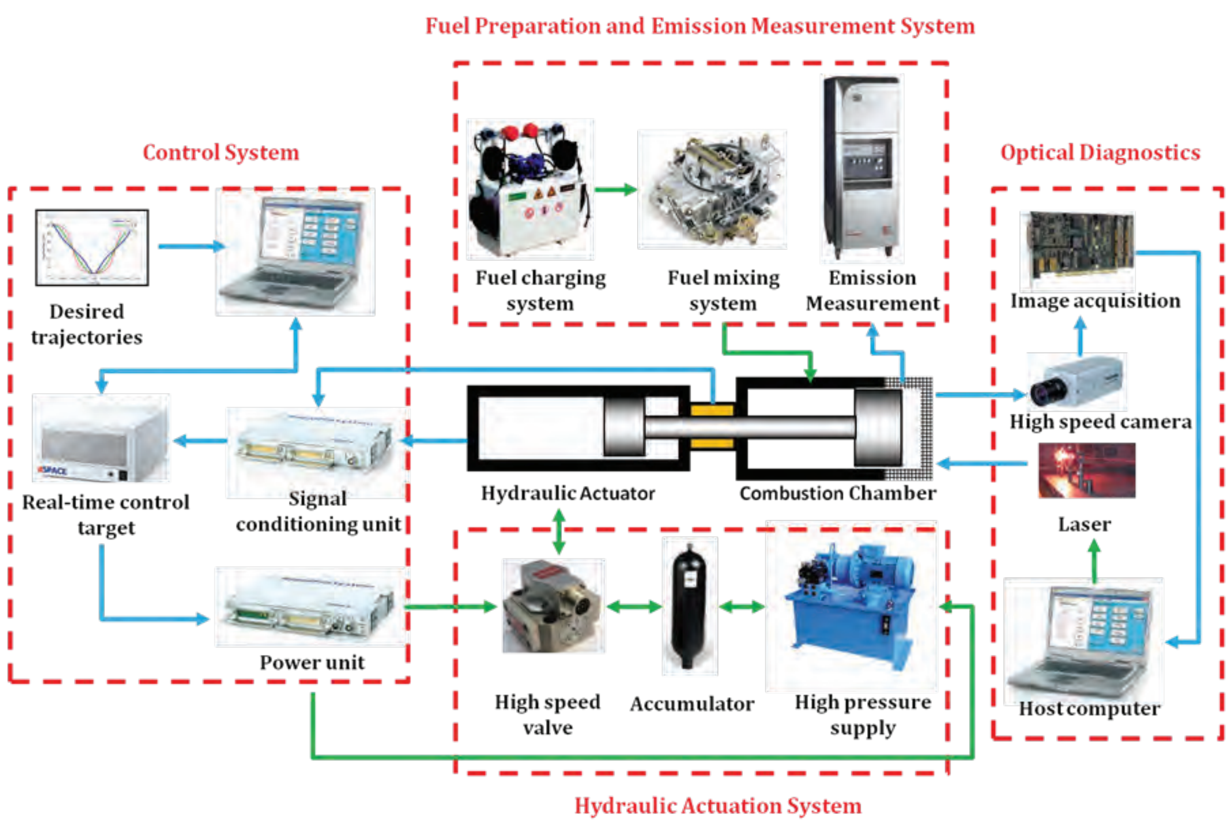


Adjustable Linkage Pump Prototype

INFRASTRUCTURE HIGHLIGHTS

Construction Planned for a Controlled Trajectory Rapid Compression and Expansion Machine

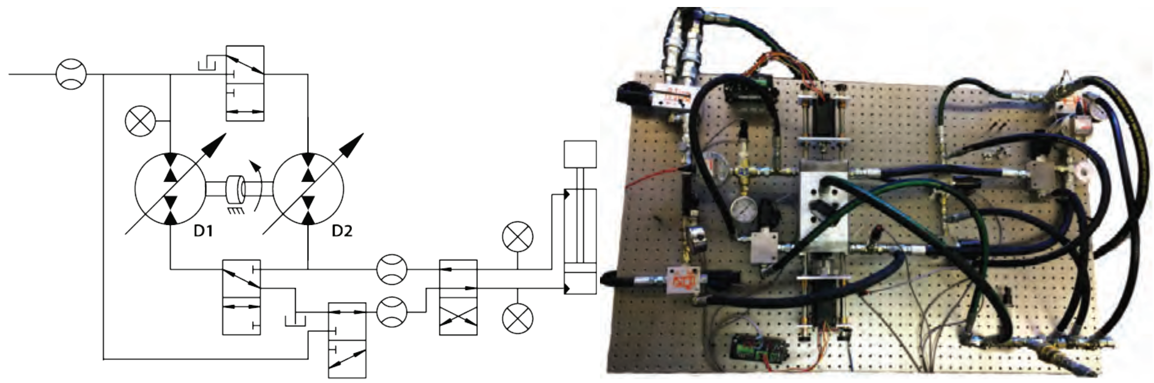
Rapid compression machines are instruments that use a single piston or opposed pistons to compress the gas mixture in a cylinder rapidly and create desired temperature and pressure conditions to investigate the fuel ignition, emission formation mechanism, and fluid and chemistry interaction etc. The objective of this project is to develop a rapid compression and expansion machine with the ability to control its piston trajectory in real-time (schematic below). Unlike conventional rapid compression machines, the proposed instrument can control the trajectory of the piston to track any desired reference signal. This unique capability enables the real-time control of the combustion chamber volume and therefore affects the time history of the temperature, pressure and species concentration. Such functionalities when combined with gas sampling analysis and optical measurement will allow researchers to directly access the combustion processes in a dynamic and controlled fashion. This instrument utilizes high pressure and high speed hydraulic actuation system and unique motion control methodologies to achieve precise and flexible compression and expansion processes. This new design and control approach offers added flexibility with piston trajectory control, better repeatability with real-time feedback, and improved throughput without the need for physical adjustment of the mechanical system. Given its unique capabilities, the proposed instrument will enable novel and exciting research work in fuel, advanced combustion, new engine architectures and control, which could significantly reduce the energy consumption and emissions for transportation, construction, and agriculture. The proposed instrument will advance the shared research infrastructure at the University of Minnesota and promote multi-disciplinary research. The instrument is currently being designed and the manufacturing and construction of the instrument will start in April 2015.



Schematic of Rapid Compression and Expansion Machine

Reconfigurable port-switching hydraulic transformer setup

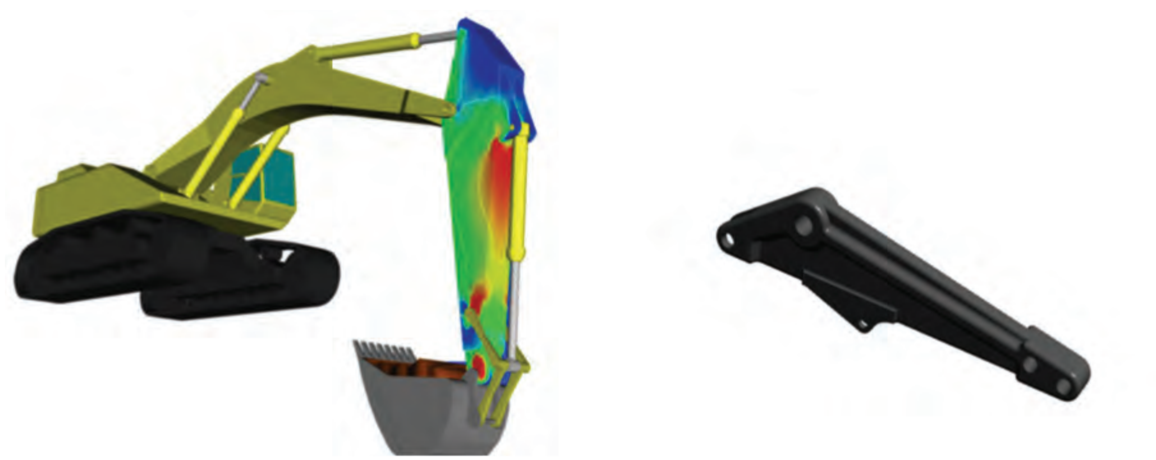
System Configuration and Control with Hydraulic Transformers have constructed a modular test bench on which new approaches in controlling hydraulic transformer will be tested. The hydraulic transformer in this test bench is a 3.15cc-3.15cc variable displacement pump/motor unit from Takako industries. This test bench could be connected to a hydraulic motor, cylinder or an orifice load depending on experiment criteria and is capable of switching among different configurations while in operation, an idea this project is proposing and exploring to broaden the region of high efficiency operation of the hydraulic transformer. A schematic of the test bench and a picture of the lab test bench are shown below.



Reconfigurable port-switching hydraulic transformer setup schematic and modular test bench

Additive Manufacturing Excavator Demonstration at IFPE 2017

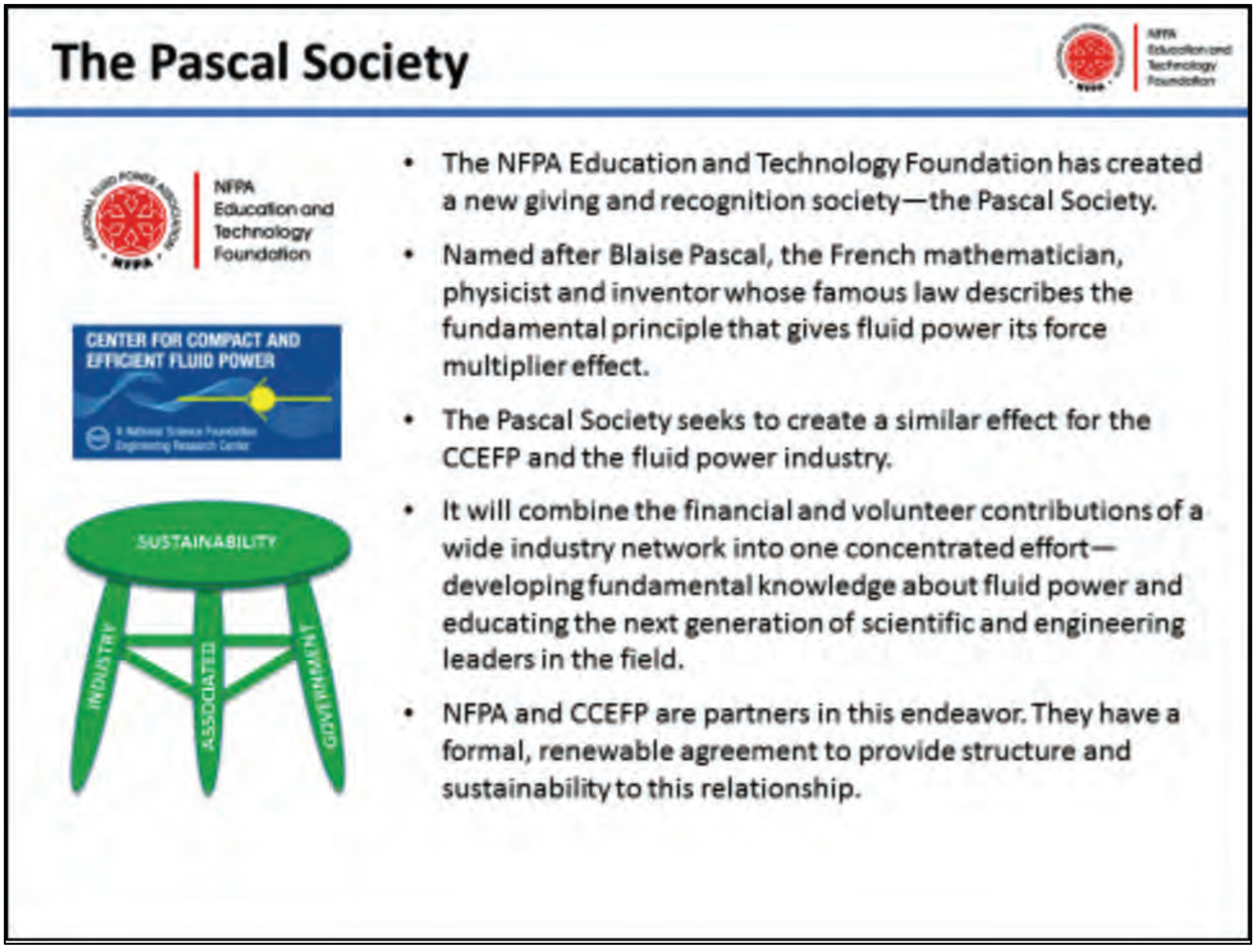
The CCEFP Industry Engagement Committee (IEC) is leading a collaborative effort with Oak Ridge National Lab's (ORNL) Manufacturing Demonstration Facility to produce a 3D printed excavator. The excavator is slated to be prominently displayed at the upcoming 2017 CONEXPO-CON/AGG IFPE show in Las Vegas…the largest such show of its kind in North America with over 125,000 attendees expected. The goal of the display is to demonstrate the disruptive potential of 3D manufacturing on the way fluid power components and systems are currently made today. One possible example under evaluation is to embed fluid power actuators and flow passages inside of 3D printed construction vehicle manipulators to dramatically reduce overall weight while increasing overall functionality. Several CCEFP research highlight displays are planned to encircle the vehicle to further illustrate the role that the CCEFP has played in advancing the state of fluid power research in America.



3D printed excavator arm with embedded hydraulics

Founding of the Pascal Society

As part of its long term sustainability efforts the CCEFP has entered into an agreement with the National Fluid Power Association to establish a giving society funded by industry donations whose primary goals are to fund pre-competitive fluid power research while educating the next generation of fluid power scientific and engineering leaders. Although the Pascal Society has been in existence for less than a year it has already raised over $800,000 in pledges.



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2. STRATEGIC RESEARCH PLAN AND OVERALL RESEARCH PROGRAM

Fluid power is the use of fluids under pressure to generate, transmit and control power. Fluid power is sub-divided into *hydraulics*, which uses a liquid (typically mineral oil or water) as the working medium, and *pneumatics*, which uses a gas (typically air) as the working medium. Fluid power is used in a wide range of industries, including manufacturing, transportation, aerospace, and agricultural, construction, mining and forestry. Nearly all U.S. manufacturing plants rely on fluid power in their production of goods and over half of all U.S. industrial products have fluid power critical components [1]. Fluid power has the advantages of flexibility in installation and high power density. Based on magnetic material properties, an electric motor can develop the same torque as a hydraulic motor of the same size operating at a pressure of 17 bar (250 psi)[2]. Since hydraulic systems routinely operate at pressures of 200-350 bar (3-5000 psi), such a hydraulic motor will have twelve to twenty times the torque of the same sized electric motor. If the shaft speeds are the same, the power ratio will also be twelve to twenty, which demonstrates the much higher power density of fluid power systems when compares to electric systems. In a comparison of rotary and linear actuators for robots, it is found that hydraulic actuators have a power density that is up to one hundred times greater than for electric motors based on volume and five hundred times greater based on weight [3]. Fluid power systems also have one to two orders of magnitude greater bandwidth than electromechanical systems with similar power ratings [4]. Since there is no other technology comparable to fluid power in high-power, high- force applications, it is essential for large equipment. Fluid power is widely used, so improvements in efficiency will have an important impact on energy consumption. Further, the intrinsic bandwidth and power density advantages of fluid power has not been exploited on smaller scale, portable and self-powered systems.

Although fluid power offers advantages over competing technologies, it has been confined to applications where the required power density precludes other solutions. Fluid power has a number of shortcomings that are barriers to more widespread use. These barriers are 1) inefficient components and systems; 2) excessive weight and size for portable applications; and 3) noise, leakage, contamination and awkward operator interfaces. Inefficient components and systems waste energy and cause excessive heating of working fluids which decreases fluid and component life.

State of the Art for Fluid Power

The commercial success of a technology flows from its strengths and weaknesses. An analysis of the state of the art of the four most common power transmission technologies - hydraulic, pneumatic, mechanical and electrical - can identify key attributes and rate how each of the technologies compares to the alternatives. This analysis is shown on the following pages for several large market segments in which fluid power has a considerable market share (mobile hydraulics, industrial equipment and factory automation) and two market segments that CCEFP is targeting with its research (human scale powered devices and hybrid passenger vehicles). The latter two market segments represent substantial growth opportunities for the fluid power industry. However, a number of technical barriers need to be overcome before that growth can be realized.

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1. Esposito, A., 1997, *Fluid Power with Applications*, 4th edition. Prentice Hall, Upper Saddle River, New Jersey.
2. McCloy, D. J. and H. R. Martin, 1980, *Control of Fluid Power: Analysis and Design*, 2^{nd} ed., Ellis Horwood, Chichester, pp. 12-13.
3. Kuribayashi, K. 1993, "Criteria for the Evaluation of New Actuators as Energy Converters", *Advanced Robotics*, Vol. 7, No. 4, pp. 289-37.
4. Maskrey, R. H. and W. J. Thayer, 1978, "A Brief History of Electrohydraulic Servomechanisms," Technical Report 141, Moog, Inc., East Aurora, NY.

Mobile Off-Road Equipment

Hydraulics has been the dominant power transmission choice for mobile off-road equipment, such as agricultural, construction, mining and forestry vehicles, for many decades. These machines are heavy (1-100+ tons), require actuation for propulsion, steering and multiple work circuits, and have varying power requirements including very low speed and high torque for some functions. Because of the characteristics of the equipment and their duty cycles, mobile off-road equipment users place a premium on certain attributes. These high priority attributes for mobile off-road equipment are highlighted in purple in Figure 1.

	Power Transmission Technology			
Attribute	**Hydraulics**	**Pneumatics**	**Mechanical**	**Electrical**
Power to weight ratio (prime mover)	++	−−	+	−
Energy to weight ratio (prime mover)	++	−−	+	−
Power to weight ratio (storage)	++	−	++	−
Energy to weight ratio (storage)	−−	−	−−	++
Power to weight ratio (actuation)	++	−	++	−
High torque and force	+	−−	−	−−
High power bi-directional transients	+	−−	++	−
Bandwidth	++	−	−−	+
Load holding without energy	++	+	+	−
Flexible routing	++	++	−−	++
Power transmission loss	−−	−	++	++
Infinitely variable transmission of power	++	+	−−	++
Efficiency	−−	−−	++	+
Noise	−−	−	+	++
Cleanliness	−−	++	+	++
Design tools	−−	−−	+	++
Educated workforce	−−	−−	+	++
	Excellent	**Good**	**Poor**	**Deficient**

Figure 1: Power transmission attributes and priorities for mobile off-road equipment

The relatively low efficiency of hydraulic systems has not deterred its use in mobile off-road equipment because its inherent advantages outweigh the efficiency challenge. Large fluctuations in fuel prices and the more demanding Tier IV emissions standards have caused mobile off-road equipment users to demand increased efficiency from their new equipment to lower acquisition and operating costs. This can be achieved by increasing the overall system efficiency through lowering component losses, and improving control and energy management. Hybridization can further improve efficiency. At present, these technologies are not broadly available in the marketplace and provide a differentiation for equipment OEMs. However, the trend is that higher efficiency machines will become the norm. Thus, an important need to maintain fluid power's dominance in mobile off-road equipment is to significantly improve its efficiency.

Industrial Equipment

Industrial equipment uses power transmission systems similar to those in mobile hydraulics. A major difference is that industrial equipment is stationary so that power or energy to weight ratio becomes less important. In addition, in the industrial setting electric motors are used to drive the hydraulic pumps and pneumatic compressors instead of the internal combustion engines generally used in mobile hydraulics. The critical attributes for industrial hydraulics are highlighted in purple in Figure 2.

	Power Transmission Technology			
Attribute	**Hydraulics**	**Pneumatics**	**Mechanical**	**Electrical**
Power to weight ratio (prime mover)	++	– –	+	–
Energy to weight ratio (prime mover)	++	– –	+	–
Power to weight ratio (storage)	++	–	++	–
Energy to weight ratio (storage)	– –	–	– –	++
Power to weight ratio (actuation)	++	–	++	–
High torque and force	+	– –	–	– –
High power bi-directional transients	+	– –	++	–
Bandwidth	++	–	– –	+
Load holding without energy	++	+	+	–
Flexible routing	++	++	– –	++
Power transmission loss	– –	–	++	++
Infinitely variable transmission of power	++	+	– –	++
Efficiency	– –	– –	++	+
Noise	– –	–	+	++
Cleanliness	– –	++	+	++
Design tools	– –	– –	+	++
Educated workforce	– –	– –	+	++

Excellent	Good	**Poor**	**Deficient**

Figure 2: Power transmission attributes and priorities for industrial hydraulics

Fluid power has been losing market share to electrical systems in industrial hydraulics applications and markets for more than 20 years. By comparing the performance of hydraulic and electric power transmission systems in the attributes that are critical for industrial hydraulics, one can identify the attributes that must be improved for fluid power to be competitive. Noise and cleanliness are high priorities in factories. Efficiency is another critical attribute in industrial hydraulics where the electrical power consumption is an important component in a factory's operating costs. Thus, the technical barriers that must be overcome in industrial hydraulics are noise, cleanliness (no leaks) and system efficiency.

Factory Automation

For factory automation, pneumatics is often the technology of choice due to its simplicity, flexibility and low cost. Functions include cleaning a work area (e.g., blowing chips off of a machine tool or workpiece), motion control and power transmission. The attributes of different power transmission methods that are important for factory automation are highlighted in purple in Figure 3. As was the case with industrial equipment, noise, cleanliness and efficiency are high priorities.

	Power Transmission Technology			
Attribute	Hydraulics	Pneumatics	Mechanical	Electrical
Power to weight ratio (prime mover)	++	– –	+	–
Energy to weight ratio (prime mover)	++	– –	+	–
Power to weight ratio (storage)	++	–	++	–
Energy to weight ratio (storage)	– –	–	– –	++
Power to weight ratio (actuation)	++	–	++	–
High torque and force	+	– –	–	– –
High power bi-directional transients	+	– –	++	–
Bandwidth	++	–	– –	+
Load holding without energy	++	+	+	–
Flexible routing	++	++	– –	++
Power transmission loss	– –	–	++	++
Infinitely variable transmission of power	++	+	– –	++
Efficiency	– –	– –	++	–
Noise	– –	–	+	–
Cleanliness	– –	++	+	++
Design tools	– –	– –	+	++
Educated workforce	– –	– –	+	++

Excellent	Good	Poor	Deficient

Figure 3: Power transmission attributes and priorities for factory automation

Factories using pneumatics require a supply of compressed air that is supplied by an electrically powered compressor and stored in a pressure vessel. Air lines are routed to the locations requiring pressurized air. Large plants may have multiple compressors serving various segments of the building. A vast number of pneumatic hand tools have been developed that require pressurized air to function. These tools are light, robust and inexpensive and are a fixture in many sites using pneumatics. In theory, a plant could use electrical tools instead of air tools, but the electrical devices tend to be more expensive and more prone to being damaged by the processes being used in the plant. An "all electric" factory would need a compressed air system to use for cleaning and other non-power transmission needs. Neither hydraulic nor mechanical power transmission technologies offer the flexibility that pneumatics provides, so pneumatics is the dominant technology in factory automation.

Human-scale Powered Devices

The Center sees opportunities to expand fluid power's use in human-scaled fluid power devices. Some examples of new market opportunities are medical applications, portable, self-powered tools and self-powered exoskeletons. The attributes that are critical to growth in current human-scale applications and creating new market opportunities are highlighted in purple in Figure 4.

	Power Transmission Technology			
Attribute	Hydraulics	Pneumatics	Mechanical	Electrical
Power to weight ratio (prime mover)	–	– –	+	–
Energy to weight ratio (prime mover)	–	– –	+	–
Power to weight ratio (storage)	–	–	++	–
Energy to weight ratio (storage)	– –	–	– –	++
Power to weight ratio (actuation)	–	–	++	–
High torque and force	+	– –	–	– –
High power bi-directional transients	+	– –	++	–
Bandwidth	++	–	– –	+
Load holding without energy	++	+	+	–
Flexible routing	++	++	– –	++
Power transmission loss	– –	–	++	++
Infinitely variable transmission of power	–	+	– –	++
Efficiency	– –	– –	++	+
Noise	– –	–	+	++
Cleanliness	– –	++	+	++
Design tools	– –	– –	+	++
Educated workforce	– –	– –	+	++

Excellent	Good	Poor	Deficient

Figure 4: Power transmission attributes and priorities for human scale powered devices

Because human scale devices are small and low-powered when compared to most current fluid power applications, the assessments of a number of attributes in hydraulic power transmission have been changed. Current hydraulic solutions do not scale well into the low power range required for human-scale. The key challenges to realizing the Center's objective of expanding fluid power use in current human-scale powered devices is making the power supplies smaller, developing more compact energy storage, increasing system efficiency, reducing noise and, in the case of hydraulics, making the system leak-free.

Hybrid Personal Use Vehicles

The attributes that are critical to the use of hybrids in the personal use (passenger car and light duty truck) market are highlighted in purple in Figure 5.

	Power Transmission Technology			
Attribute	**Hydraulics**	**Pneumatics**	**Mechanical**	**Electrical**
Power to weight ratio (prime mover)	++	– –	+	–
Energy to weight ratio (prime mover)	++	– –	+	–
Power to weight ratio (storage)	++	–	++	–
Energy to weight ratio (storage)	– –	–	– –	++
Power to weight ratio (actuation)	++	–	++	–
High torque and force	+	– –	–	– –
High power bi-directional transients	+	– –	++	–
Bandwidth	++	–	– –	+
Load holding without energy	++	+	+	–
Flexible routing	++	++	– –	++
Power transmission loss	– –	–	++	++
Infinitely variable transmission of power	++	+	– –	++
Efficiency	– –	– –	++	+
Noise	– –	–	+	++
Cleanliness	– –	++	+	++
Design tools	– –	– –	+	++
Educated workforce	– –	– –	+	++

Excellent	Good	Poor	Deficient

Figure 5: Power transmission attributes and priorities for hybrid passenger vehicles

The hybrid vehicle market has enormous potential for the fluid power industry. However, the levels of noise, vibration and harshness that are acceptable in mobile off-road equipment are unacceptable in passenger cars. As can be seen in the figure above, hydraulic hybrids offer advantages over electric hybrids in six attributes considered critical by vehicle manufacturers and car buyers. However, the hydraulic hybrid solution is also significantly worse than an electric hybrid in four categories. The goal of increasing the use of hydraulics in transportation by making hydraulic hybrid passenger cars a commercial success can only be realized if the technical barriers of low energy to weight ratio for storage (i.e. compact energy storage), system efficiency, noise and cleanliness (no leaks) are overcome.

Desired Future State

From its inception in 2006, the Center's mission has been to change the way fluid power is researched, applied and taught and its vision has been to make fluid power compact, efficient and effective.

The Center's four major goals are:

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 miniature fluid power components and systems including power supplies that are one to two orders of magnitude smaller than anything currently available.
4. Making fluid power ubiquitous meaning able to be used in any environment. This requires fluid power that is clean, quiet, safe and easy to use.

The ultimate objective of the Center and the focus of its mission, vision and goals is to transform the fluid power industry. The definition of success in achieving this objective, which is the desired future state, has several aspects. Part of it is ongoing research that leverages fluid power's inherent strengths and eliminates or substantially reduces key technical barriers, to transfer the discoveries to industry and have industry commercialize them to make transformational changes that will create growth in current markets and expand the use and benefits of fluid power into new, high growth markets and provide benefits to the fluid power industry, its customers and society. A second aspect of the desired future state is the continuation of the pipeline of students trained in fluid power. Some of these students will go into fluid power companies to use their knowledge to create new and better products, some will remain in academia to train the next generation of engineers and some will go into non-fluid power companies where they may bring fluid power's benefits to other industries. In order to continue this pipeline of students the Center must have a critical mass of researchers (PIs and students) and industry partners to generate the resources required to continue its research, education and intellectual capital transfer on an ongoing basis. Intellectual capital includes assets that a research university can provide to industry such as access to qualified students (graduate and undergraduate) both as university researchers and company employees, as well as access to researchers and research facilities and the potential for licensing and/or creating intellectual property.

The desired future state is a Center that has a proven record of delivering these aspects of success and has implemented a strategy that makes it self-sustaining. We believe that CCEFP's sustainability plan provides a strategy that will bring about the desired future state and ensure that the Center continues to bring transformational changes to the fluid power industry for years to come.

Barriers to Achieving the Desired Future State

The technical barriers that the CCEFP strategic research plan addresses were derived from the weaknesses of fluid power identified in the state of the art analysis in the previous pages. The significant technical barriers facing fluid power are:

1. Efficient Components and Systems
2. Efficient Control
3. Efficient Energy Management
4. Compact Power Supplies
5. Compact Energy Storage
6. Compact Integration
7. Safe and Easy-to-Use
8. Leak-free
9. Quiet

Technical barriers 1, 2 and 3 stem from the low efficiency that hydraulics and pneumatics have when compared to mechanical and electrical alternatives (tables 1-3) and the Center's major goal of doubling fluid power efficiency. Technical barriers 4 and 6 come from the Center's major goal of developing new miniature fluid power components and systems. Technical barrier 5 also supports the miniature components and systems goal, but also addresses the disadvantage that fluid power has compared to alternative technologies in the energy to weight ratio of its energy storage devices (tables 1, 4 and 5). Technical barrier 7 is derived from, among other things, the lack of design tools and an educated workforce challenges for fluid power (tables 1-5). Technical barriers 8 and 9 address the cleanliness and noise attributes in the state of the art assessment, respectively (tables 2-5). Fluid power is at a competitive disadvantage in cleanliness and noise when compared to alternatives at a minimum. In some applications these may represent "show stoppers".

The nine technical barriers can be grouped in three broad categories. Efficiency includes the barriers of efficient components and systems, efficient control and efficient energy management. Compactness includes the barriers of compact power supplies, compact energy storage and compact integration. Effectiveness includes the barriers of safe and easy-to-use, leak-free and quiet.

Three of these technical barriers are transformational: efficient components and systems, compact power supplies and compact energy storage. These transformational technical barriers in fluid power generally provide the largest benefits in mobile applications. As a result, mobile hydraulics has been the dominant research focus for Center since its inception. Three of the Center's four test beds focus on mobile hydraulics and the fourth, the ankle-foot orthosis, has researchers working on both hydraulic and pneumatic solutions.

Research Strategy

The CCEFP research strategy addresses the significant and transformational technical barriers that must be overcome to achieve the desired future state for fluid power as well as the major goals of the Center. The CCEFP strategic research plan is designed to overcome the technical barriers to achieving the Center's vision as well as the major goals of the Center. To overcome the barrier of inefficiency, the Center is developing new components and systems and novel control methods to improve system performance and reduce energy consumption. The approaches include displacement control to replace current inefficient valve throttling, regeneration, and on-off valve based control. The lack of compact power supply barrier is related to the efficiency in transforming energy in fuel to fluid power. The Center is working to overcome this barrier by tightly coupling the energy source to the fluid power domain through the development of free-piston engine pumps and compressors. The lack of compact high energy density storage will be overcome by developing new energy storage devices using novel approaches such as storing energy in the strain of an elastomer rather than by compressing a gas. Use of composite and functionally graded materials and the integration of components into unified systems will minimize the weight and volume of fluid power systems. Fluid power has problems such as noise and vibration, leakage and awkward interfaces that hinder its use. The Center is working to overcome these barriers through innovative approaches to user interfaces and breakthrough technology for sound suppression and seals. Overcoming these barriers will lead to wider use of fluid power and allow the inherent advantages of fluid power to migrate into applications beyond its current markets.

As described above, the nine technical barriers naturally group into the three broad categories. These define the thrusts of Center's research strategy:

- **Thrust 1: Efficiency** includes the barriers of efficient components and systems, efficient control and efficient energy management.
- **Thrust 2: Compactness** includes the barriers of compact power supplies, compact energy storage and compact integration.
- **Thrust 3: Effectiveness** includes the barriers of safe and easy-to-use, leak-free and quiet.

The review of the current state of the art for fluid power and other power transmission technologies revealed a number of opportunities for growing fluid power use in current and adjacent markets by overcoming certain technical barriers. Hydraulics is the dominant choice for the propulsion, work and in many cases steering of mobile off-road equipment used in the agricultural, mining, forestry and construction markets. This is a mature market, so there is limited growth opportunity. Adjacent markets represent greater growth opportunities for fluid power. One potential adjacent market is on-highway vehicles. Hydraulic hybrid drivetrains have already been commercialized in medium and heavy duty commercial vehicles, but very little research is being done on hydraulic hybrid systems for light duty and personal use vehicles. The commercialization of compact, efficient and effective hydraulic hybrid drivetrains for these smaller vehicles would be transformational. Unit sales volumes for these types of vehicles are in the tens of millions.

In addition, the state of the art review investigated potential new “white space” markets in which fluid power could provide transformational benefits. The Center has identified human-scale powered devices as one such area and human-scale powered medical devices as a particularly promising market niche.

The CCEFP test beds represent systems that were carefully selected to align with the technical barriers and Center goals.

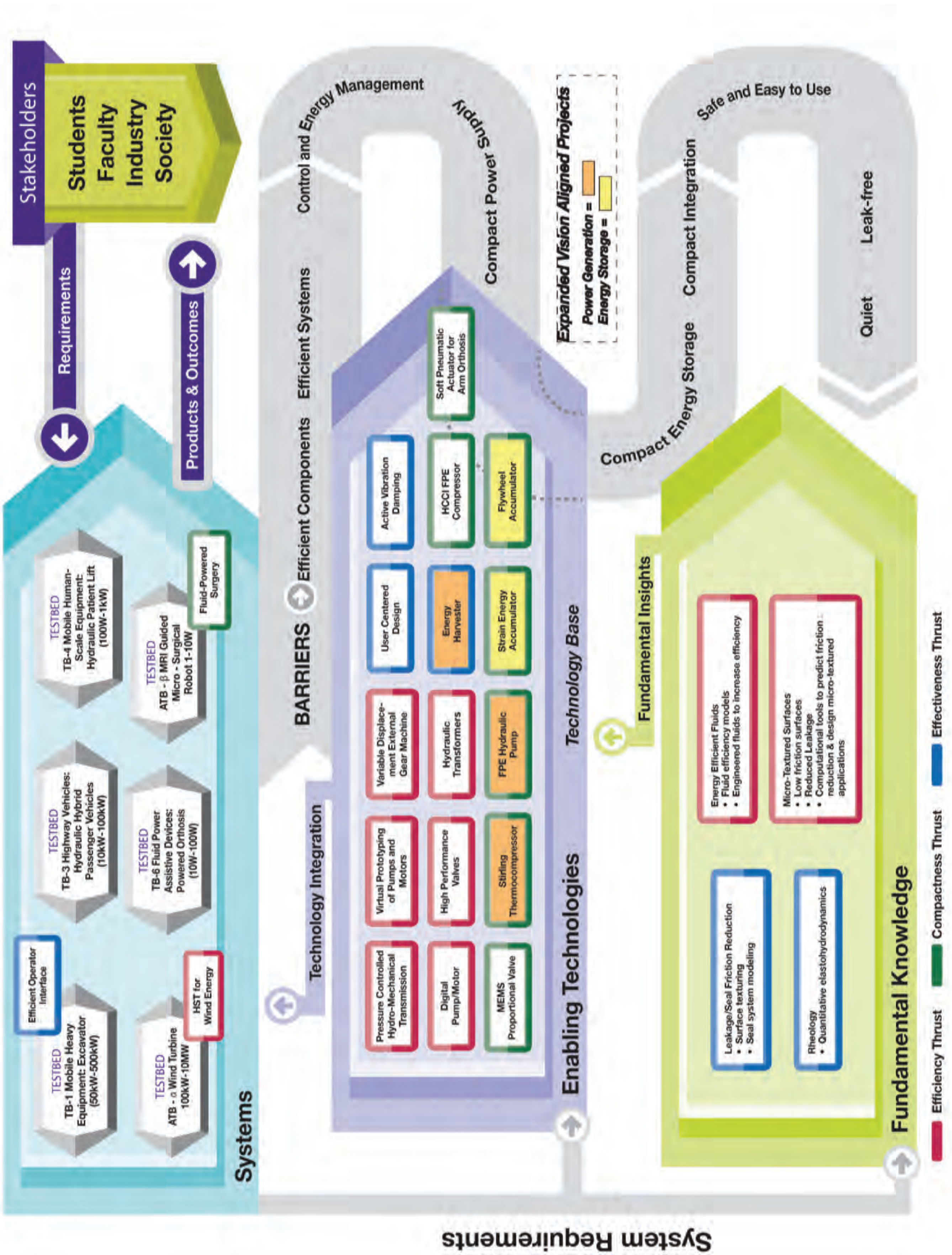
- Test bed 1, the high efficiency excavator (mobile heavy equipment), was chosen to address efficiency and effectiveness thrusts. The vehicle also represents the largest single segment of hydraulics, mobile off-road equipment, and aligns with the Center’s goal of increasing fluid power efficiency in current applications.
- Test bed 3, the hydraulic hybrid vehicle (on-highway vehicles), addresses all three of the Center’s thrusts. In order to be commercially successful, the efficiency of the fluid power components and systems must improve. In addition, optimizing the control and energy management is required to further improve the overall system efficiency. The size and weight of the hybrid system, especially the accumulator, must be reduced in order for the hydraulic hybrid to succeed in the passenger car market. Finally, the expectations of a car owner are vastly different than those of the owner of off-road mobile equipment. Noise and leaks are technical barriers that must be overcome for hydraulic hybrid passenger vehicles to be viable. Test bed 3 also addresses the Center’s goals of expanding fluid power use in transportation and increasing the energy density of fluid power energy storage by an order of magnitude.
- Test beds 4 and 6, the human-scale equipment and the human-assist device test beds, were chosen as examples of future portable human-scale fluid power applications. Both of the test beds address nearly all of the technical barriers. In addition, these test beds align with the Center’s goal of ubiquity.

Although stationary fluid power applications will also benefit from CCEFP research, the core test beds are mobile applications where the advantages of the transformational changes in fluid power which the Center is working toward are most evident. CCEFP has added two associated test beds that are focused on stationary applications. The addition of these test beds extends the range of power and weight spanned by all Center test beds to greater than 6 orders of magnitude. The new test beds are:

- Test bed α - Wind Power Generation (mid-wind and utility scale wind turbine drivetrains, 100 kW - 10 MW). This test bed will benefit greatly from improvements in the efficiency thrust. It also addresses the compact energy storage technical barrier. The open accumulator can be validated at lab scale on the new hydraulic drivetrain for wind test stand being built at the University of Minnesota. Finally, the effectiveness thrust barriers of leak-free and quiet are important attributes of commercially viable hydraulic wind turbine drivetrains.
- Test bed β - Precision Pneumatics MRI-Guided Surgery (MRI-compatible surgical devices, 5W - 50W). This test bed addresses literally all of the technical barriers identified by the Center.

The relationship of the test beds and the technical barriers is shown in Section 2.1.

The 3-plane chart appears on the following page.



Stakeholders
Students
Faculty
Industry
Society
Requirements
Products & Outcomes
Systems
TESTBED
TB-1 Mobile Heavy Equipment: Excavator (50kW-500kW)
Efficient Operator Interface
TESTBED
TB-3 Highway Vehicles: Hydraulic Hybrid Passenger Vehicles (10kW-100kW)
TESTBED
TB-4 Mobile Human-Scale Equipment: Hydraulic Patient Lift (100W-1kW)
TESTBED
ATB - α Wind Turbine 100kW-10MW
HST for Wind Energy
TESTBED
TB-6 Fluid Power Assistive Devices: Powered Orthosis (10W-100W)
TESTBED
ATB - β MRI Guided Micro - Surgical Robot 1-10W
Fluid-Powered Surgery
BARRIERS
Efficient Components
Efficient Systems
Control and Energy Management
Compact Power Supply
Technology Integration
Enabling Technologies
Technology Base
Pressure Controlled Hydro-Mechanical Transmission
Virtual Prototyping of Pumps and Motors
Variable Displacement External Gear Machine
User Centered Design
Active Vibration Damping
Digital Pump/Motor
High Performance Valves
Hydraulic Transformers
Energy Harvester
HCCI FPE Compressor
Soft Pneumatic Actuator for Arm Orthosis
MEMS Proportional Valve
Stirling Thermocompressor
FPE Hydraulic Pump
Strain Energy Accumulator
Flywheel Accumulator
Expanded Vision Aligned Projects
Power Generation =
Energy Storage =
Compact Energy Storage
Compact Integration
Safe and Easy to Use
Quiet
Leak-free
Fundamental Insights
Fundamental Knowledge
Leakage/Seal Friction Reduction
• Surface texturing
• Seal system modeling
Rheology
• Quantitative elastohydrodynamics
Energy Efficient Fluids
• Fluid efficiency models
• Engineered fluids to increase efficiency
Micro-Textured Surfaces
• Low friction surfaces
• Reduced Leakage
• Computational tools to predict friction reduction & design micro-textured applications
Efficiency Thrust
Compactness Thrust
Effectiveness Thrust
System Requirements

Translational Research

The CCEFP's membership agreement specifies that any revenue stream from licenses issued for Center-funded inventions flow to the inventing University. Therefore, licensing revenues are not relied upon in the Center's sustainability plans. Nonetheless, "success stories" are critical to establishing and maintaining the Center's reputation as the premier fluid power research collaboration in the U.S. Thus, an important aspect of the Center's mission is being a matchmaker between industry and the technology transfer offices at CCEFP member universities to get Center inventions licensed and commercialized. The Industrial Liaison Officer has primary responsibility for this activity.

The CCEFP has adopted a Technology Readiness Level (TRL) system for notifying its industry members when a project has progressed to a point where it is ready to transfer from the pre-competitive research phase to commercialization. TRL 4 is a good metric for when this has occurred. An overview of Center translational research projects that are judged to be at a Technology Readiness Level (TRL) 4 and above is provided below. Additional details on the projects funded in Year 7 and/or 8 can be found in Volume II of the CCEFP 8th annual report.

Multi Actuator Hydraulic Hybrid Machine Systems (Project 1A.2; Test Bed 1)

This project created displacement-controlled hydraulic systems. It has been demonstrated on test bed 1 and is estimated to be at TRL 4. Since its demonstration on the ERC test bed 1, this technology has attracted researchers as well as industry partners to bring displacement-control closer to commercialization. The inventors have formed a startup company to facilitate the transfer of the technology to industry. The most recent success story of displacement-controlled actuation was part of an associated industry project, where the world's first 22-ton displacement-controlled excavator was analyzed, built and tested.

Project 1A.2 created two translational research advances that have been patented and transferred to industry. One is an "Axial Sliding Bearing with Structural Sliding Surface" that is estimated to be at TRL 4-5. The technology has been demonstrated in a pump and has been licensed to a CCEFP industry member. The second is a "Piston with a Waved Surface for Pumps and Motors" which is also estimated to be at TRL 4-5. This technology has been demonstrated in a pump and has been licensed to a CCEFP industry member.

Pressure Ripple Energy Harvester (Project 3E.1)

The goal of this project is to harvest energy from the flow ripple present in fluid power conduits and store it in a battery. Such a system will enable "self-powered" sensors and wireless communication, thus eliminating the need for running power wires to every sensor. Early versions of the technology have been demonstrated in a research lab environment and estimated to be at TRL 4. A follow-on affiliated project funded through an NSF STTR will explore a commercial application for a pressure ripple energy harvesting powered pipeline leak detection system. Another affiliated project is in development with a member company to develop similarly powered diagnostic sensors for fluid power systems.

Toolkit for Energy Management Systems (Project 1A.1)

The goal of this project is to develop and implement a well-defined process for transferring energy management methodologies developed within the CCEFP to its industrial partners. Previous Center funded work in the study of energy management strategies (EMS) has shown that no single strategy is best for all applications. Therefore, multiple EMS tools were created within this toolbox to be applied to different problems and duty cycles. These tools are rule-based, model predictive and stochastic dynamic programming controllers. Which tools are utilized depends on the prior level of knowledge about the system duty cycle and the system characteristics. Going forward, the goal is to incorporate these algorithms into a user-friendlier tool. As a pilot study, two CCEFP member companies used the software to design an EMS for distinctly different vehicles and duty cycles.

Compact Energy Storage using Open Accumulator (Project 2C.1)

This project is researching storing energy by compressing air to high pressure. The energy density was shown to be more than 20 times that of conventional gas-charged accumulators. The open accumulator ended as a CCEFP core project in 2009 and is now an associated project focused on developing utility scale wind energy storage with NSF-EFRI program support (2010). The technology has been demonstrated at lab scale is estimated to be at TRL 4. The technology has been licensed to two companies.

Advanced Strain Energy Accumulator (Project 2C.2)

This project has created a novel compact accumulator that stores energy as strain in an elastomer. The technology has a potential energy density improvement of 2-3 times. The technology was demonstrated in a research lab environment and is estimated to be at TRL 4. Negotiations for licensing the technology are ongoing with one industry member.

Passive Noise Control in Fluid Power (Project 3B.1)

A design for a tunable compact noise attenuation device using engineered compliant linings was created in Project 3B.1. Comprehensive models were also been created that have led to designs of various types. A prototype hydraulic noise attenuation device is estimated to be at TRL 4-5. Several CCEFP industry members are in discussions regarding licensing with intent to commercialize. It is also being evaluated by an industry member.

Variable Displacement Gear Machine (Project 1F.1)

This project has developed a working prototype concept for variable displacement external gear pump which leverages the well-known advantages of current fixed displacement gear pumps such as ease of manufacturability, robustness, low cost high pressure range of operation and good operating efficiency. Several CCEFP industry members have expressed an interest in potential commercialization.

A Novel Pressure-controlled Hydro-Mechanical Transmission (Project 1J.1)

This project's goal is to develop a novel compact and efficient hydro-mechanical transmission suitable for both on & off road vehicles and mid-size wind turbines. The new transmission is expected to be as efficient as conventional HMT with planetary gears but is more compact and cost-effective. A prototype is currently under design and will be built in partnership with Mathers Hydraulics, a small Australian R & D firm, and Yuken India. A first generation bench test prototype is scheduled for 3rd quarter 2015. Industry supporters are excited to see what initial test results reveal.

EndoInSight Medical Systems

A team of researchers from Vanderbilt University have invented a novel approach that leverages fluid power for medical applications and launched a startup to ensure commercialization. The EndoInsight LLC system uses a disposable CO2 insufflation system to provide colonoscopy patients with a less-painful experience. The team is excited about the market potential, as well as, the initial positive customer feedback. Plans are underway to seek industry partners for commercialization.

Non-contacting Magnetic Based Position Measurement System

A team of researchers at the University of Minnesota have shown that the position of a ferromagnetic object can be measured quite accurately using a small inexpensive magnetic sensor and advanced modeling of the object's inherent magnetic field variation. They have 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 and hydraulic cylinders, as well as moving parts in many machines. A primary motivation behind this discovery was the CCEFP Free Piston Engine Pump (2B.3) project. The team recently formed a startup company, Innotronics LLC, with intent to commercialize after receiving a second $30K MnDRIVE Entrepreneurship Award from the University of Minnesota in addition to a previous $50K grant for help with commercialization.

Variable Displacement via Variable Linkage Pump

Another team of researchers at the University of Minnesota were awarded a $50k MnDRIVE Entrepreneurship Award to aid in the commercialization of a novel variable displacement, variable linkage piston pump. The linkage is adjusted by moving the ground pivot of a link through an arc with a linear actuator and has the ability to attain true zero displacement. The architecture has the potential to achieve very high efficiencies even at low displacements. A detailed efficiency model has been developed and experimentally validated with a low-power single-cylinder pump. A higher power three-cylinder prototype has been designed and is currently under fabrication. This project team was recently awarded a NSF PFI:AIR-TT grant to help with the construction of a real-world prototype.

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2.1 ERC RESEARCH PROGRAM (BY THRUST AND TESTBED)

The project numbering system at CCEFP categorizes projects by which of the three thrusts of Center research is most closely aligned with the project's objectives. The first digit in the project number identifies the research project's primary thrust. The numbers 1, 2 and 3 represent efficiency, compactness and effectiveness, respectively. The second character in a project number is an alphabetical letter. Within a given thrust, these letters are used to categorize the focus of the research in projects into groups. For example, the primary focus of "1A" projects is improving efficiency by means of control and "1B" projects primarily focus on increasing efficiency though improvements in material surfaces and interfaces.

In actuality, nearly all of the projects have substantial elements of more than one thrust embedded in the research. Thus, the project numbering system, while useful, does not capture all of the aspects of a given project. One example is Project 2C.2, the strain energy accumulator. The primary transformational technical barrier it addresses is to provide a more compact energy storage system for mobile hydraulics. However, there are also both significant efficiency and effectiveness elements to the project. The accumulator can improve efficiency by increasing the amount of energy that a hybrid system can store in the same space, thus allowing more engine off operation and allowing the vehicle to begin storing braking energy at a higher speed. In addition, the near constant pressure discharge from the strain energy accumulator allows effectiveness to be improved by reducing the secondary control challenges faced by hydraulic systems using accumulators. Roughly 90 percent of Center-funded projects exhibit similar intermingling of the thrusts. Thus, the number of projects in each thrust is not an accurate indicator of the Center's research in a given thrust.

The following pages provide an overview of all of the CCEFP-funded projects in each thrust as well as milestone charts. Test bed summaries (without references) and information about test bed integration is also provided. The complete project and test bed summary reports are found in Volume 2.

EFFICIENCY

Efficiency projects are primarily focused in three areas to overcome technical barriers facing fluid power. These areas are (1) creating more efficient components and systems, (2) improving efficiency through control optimization and (3) energy management. Creating efficient components and systems is one of the three transformational barriers for fluid power. The thrust also supports two of the Center's major goals: doubling the efficiency of fluid power in current applications and expanding the use of fluid power in transportation.

The Center started a new funding cycle for projects and test beds in FY9. Two new efficiency thrust projects were added (1G.3 and 1J.2) and four previously funded projects were graduated (1A.1, 1A.2, 1D, and 1E.1).

The table below shows the efficiency thrust projects funded in FY9 and the barriers that they address. Further details about each project can be found in the following pages and in Volume 2.

	Technical Barriers									Supported Projects and Test Beds
	Efficient Components and Systems	Efficient Control	Efficient Energy Management	Compact Power Supply	Compact Energy Storage	Compact Integration	Safe and Easy to Use	Leak-free	Quiet	
1B.1: Next Steps towards Digital Prototyping of Pumps and Motors	•									TB1
1E.3: High Efficiency, High Bandwidth, Actively Controlled Variable Displacement Pump/Motor	•	•				•				TB1
1E.4: Piston-by-Piston Control of Pumps and Motors Using Mechanical Methods	•	•				•				TB1, TB3
1E.5: System Configuration and Control Using Hydraulic Transformers	•	•	•			•				TB4
1E.6: High Performance Actuation System Enabled by Energy Coupling Mechanism	•	•	•			•				TB3
1F.1: Variable Displacement Gear Machine	•	•				•				TB1
1G.1: Energy Efficient Fluids	•					•				TB1, TB3
1G.3: Rheological Design for Efficient Fluid Power	•					•				TB1, TB3
1J.1: Hydraulic Transmissions for Wind Energy	•	•	•			•				TB-α
1J.2: A Novel Pressure-controlled Hydro-Mechanical Transmission	•	•	•			•				TB3

Efficiency Thrust Technical Barriers

Efficiency Projects

Project 1B.1: Next Steps towards Digital Prototyping of Pumps and Motors

The goal of this project is to help transform the design of hydraulic pumps and motors from a cumbersome task, requiring significant trial-and-error testing, to a modern approach driven by numerical simulation and digital prototyping. Previous research has developed fluid-structure-thermal simulation models which are capable of predicting the performance of critical lubricating interfaces inside axial piston machines. This research addresses three key areas which must be investigated before these models can be used in practical pump design. They are:

1. Only two of the three lubricating interface models have been directly validated with physical measurements to date. This project is constructing a test rig to measure the fluid film thickness between the slipper-swashplate and compare measured values to simulation results.
2. A good estimation of the pump leakage and discharge port temperatures are needed by the new lubrication models and this information is unknown at the design stage of a new pump or motor. The development of a pump thermodynamic model that solves for these unknown boundary temperatures is essential to enable practical virtual prototyping.
3. This research will use the latest virtual prototyping and optimization techniques to propose surface/material modifications to improve pump efficiency. Simulated designs will be manufactured and physically tested to validate the computational work.

Piston pumps are often at the heart of many high power hydraulic systems and are especially critical in the energy saving displacement control and hydraulic hybrid architectures, both of which are concepts that have been proposed and developed in the CCEFP. By improving the efficiency of pumps and motors over a wide range of operating conditions, it enables system designs to successfully compete with alternative technologies. This project aims to complete the three goals listed above, enabling a digital prototyping approach to a new generation of pumps and motors. Virtual prototyping represents the only practical design method to create more efficient designs, utilizing new technologies for surface shaping, material coatings and other advanced manufacturing technologies.

Project 1E.1: Helical Ring On/Off Valve Based 4-quadrant Virtually Variable Displacement Pump/Motor

The goal of the project is to demonstrate efficient, high performance control of hydraulic power using on/off valves in a throttle-less manner. This goal will be met through the development of critical enabling technologies such as novel high speed rotary on/off valves that will be integrated with fixed displacement pump/motors to create "virtually variable displacement pump/motors (VVDPM)". A prototype VVDPM will then be performance mapped using an existing CCEFP test stand. Due to limitations of the power unit and dynamometer on the test stand, prototype performance is to be mapped up to 20 MPa operating pressure and 3000 RPM shaft speed.

Pulse-width-modulation (PWM) of hydraulic power using on/off valves is a potentially efficient control concept that is analogous to switched mode converters used in power electronics. This project addresses the Center's efficiency goal by developing efficient pulse width modulated alternatives to inefficient throttling valves. By pairing these valves with fixed displacement pumps or motors of any type, variable displacement functionality can be achieved with designs that are inherently efficient or compact but traditionally fixed. The project also addresses the compactness goal by enabling variable displacement functionality using compact, inexpensive fixed displacement components.

Project 1E.3: High Efficiency, High Bandwidth, Actively Controlled Variable Displacement Pump/Motor

The goal of this project is to translate the successful fundamental research of pump chamber voiding and test bench experimental results of a three piston digital pump/motor to implementation on a test bed (hydraulic vehicle or excavator) for demonstration and industrial commercialization. This requires two outcomes: the development of optimal control strategies that allow the digital pump/motor to switch seamlessly between operating modes (flow limiting/flow diverting) while maintaining optimal efficiency and minimal noise, and the compact integration of valves and embedded controls to enable mobile operation. Full four-quadrant operation has been demonstrated in all proposed operating modes, and efficiency and noise tradeoffs were characterized for each mode. The results have been encouraging and provide motivation for a focused effort to implement a digital pump/motor on a test bed.

The project will overcome a major system efficiency limitation in the fluid power industry by improving the efficiency and dynamic performance of piston pump/motors. Regardless of the fluid power system, overall efficiency is limited by the efficiency of the primary pump/motor. Project goals will be achieved by leveraging the test bench, simulation, and experimental results to migrate the pump/motor design to a test bed. Current test bed results have demonstrated higher operating efficiencies at lower displacements, four quadrant operation, high displacement control bandwidth, and high operating pressures.

The project directly supports Thrust 1: Efficiency, and improves Test Bed 1 and Test Bed 3 overall performance. It also impacts Thrusts 2 and 3, Compactness and Efficiency, respectively. Specifically, this project overcomes the following technical barriers for each thrust:

- Efficient Components and Systems (improve P/M efficiency at low displacements)
- Efficient Control (real-time optimal control flexibility)
- Efficiency Energy Management (piston-by-piston control of energy)
- Leak Free (positive sealing poppets replacing port plates)

Project 1E.4: Piston-by-Piston Control of Pumps and Motors Using Mechanical Methods

The goal of this project is to develop simple and efficient strategies for controlling hydraulic power transformation machines (i.e. pumps, motors, or transformers) on a piston-by-piston basis. This project will focus on creating a variable displacement pump/motor that can meet or exceed existing designs in peak efficiency, and demonstrate a shallower drop off in efficiency as the displacement is decreased. By utilizing a two degree of freedom rotary valve, the expected efficiency benefits of piston-by-piston control will be achieved with a control mechanism that is simpler and more cost effective than competing research approaches.

The need for efficient hydraulic components is listed as a transformational barrier for the fluid power industry. The development of high efficiency variable displacement pump/motors is essential to overcoming this barrier. A pump or pump/motor that is more efficient than current technology is essential for realizing practical hydraulic hybrid powertrains in both on-highway and off-highway vehicles. The key element to the new design described here is a single rotary valve, which replaces multiple solenoid valves used in competing designs. This valving strategy has the potential to be more compact and less costly than current approaches, while maintaining high efficiency.

Project 1E.5: System Configuration and Control Using Hydraulic Transformers

This project investigates how hydraulic motion control systems can best make use of hydraulic transformers to improve efficiency while maintaining control performance. Various existing and novel transformer designs and system architectures will be modeled, analyzed and evaluated. Control approaches that maximize both efficiency and precision will be developed and demonstrated. These control approaches will be experimentally implemented on a transformer test bench and on the patient mover test bed (new Test Bed 4).

Transformers address the efficiency goal of the center by providing a throttle-less and regeneration capable means to control hydraulic actuators. Transformers may also be amenable to compact integration with actuators. Efficient and high performance control of actuators with appropriate form factors could expand the use of hydraulics in human scale robotic applications. Demonstration of transformer performance in the new test bed 4 (patient mover) is targeted, although transformers also have applications in hydraulic hybrid vehicles, excavators, energy storage systems, and in small scale human wearable devices as well.

Project 1E.6: High Performance Actuation System Enabled by Energy Coupling Mechanism

The goals of the project are to (1) develop the bidirectional proportional control algorithms for the Energy Coupler Actuated Valve (ECAV), (2) integrate the ECAV with both a poppet and a spool valve body and experimentally investigate the pressure-flow-time performance, and (3) develop an integrated electrical systems (driver circuits and sensor), actuator, and valve system that can be easily incorporated into center and industry projects.

This project addresses the technical barriers of efficient components and is an enabler for efficient and effective systems. Hydraulic valves are found on nearly every fluid power system in production. The core technology developed in this project: compact, modular, high performance, proportional and scalable valves are enablers or enhancers for every test bed in the center. Test beds 1 and 3 would benefit from high efficiency pumps/motors enabled by these valves, or from increased bandwidth displacement control when using current state-of-the-art variable displacement units.

Project 1F.1: Variable Displacement Gear Machine

The primary goal of this project is to formulate and develop a unique concept for variable displacement external gear machines (VD-EGMs). The new innovative design of the machine will preserve the well-known advantages of current fixed displacement EGMs such as ease of manufacturability, low cost high pressure range of operation and good operating efficiency. To reach the primary goal, the project also proposes a general and innovative design method for EGMs that surpasses the current empirical design approach used to design such units. Particularly, the project will take into consideration unconventional designs, such as non-involute or helical gear profiles. Therefore, the goals of the project can be stated as:

- Objective 1: Formulate a new design principle for VD-EGM
- Objective 2: Propose a novel and general design methodology for EGMs.

The proposed research directly addresses the technical barriers "efficient components" and "efficient systems" by introducing a new concept for a VD hydraulic machine. CCEFP is extensively researching new system concepts to minimize energy consumption of the fluid power applications, and many solutions are based on the potentials of VD units. However, the diffusion of efficient system layout architectures based on VD units is not as broad as it should be, due to the inherent high cost factor associated with VD pumps and motors. Therefore, research toward more cost effective solutions for VD units is needed in the fluid power field. By proposing a new VD design concept, this project will support the ongoing research on novel architecture and will permit a wider diffusion on more efficient systems also in low cost fluid power machines. With a strong fundamental component on the approach for designing EGMs, the research aims to surpass the current empirical methods that limit the possibilities of formulating new design concepts for EGMs.

Project 1G.1: Energy Efficient Fluids

The goal of this project is to bridge the gap between the fundamental understanding of tribology and the performance of complex fluid power systems. This goal is being pursued by characterizing hydraulic fluids in benchtop instruments, analyzing fluid efficiency effects in a hydraulic dynamometer, and modeling fluid-component interactions. Improvements in the bulk modulus, boundary friction, and shear stability properties of fluids yielded double-digit reductions in hydraulic motor friction and pump flow losses. These results have been used to develop and validate efficiency models that incorporate fundamental properties of hydraulic fluids. While significant efficiency improvements have been realized, gaps remain with respect to understanding the relationship between efficiency and the properties of the hydraulic fluids.

This project will increase system efficiency by advancing hydraulic fluid technology. The CCEFP has identified system efficiency as a major technical barrier that must be overcome to achieve the test bed performance objectives. Increased system efficiency also makes possible the use of smaller, more compact valves, pumps, and motors. This project, which incorporates the high-pressure research in project 3D.2, was used to guide the formulation of a hydraulic fluid that improved the low-speed mechanical efficiency properties of the test fluid for the hydraulic hybrid vehicle test bed (test bed 3).

Project 1G.3: Rheological Design for Efficient Fluid Power

The overall objective of this project is to increase the efficiency of fluid power components through the rational design of fluids with rheological complexity. We will evaluate the potential of nonlinear viscoelastic fluid properties, coupled with asymmetric surface textures, to meet diverse design objectives for efficiency, such as low friction, high normal stress, and low leakage. These performance enhancements will be achieved through a fundamental understanding of Non-Newtonian lubricant behavior on textured surfaces, utilizing new mathematical techniques to optimize high-dimensional complex fluid properties, and implementation of the fluid and textures in fluid power components. Target applications include reciprocating rods, as well as seals and rotating components. We will fabricate and test textured plates in a novel gap controlled tribo-rheometer. Integration of the designed Non-Newtonian fluids will be applied to the excavator and the orthosis test beds.

Fluid properties and efficiency are fundamental and applicable broadly to fluid power applications. The target application would be to overcome current barriers to fluid power systems and provide a transformational capability for future fluid power systems. The work constitutes fundamental research in the areas of fluids, tribology, and design. The project will develop expertise in fluid design for the CCEFP, creating new opportunities for engagement with industry. Designs will be validated through collaboration with industry and through application to the excavator and orthosis test beds.

Project 1J.1: Hydraulic Transmissions for Wind Energy

Wind power is a plentiful, renewable source of energy, able to produce emission-free power in the kilowatt to megawatt range. The US Department of Energy has a goal of having 20% of the nation's energy come from wind by 2030. Land-based or off-shore wind farms can provide wind energy to the grid. However, grid-connected facilities require expensive power transmission lines, typically incur significant construction and maintenance costs, and are highly regulated. A small wind facility can be a cost-effective method of power generation for areas with limited power needs, such as farms or factories. Usually, mid-sized turbines are designed as fixed speed machines which reduce costs by eliminating the power converter. However, fixed speed operation does not allow the rotor to capture the maximum energy as wind speed varies. To capture wind energy more efficiently, a continuously variable transmission (CVT) is required.

A hydrostatic transmission (HST) functions as a continuously variable transmission and eliminates the need for the gearbox. Gearbox reliability is a major issue and gearbox replacement is quite expensive. In a recent study by Reliawind, it was reported that the major components contributing to low reliability and increased downtime of wind turbines are the gearbox, power electronics and pitch systems. An HST has the potential to increase system efficiency, improve system reliability and decrease the lifetime cost of energy. The application of HST is mainly on the mid-sized wind turbine since most commercially available hydraulic components (pumps and motors) match that power level well. This reduces the technology risk of developing new hydraulic components for the turbine.

The objective of this project is to investigate the possibility of applying HST to the mid-sized wind turbine, identify the technical barriers of the hydrostatic wind turbine, explore different control methods and energy strategy to maximum energy capture, and establish a hydrostatic wind turbine test platform in the lab.

The project aligns with the Center's efficiency thrust and addresses the transformational barrier of efficient components and systems. The system efficiency of a wind turbine has three components: aerodynamic efficiency (converting the wind stream to power in the rotor shaft), drivetrain efficiency (transferring the rotor shaft power to the generator; usually includes increasing rotation speed) and electrical efficiency. Replacing the gearbox in a wind turbine with an HST lowers drivetrain efficiency, but substantially reduces maintenance and repair costs. In addition, the HST will allow the aerodynamic efficiency and generator efficiency to increase resulting in a higher system efficiency.

Project 1J.2: A Novel Pressure-controlled Hydro-Mechanical Transmission

The growing demand of fuel efficient vehicles, low carbon footprint technologies and drivability requires more efficient vehicle drives. This creates opportunities to integrate new technologies to achieve better performance with energy efficiency. The automatic transmission is a widely acceptable solution. However it is unable to maintain optimal efficiency over the entire engine operating range. In contrast, a continuously variable transmission (CVT) can decouple the engine speed from the wheel speed, making the engine run more efficiently. The hydraulic form of a CVT is a hydrostatic transmission that uses a hydraulic pump to drive a hydraulic motor. Due to its high power density, durability, continuously variable ratio and smooth operation, the hydrostatic transmission (HST) has been widely used in off-road applications such as agricultural, construction and forestry machinery.

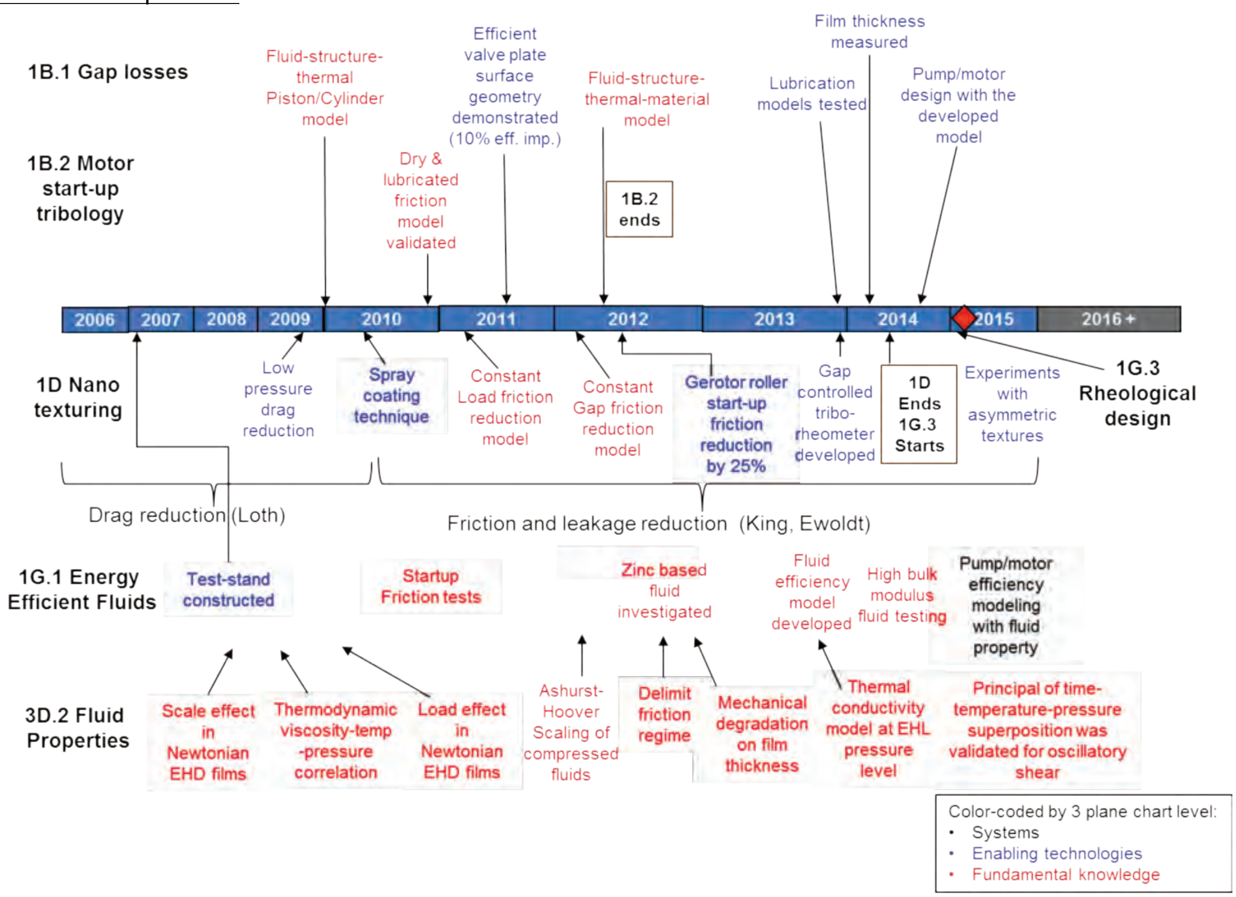
With continuously variable transmission and energy storage, full engine management becomes possible. The high power density of the hydraulic powertrain allows for lower vehicle weight, more regenerative braking and faster acceleration. The EPA's world first series hydraulic hybrid delivery vehicle has 60-70% better fuel economy and 40% or more reduction in CO2 emissions. Altair's series hydraulic hybrid city bus delivers 30% or more fuel efficiency than other diesel-electric buses available today.

The objective of the project is to develop a compact and efficient pressure-controlled hydro-mechanical transmission suitable for vehicles and mid-size wind turbines. The new transmission is expected to be as efficient as conventional HMT with planetary gears but is more compact and cost-effective. A prototype will be built in partnership with Mathers Hydraulics. The full characteristics of the transmission will be developed and validated through tests. Simulation studies will be conducted to investigate the potential of the transmission in both on-road and off-road vehicles and mid-size wind turbines.

Strategic barriers addressed include: (1) efficient components and systems (2) compact integration and (3) energy management & efficient control. The outcome of this project could result in a simple, compact, cost-effective, efficient drive with an integral clutch. In addition, it readily accommodates future energy storage for hybridization. This transmission could be integrated into the hydraulic hybrid passenger vehicle test bed (TB 3) or the wind power test bed (TB β).

Efficiency Thrust Technology Integration

Efficient Components



Efficient Components Milestone Chart

At the component level, the efficiency barrier is addressed via several approaches:

- A fundamental understanding of the losses in tribological gaps (1B.1, 1B.2)
- A fundamental understanding of fluid properties and their effects on losses (1G.1, 3D.2)
- The use of nano-texturing to reduce drag, friction and leakage (1D, 1G.3).

Gap losses

At the fundamental level, detailed computational models have been developed in Project 1B.1 to predict losses in the lubricating interfaces of a piston machines, including deformation and thermal effects (2009-2013). Some of these models have been validated experimentally. Based on these models, new surface shapes have been proposed that can increase efficiency by 10% in a prototype. The validated lubrication model was also utilized to investigate the sensitivity of energy dissipation as a function of piston-bore clearance. A new efficient pump design process based on these improved understanding and models has be developed.

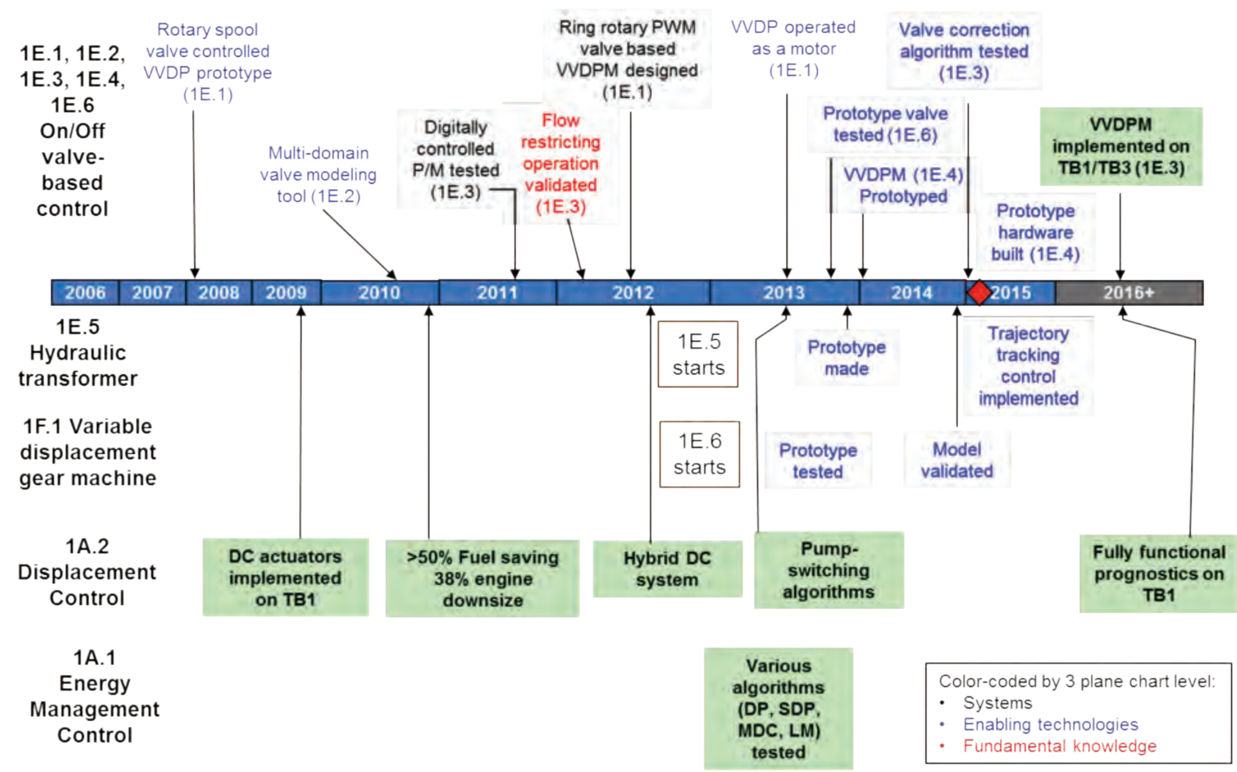
Nano-texturing

Nano-texturing research began in CCEFP with the goal of drag reduction in fluid conduits in Project 1D, under direction of Prof. Eric Loth. A robust, cheap and durable clay based nano-texturing coating was demonstrated in 2010 in low pressure operation. Drag reduction in high pressure, however, turned out to be difficult. When Prof. Loth left the Center (for a non-CCEFP institution), the project was redirected to use nano-texturing using a cost-effective manufacturing technique for friction and leakage reduction under Prof. King. Project 1D developed friction / leakage prediction models for constant load in 2011 and constant gap in 2013. In collaboration with Project 2B.2, this technique was experimentally demonstrated on geroter roller surfaces to reduce start-up friction by 25% in 2011. A gap controlled tribo-rheometer has been designed and utilized to validate the previously developed models. This device has been used in a new project 1G.3 to conduct experiments with asymmetric textures.

Fluid Properties

An unexpected effect of scale in generalized Newtonian elastohydrodynamic films was discovered in 2008. A thermodynamic scaling function for the accurate correlation of viscosity with temperature and pressure was developed in 2008. An unexpected effect of load in generalized Newtonian elastohydrodynamic films was discovered in 2009. The role of fragility in EHL entrapment was discovered 2010. A Newtonian elastohydrodynamic film thickness formula for linear piezoviscosity was found in 2010. The mechanical degradation of the liquid in an operating EHL contact was demonstrated in 2010. A molecule-based Ashurst-Hoover scaling for compressed liquids was found in 2011. Dimensionless groups which delimit friction regimes in EHL were derived in 2012. An elastohydrodynamic film thickness formula for double-Newtonian shear-thinning was found in 2012. The surprising effect of mechanical degradation on film thickness was demonstrated using measured shear-thinning response in 2012. Models for thermal conductivity at EHL pressure levels has been investigated in 2013. A thermal conductivity cell at 700MPa has been built in 2014. The principal of time-temperature-pressure superposition was validated for oscillatory shear for the first time.

Efficient Components and Systems, Control and Energy Management



Efficient Components and Systems, Control and Energy Management Milestone Chart

At the systems level, the efficiency barrier is addressed by developing:

- Displacement control strategy to replace throttling valves (1A.2)
- On/off valve based control strategies (1E.1, 1E.2, 1E.3, 1E.4, 1E.6)

- Recently with the investigation of hydraulic transformer configurations (1E.5) and variable displacement gear machines (1F.1).

Displacement control

Closed circuit displacement control was demonstrated in TB1 (2009-2011), with 56% fuel-saving, 50% cooling power reduction. A series-parallel architecture has been proposed and analyzed with the possibility of further 25% fuel saving and 38% engine-downsize (2011). Pump-switching algorithms have been developed (2013). Major future milestones include simulation and implementation of system prognostic (2016).

On/off valve based control

In Project 1E.1, on/off valves are used in a PWM method for modulating whole unit pressure and flow to create a variable displacement (VVD) pump (P) or pump/motor (PM). Two rotary valves concepts have been proposed. A rotary spool valve concept with a first prototype VVDP was developed (2008) and an optimized VVDPM prototype was successfully operated as a motor (2013).

In Project 1E.3 - individually controlled on/off valves from (1E.2, 1E.6) via different modes, and 1E.4 - mechanically timed using a rotary valve, on/off valves are used to control P/M on a piston-by-piston concept. Effectiveness of flow restricting operating strategy has been validated (2012). 1E.3's VVDMP prototype has been tested in low pressure (2012) and will be tested in TB1/TB3 in (2016). Valve correction algorithm for better efficiency has been tested on 1E.3. The VVDPM design in 1E.4 is finished and the prototype device is expected to complete soon (2015). Both projects predict significant efficiency improvement over conventional variable displacement pumps at low displacements.

Hydraulic transformers and variable gear machines

Hydraulic transformers (1E.5) are potentially a throttle-less control alternative for multi-actuator systems using a common pressure rail. Prototype device has been made (2013). A trajectory tracking control has been tested on the prototype device. Demonstration of this approach is planned for the new patient handler (TB4). Gear machines are typically fixed displacements, by making them variable, energy use can be reduced. A prototype has been tested and the model has been validated. Demonstration of this approach is planned for the cooling system in TB1.

Finally, control algorithms that optimize the overall system operation are needed to realize the efficiency and performance potentials of the systems. Algorithms are being developed in Projects 1A.1 and TB3 are targeted for TB3, algorithms developed in 1A.2 are targeted for TB1. 1A.2 algorithms are continually being implemented on TB1. 1A.1 Algorithms have been tested on a hardware in the loop platform.

COMPACTNESS

Compactness thrust projects are primarily focused on the technical barriers of compact power supplies, compact energy storage, and compact integration. Compactness also supports CCEFP's major goal of creating portable, human-scale fluid power applications.

The Center started a new funding cycle for projects and test beds in FY9. All compactness projects funded in FY7-8 were funded in FY9 and one new compactness thrust projects was added (2F.1).

The table below shows the compactness thrust projects funded in FY9 and the barriers that they address. Further details about each project can be found in the following pages and in Volume 2.

	Technical Barriers									Supported Projects and Test Beds
	Efficient Components and Systems	Efficient Control	Efficient Energy Management	Compact Power Supply	Compact Energy Storage	Compact Integration	Safe and Easy to Use	Leak-free	Quiet	
2B.2: Miniature HCCI Free-Piston Engine-Compressor				•						TB4, TB6
2B.3: Free Piston Engine Hydraulic Pump	•	•	•	•	•	•				TB3
2B.4: Controlled Stirling Thermocompressor		•		•		•			•	TB6
2C.2: Advanced Strain Energy Accumulator		•	•		•	•	•			TB3, TB6
2C.3: Flywheel Accumulator for Compact Energy Storage		•	•		•	•	•			TB3
2F: MEMS Proportional Pneumatic Valve	•	•				•		•		TB6
2F.1: Soft Pneumatic Actuator for Arm Orthosis						•	•			TB-β
2G: Fluid Powered Surgery and Rehabilitation via Compact, Integrated Systems						•	•			TB-β

Compactness Thrust Technical Barriers

Compactness Projects

Project 2B.2: Miniature HCCI Free-Piston Engine Compressor

This project has two goals. The first is to generate new knowledge about the science and engineering of homogeneous charge compression ignition (HCCI) in free-piston engine-compressors on a small scale. Such devices would be suitable as tiny power supplies for fluid power systems. The second goal is to design, build, evaluate and deliver a tiny, high-efficiency free-piston air compressor that delivers approximately 20 W of cold compressed air and runs on cartridges of clean-burning dimethyl ether (DME) fuel. The engine compressor will be suitable for projects in CCEFP Test Bed 6, such as the Portable Pneumatic Ankle Foot Orthosis, and other small scale mobile pneumatic fluid power devices including hand tools and robots.

This project supports CCEFP's goal of developing new fluid power supplies that are one to two orders of magnitude smaller than anything currently available (10 W – 1 kW). This in turn supports the CCEFP vision of revolutionary new portable and wearable applications of fluid power that operate in the 10 to 100 W range, including human assist devices. A major barrier that prevents these new applications of fluid power is the lack of a compact, light, high energy density source of pressurized fluid. This project addresses this problem with an internal combustion free-piston engine coupled with an air compressor that will be more compact, lighter in weight, and run longer than current pneumatic supplies that use a battery powered electric motor to run an air compressor.

Project 2B.3: Free Piston Engine Hydraulic Pump

The goal of this project is to provide a compact and efficient fluid power source for mobile applications (10 kW-500 kW), including on-road vehicles and off-road heavy machineries. This is achieved through the development of a hydraulic free-piston engine (HFPE).

The project will address two transformational barriers as outlined in the CCEFP strategic plan: compact power supply and compact energy storage. This is achieved by proposing a hydraulic free-piston engine (HFPE), which stores energy in hydrocarbon fuel and convert it to fluid power in real time according to the power demand, as the main power unit for on-road vehicles or off-road heavy machineries.

Project 2B.4: Controlled Stirling Thermocompressors

The goal is to design and build a second generation Stirling thermocompressor as a design evolution of the first generation device that has already been completed with CCEFP funding. The research goals are: (1) design and experimentally validate a Stirling thermocompressor for untethered fluid power applications, as driven by the challenging and representative requirements of the ankle-foot-orthosis test bed (TB6), (2) continue to pursue a dynamic model-based design approach for a Stirling-based thermocompressor based on validated models from the generation 1 device, (3) experimentally characterize the generation 2 device for model validation purposes and performance, and (4) study the scalability of technology developed for the Stirling thermocompressor from miniature pneumatic power supplies up to industrial air compressors, particularly with respect to enhancing heat transfer within the compressor to enhance efficiency. A fifth goal has been added to the project as well: (5) study different power outputs, namely a miniature hydraulic power unit based on the pressurizer portion of the thermocompressor, small-scale electric power generation, or high-pressure water filtration units. The goals of the project will be achieved by paying attention to the lessons learned from the generation 1 device from both a model-based / fundamental standpoint, as well as from an implementation standpoint.

This project contributes to two thrusts within the Center: compactness and efficiency. The compactness and efficiency barrier are addressed by developing a fluid power based, portable, and compact power and actuation system that will provide an order of magnitude greater power and energy density than the current state-of-art batteries. High heat transfer will be achieved by maximizing the heat transfer area and by utilizing pre-pressurized helium as the working fluid within the device; therefore increasing the efficiency and power density. Compactness is essential for a human assist device like the ankle-foot orthosis. By designing this small, compact device, it will be determined whether the energy/weight and power/weight advantages of fluid power will hold for small devices. The ultimate goal of this work is to fulfill the CCEFP's strategic vision of providing a source of power for untethered fluid power devices in a way that will open up whole new applications and whole new markets in robotics.

Project 2C.2: Advanced Strain Energy Accumulator

The goals of this project are to achieve accurate material characterization, address manufacturability issues, improve energy density and strength properties, and achieve distributed strain sensing by incorporating carbon nanotubes into the advanced strain energy accumulator. In year one, selection of an appropriate rubber compound for the accumulator will be completed and manufacturability issues will be addressed. In year two, carbon nanotubes (CNTs) will be incorporated into the new rubber material, the resulting material properties will be measured and compared with the baseline accumulator and distributed strain sensing using the embedded carbon nanotubes will be attempted. If successful, the carbon nanotube strain measurements will be compared with existing measurement methods. The improved rubber material can be applied to both pneumatic and hydraulic accumulators.

First, with the recent interest of Lord Corporation, Enfield Technologies, General Nano, and the Department of Defense, the project has the potential to attract new industrial partners and supporting government agencies thus supporting the sustainability portion of the Center's strategic plan. Next, the project aims to accurately characterize material properties and address manufacturability issues increasing the likelihood of successful transition to production. Additionally, with the incorporation of carbon nanotubes into the elastomeric accumulator, improvements in material properties and energy density can be realized resulting in more efficient and compact energy storage. Furthermore, the addition of carbon nanotubes has the added potential to provide a distributed sensing capability and with it, the ability to monitor the structural integrity of the component, making it safer and easier to use.

Project 2C.3: Flywheel Accumulator for Compact Energy Storage

The goal of this project is to develop a novel high energy density hydraulic storage system, the hydraulic flywheel accumulator. The system will be demonstrated in a bench top prototype with an energy density of 18 kJ/kg, which is three times higher than a conventional carbon fiber-wrapped accumulator. The target round-trip efficiency for the prototype energy storage device is >80%.

The hydraulic flywheel accumulator can theoretically increase the energy density of hydraulic energy storage by over an order of magnitude while maintaining, good round-trip (storage-regeneration) efficiency. Overcoming the energy density barrier is key to implementing a hydraulic hybrid power train in a passenger vehicle. The proposed work will demonstrate the hydraulic flywheel accumulator at an energy density of three times that of an advanced conventional accumulator, while generating the modeling, simulation, and optimization tools necessary to further increase the energy density in follow-on work.

Project 2F: MEMS Proportional Pneumatic Valve

The goal of this project is to utilize Micro-Electro-Mechanical (MEMS) technology to create extremely efficient proportional valves for pneumatic systems. The valves are expected to require under 5 milliwatts of actuation power to hold them in the fully open state while producing a maximum flow rate of 40 slpm when venting from a pressure of 6 bar to 5 bar. They are also compact: the target envelope of the valves is just 4 cc. Supporting goals of this project include: leveraging the potential of piezoelectric materials such as lead zirconate titanate (PZT), developing MEMS-scale sealing technologies and developing position sensing strategies for the MEMS scale devices.

This project has breakthrough potential toward the Center's transformational strategic goal of developing efficient fluid power components. While we are developing generic proportional valves, the extremely low power requirements and compactness of these valves make them especially attractive for portable and mobile applications. The project also contributes to the Center's goals of developing leak-free systems and compact integrated systems. The project involves developing original sealing technologies for MEMS scale valves, a technology necessary for bringing these valves to commercial markets. The project was originally inspired by, and will be showcased on, the Ankle-Foot Orthosis of Test Bed 6.

Project 2F.1: Soft Pneumatic Actuator for Arm Orthosis

This newly-funded project has two main goals: to develop novel high-force, energy storing, miniature soft pneumatic actuators, and to directly integrate them as the structure for soft robotic upper extremity orthoses for pediatric patients that use crutches for ambulation. While walking with crutches, peak loads observed in the wrist typically approach 50% of body weight and wrist postures experience extreme extension angles ~35°. We seek to develop a light-weight (< 1 kg), pliable (tunable modulus of rigidity), powered (by <100 psi) wrist orthosis and integrated compact actuators to reduce transient loads and associated wrist stresses by 50% and improve wrist posture to a more neutral position; therefore lowering the risk for joint injury such as carpal tunnel syndrome, while allowing for normal wrist and arm range of motion when not used for load bearing. To this end, we will develop new knowledge and tools for the design-for-manufacturability of soft pneumatic actuators known as Fiber Reinforced Elastomeric Enclosures (FREE). We will expand the range and functionality of current contracting McKibben muscles, which are based on simple equal and opposite fibers, by developing a robust analysis framework to generalize the construction and operating principles for FREE actuators to yield different deformation patterns. Further, we will develop a new manufacturing process where flat elastomeric sheets patterned with variable angle vascular microchannels and high strength fibers will be rolled into generalized FREE actuators to provide higher energy density at the same operation pressure and additional deformation patterns: expansion, rotation, and spiraling snake-like motion to produce compressive forces, torque, and constriction forces, respectively.

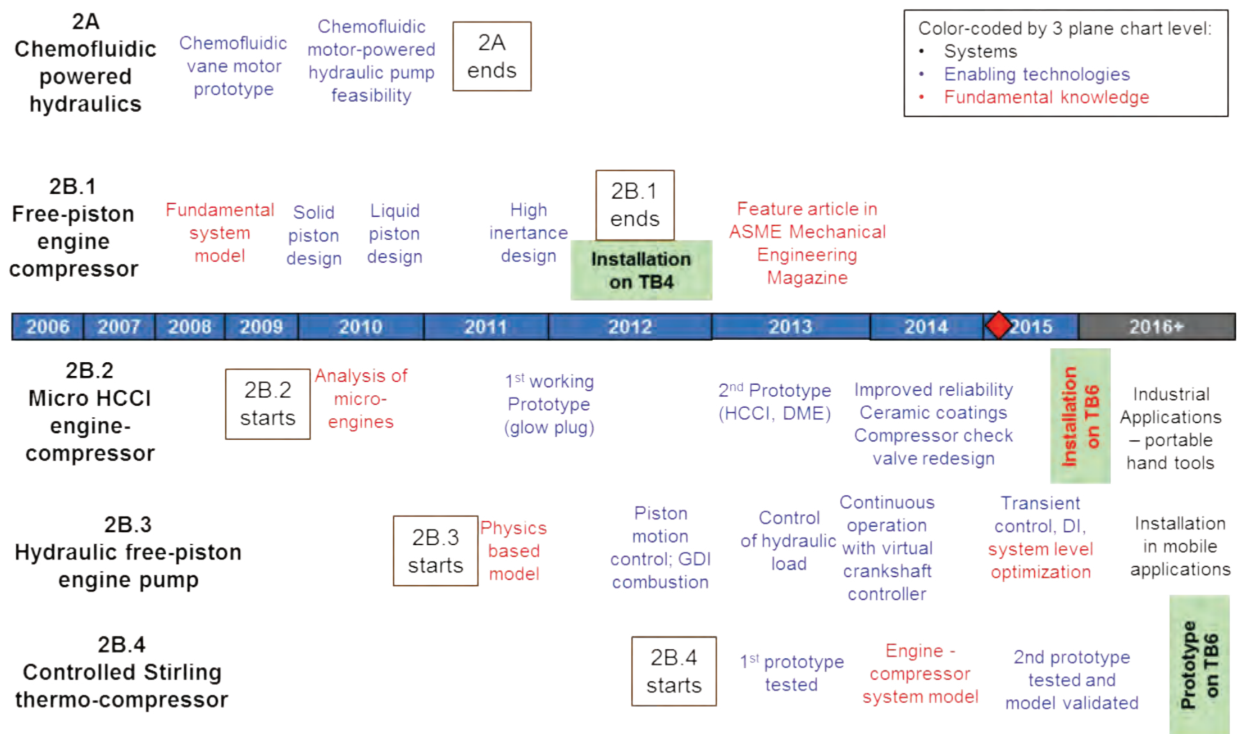
The development of miniature soft pneumatic actuators and soft pneumatic arm orthosis directly address one of the four major goals of the Center, namely the development of “new miniature fluid power components and systems … that are one to two orders of magnitude smaller than anything currently available”. This project will also address at least four of the nine technical barriers to fluid power: compact energy storage (5), compact integration (6), safe and easy-to-use (7), and quiet (9). Further, the pediatric wrist orthosis would be an added test bed platform that complements the work being accomplished on the pneumatic ankle-foot orthosis of Test Bed 6 (Human Assist Devices) at the University of Illinois. The development of compact, light-weight, high-force, energy storing, soft fluid powered actuators has the potential to revolutionize the creation of portable medical assistive devices such as powered prosthetics and orthotics.

Project 2G: Fluid-Powered Surgery & Rehabilitation via Compact, Integrated Systems

The research goal is to extend fundamental understanding of the unique characteristics of fluid power that enable precise machines to withstand intense magnetic fields. Toward this end, the project will develop compact systems where actuators, mechanisms, and sensors are no longer independent entities assembled together, but are a single integrated system that can be manufactured simultaneously using additive manufacturing. Magnetic Resonance Imaging (MRI) compatible devices are the perfect focusing application for this research. In surgery MRI provides exquisite soft tissue resolution, but robots are required to effectively make intraoperative use of this information. In rehabilitation, functional MRI (fMRI) offers the unique ability to visualize brain activity during therapy. Fluid power is an essential enabler in both contexts, because traditional electromagnetic actuators fail (or cause artifacts) in intense magnetic fields.

We aim to break the Major Technical Barriers relating to 1) Compact integrated systems (by designing systems where actuators, mechanisms, and sensors are not separate entities), and 2) making fluid-power systems safe and easy to use (new force sensors will ensure human safety when interacting with machines in an MRI). Furthermore, we will break a Transformational Barrier by applying fluid power in medicine.

Compact Power Supplies Technology Integration



Compact Power Supplies Milestone Chart

Compact Power Supplies aim to break the barrier of adequately energy dense sources of fluid power. This technological gap exists in not only for fluid power, but also more generally for applications requiring self-contained power systems within the human power scale range of 10W to 1kW. Breaking this barrier will require not only a high systems-level energy density, but also actuation that is adequately power dense. The high power density of hydraulic and even pneumatic actuation relative to other forms of actuation makes fluid power a logical arena of investigation. The lack of compact power supplies in the 10 kW – 500 kW range also exists, but represents a different application domain. The free piston hydraulic pump (2B.3) addresses these applications – such as series hydraulic hybrid vehicles – by matching the dynamic power demand.

Projects pursued with the CCEFP toward compact power supplies have included the following:

- Chemofluidic hot-gas pneumatics (associated project)
- Chemofluidic vane motor / hydraulic pump (2A)
- A high-inertance, liquid-piston, free-piston engine/compressor (2B.1)
- A micro HCCI engine/compressor (2B.2)
- A hydraulic free-piston engine pump for vehicle applications (2B.3)
- A controlled Stirling thermocompressor (2B.4)

These projects have utilized the following high energy density fuel sources: high concentration hydrogen peroxide (2A), propane (2B.1, 2B.4), dimethyl ether (2B.2), gasoline or diesel (2B.3), flexible fuel sources such as butane, methane, ethanol, natural gas, gel fuels, solar, or bio-mass (2B.4).

The overall system energy density of each approach (kJ of energy available for actuation work, per kg of the combined mass of the fuel and the convertor) can be found from the fuel specific output work, the mass of the convertor, and the mass of fuel carried (application specific). It should also be noted that increases in energy density are only half of the story. The use of fluid power presents a power density advantage over other power supply and actuation systems by using lightweight, high-power, fluid power actuators. By combining a high energy-density source with a high power-density actuation scheme, and tying them together in an efficient manner by utilizing the same energy domain, results in overall systems that are more capable and have better run-time longevity between refueling than other power supply and actuation system pairings, particularly in the 10W to 1kW range. Such an analysis can also be performed on a volume-specific, as opposed to a mass-specific basis, with similar conclusions.

The chemofluidic vane motor driven hydraulic pump was ended in 2011. Although shown over short running durations to be a viable approach, engineering challenges associated with sealing around the vanes in the presence of thermal expansion will require resources beyond those available to a university.

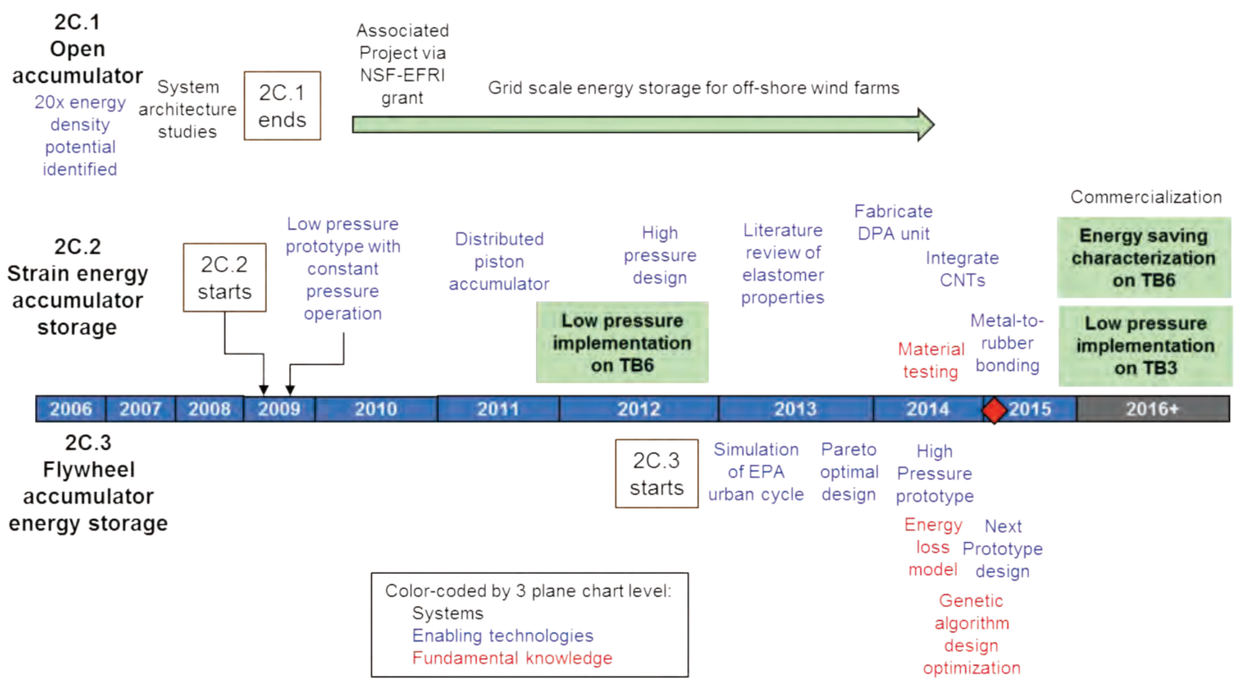
The free-piston engine compressor (2B.1) targeted for TB4 ended in 2012. Researchers developed a fundamental dynamic model of the engine compressor in 2009. This model allowed the model-based design iteration of several prototypes (solid piston in 2007, liquid piston in 2007, and high-inertance liquid piston in 2011). The project was featured in ASME's Mechanical Engineering Magazine in 2013. Accomplishments include an experimentally demonstrated efficiency of 8.1% and delivery of compressed air up to 1.2 MPa (about 160 psig). A specific work (usable stored energy per unit mass of fuel) ranging from 2040 kJ/kg to 3750 kJ/kg was experimentally demonstrated (as compared to 700 kJ/kg for Li-ion batteries).

The micro-scale homogeneous charge compression ignition (HCCI) free-piston engine-compressor (2B.2) was originally targeted for the orthosis (TB6) but is now being considered for other small-scale pneumatic fluid power devices such as hand tools and robots. Detailed modeling and analysis was completed in 2010, leading to a learning prototype and first working prototype in 2011. Detailed measurements were made in 2012. Efforts in the 2013 included improving reliability and performance by addressing the fundamental interaction between the piston and the cylinder liner. In 2014 efforts were focused on improving the runtime through materials and component design, and using measurements to develop a model of the compressor section. Future efforts will include continued development of the compressor model and hardware improvements with an emphasis on low-friction coatings and improvements to the check valves of the compressor section.

The hydraulic free-piston engine-pump (2B.3) is targeted for a higher power range (10 kW – 500 kW) than the other projects of this category. This project aims to take advantage of the control opportunities that a free-piston engine driving a hydraulic pump present. High fidelity, high bandwidth control makes the hydraulic free-piston engine-pump a viable power plant for hydraulic hybrid vehicles, as well as off-road vehicles. A physics based model was developed in 2011. Control of the engine with GDI combusted was demonstrated in 2012. Work during 2013 focused on a transient control method involving the design of a combustion detection mechanism and modification of the existing active control algorithm. This transient controller was implemented and experimental results demonstrated its effectiveness. Other accomplishments in 2013 included experimental measurement of the losses of the engine that showed a 64% reduction in engine losses over those of a conventional ICE. Accomplishments in 2014 included the integration of a custom designed high pressure fuel injection system, feedforward controllers to improve piston tracking performance that have experimentally demonstrated effectiveness, and continuous combustion which marks a first as no previous experimental results have been published showing such FPE operation. Future plans include trajectory-based combustion control development, enhancement of HFPE system capabilities via a supercharge system and other new subsystems, and optimization of the HFPE for mobile applications.

The Stirling thermo-compressor approach (2B.4) uses a Stirling heat engine to drive a compressor. This compact power approach also utilizes high energy density hydro-carbon fuel, but only as an external heat source and as such is fuel agnostic and could operate with any source offering high temperatures and high heat-flux. The Stirling thermocompressor is expected to be quiet – indeed tests of the prototype in 2014 showed it to be nearly silent. It also escapes many of the challenges of the internal combustion-based (or decomposition in the case of 2A) approaches such as high temperature sealing, friction, thermal expansion, and cycle-to-cycle variations. The first prototype of the device was tested in 2013, focusing on enhanced heat transfer using novel in-cylinder heat exchangers. Based on the measurements made, portions of the system model of the first prototype were validated. Work in 2014 saw the formulation of a system model of the entire engine-compressor, added a second hydraulic power output option to the model, and saw fabrication and testing of the second prototype. The second prototype built and tested in 2014 was made of stainless-steel and Inconel. It was tested with helium as the sealed working fluid at pressures between 10 and 20 bar and heater temperatures between 250° C and 500° C. The first-principles model of the engine was experimentally validated over a wide range of operating conditions. Near term plans include trying to work with Oak Ridge National lab's Manufacturing Demonstration Facility to 3D print a prototype that presents never-before-seen opportunities for innovative internal structures for flow and heat transfer. A final prototype that is fully functional as a stand-alone unit is expected in late 2016.

Compact Energy Storage Technology Integration



Compact Energy Storage Milestone Chart

The energy density of a conventional hydraulic accumulator (~ 7 kJ/kg for a gas charged accumulator) is two orders of magnitude less than electric batteries (~700 kJ/kg for Li-ion batteries). A goal of the Center is to increase the energy density of a fluid-power energy storage device by an order of magnitude, while preserving the superior power-density of fluid power systems over electrochemical systems, in order to make applications such as hydraulic hybrid passenger vehicles feasible. The development of such an accumulator would allow highly effective regenerative braking as well as highly efficient engine management. The CCEFP has supported 3 approaches to date:

- Open accumulator (2C.1)
- Strain energy accumulator (2C.2)
- Flywheel accumulator (2C.3).

Open accumulator (2C.1)

This project proposes to store energy by compressing air from the atmosphere to high pressure. The theoretical energy density was shown to be more than 20 times that of conventional gas-charged accumulators. A configuration that enables constant pressure operation was proposed in 2007. While progress was made to increase the efficiency and power-density of the compressor/expander, it was determined that this approach is a mismatch for the hybrid passenger vehicle test bed since the compressor/expander size would exceed the size of the open accumulator. Furthermore, analysis by the TB3 team found that the energy storage for ~200kJ would be sufficient for a hydraulic hybrid passenger vehicle. Thus, the target to increase energy density ten-fold can be relaxed. The open accumulator ended as a CCEFP core project and is now an associated project to develop utility scale wind energy storage with NSF-EFRI program support (2010). The technology has been licensed to two companies.

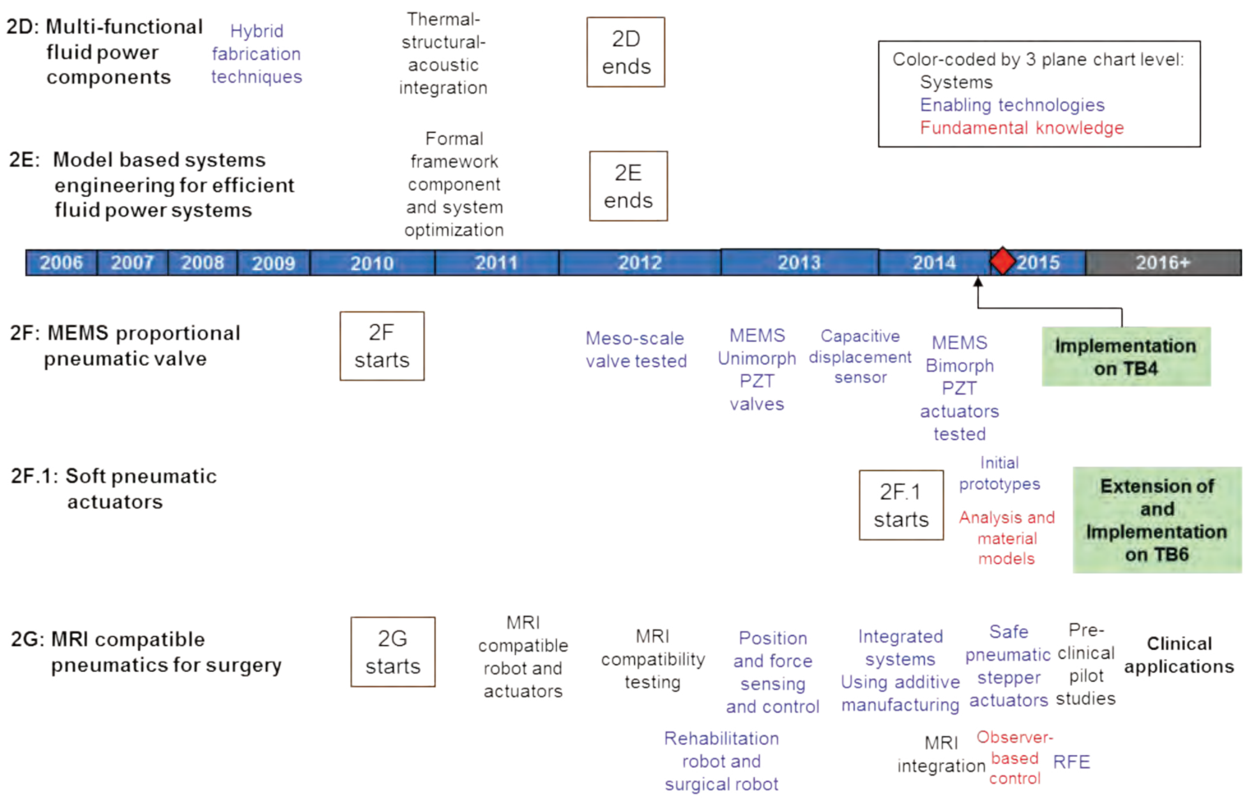
Strain energy accumulator (2C.2)

This project proposes storing energy in the strain of an elastomer. This shift from compressed gas energy storage (the energy storage mechanism in current accumulators) to strain energy as the storage mechanism comes with advantages as well as challenges. Advantages include a potential 2 to 4 times increase in energy density over gas-charged accumulators. Other advantages include lower expected cost and less frequent expected maintenance. A low pressure prototype with near constant pressure operation and 85% efficiency was demonstrated in 2009. Various improved architectures, including a distributed piston elastomeric accumulator (DPEA) configuration, were subsequently defined in 2011. A low pressure pneumatic version of the device was installed on TB6 (2012) and showed a 27% energy savings over not using an accumulator. In 2013, a broader investigation of energy savings in pneumatic system was started. New work on the hydraulic version was also started in 2013 that included a more fundamental study and investigation of material properties. The inclusion of carbon nanotubes into the elastomer will be investigated through the remainder of the project's life. The CNTs have the potential to not only strengthen the material, boost strain energy density, and improve fatigue characteristics, but it also has the potential for integrated sensing. In 2014 achievements included (1) identifying the rubber type best suited for pneumatic and hydraulic applications in collaboration with Lord corporation, (2) work with Lord corporation to address and overcome manufacturing issues by identifying an adhesive (Chemlok) that bonds rubber to metal with a strength that exceeds the strength of the rubber, (3) identification of the carbon nanotube type and supplier (University of Cincinnati), and (4) material property tests on rubber specimens that can are capable of damage detection. Near-term future work will include conducting tests of new accumulators on TB6 with a characterization of energy savings, and a push to move the technology readiness level from 3 to 5. Installation and testing of a low pressure prototype on TB3 is expected in (2016).

Flywheel accumulator (2C.3)

This project was added in 2012. It stores energy in two domains: compressed gas and rotational kinetic energy. The use of two energy domains adds a degree of freedom that allows shaping of the pressure-volume profile. Theoretically, this has the potential to increase energy density by an order of magnitude. Progress in 2013 included a design optimization for a simulated hydraulic hybrid powertrain performing the EPA Urban Dynamometer Driving Schedule. A simulation of an un-optimized design indicated an energy density of 26 kJ/kg and an efficiency of 84%. Progress in this last year 2014 included (1) an energy loss model, (2) a genetic optimization method was applied to the design for application to a hybrid vehicle was performed, (3) a detailed design of the next prototype was completed. Future work will include the fabrication and experimental characterization of the new prototype.

Compact Integration Technology Integration



Compact Integration Milestone Chart

Advancing compact integration of fluid power systems will enable new applications and potentially whole new industries. Projects within the Center that have or are currently addressing compact integration include:

- Multi-functional fluid power components (2D)
- Model based systems engineering for efficient fluid power systems (2E)
- MEMS proportional pneumatic valve (2F)
- Fluid Powered Surgery via Compact, Integrated Systems (2G Vanderbilt/MSOE)
- Fluid Powered Rehabilitation via Compact, Integrated Systems (2G Georgia Tech/MSOE)
- Soft Pneumatic Actuator for Arm Orthosis (2F.1)

The Center has had two projects (2D) and (2E) that directly addressed (1) how discrete components are to be integrated to satisfy functional requirements, and (2) to develop formal system analysis and design methodology for fluid power systems, respectively. Both projects ended and as of June 2012. Compact integration is now being pursued through three Center-funded projects: MEMS Proportional Pneumatic Valve (2F), a new project entitled “Soft Pneumatic Actuator for Arm Orthosis” (2F.1), and Fluid Powered Surgery and Rehabilitation via Compact Integrated Systems (2G).

On a component level, Project 2F, started in 2010, is developing MEMS-based high-flow, high-bandwidth, compact and low actuation power pneumatic proportional valve to satisfy a need in TB6. Targets to this end are 5 milliwatts of actuation power for a fully open state with a flow rate of 40 SLPM under conditions of upstream and downstream pressures of 6 and 5 bar respectively. These extremely compact, low-power, high-flow valves are intended for portable and mobile applications such as the Ankle-Foot Orthosis (TB6). This project leverages MEMS fabrication techniques and uses an array of small orifices controlled by piezo-actuators to achieve compactness that is not available with a discrete single orifice valve. A meso-scale prototype was demonstrated in (2012) and the fundamental question was answered in the affirmative of whether an array of many small orifices is equivalent to one large orifice of equal area in (2013). Progress in 2013 also included (1) demonstration of a MEMS unimorph PZT actuator array, (2) capacitive displacement sensor, (3) measured actuation voltage vs. PZT deflection displacement, (4) measured actuation vs. flow rate up to 100 psi. Progress in 2014 included: (1) the first successful bimorph MEMS actuators were fabricated and tested, (2) three wafers of bimorph actuators were fabricated that include many variants that can be tested, and (3) three styles of port plates were designed to match actuator geometries. Milestones for the upcoming year include developing a process to align and bond actuator arrays to port plates, performance mapping of the first complete MEMS pneumatic valve, reduction of leakage, and an optimization of the valve design for application to the Ankle-Foot Orthosis test bed (TB6).

The newly funded project 2F.1: Soft Pneumatic Actuator for Arm Orthosis seeks to develop novel high-force, energy storing, miniature soft pneumatic actuators that can be directly integrated into soft robotic upper extremity orthoses. This exciting new project addresses a need for such soft actuation and requires significant theoretical development of Fiber-Reinforced Elastomeric Enclosure (FREE) actuators. Through rigorous theoretical treatment, these actuators can be designed for various deformations, force vs displacement and torque vs rotation relationships. Initial progress already includes (1) an analysis method for large deformation behavior, (2) a material model of hyperelastic membranes to carry out the elastokinetic analysis, and (3) initial testing of preliminary prototypes. Future plans include design tools, manufacturing processes, and the testing of prototypes on human subjects.

Compact component integration is a necessary aspect of project 2G (Fluid Powered Surgery and Rehabilitation via Compact, Integrated Systems) and is actively being pursued in test-bed 6. This “project” pursues two closely related projects spread across three CCEFP institutions that share the demanding constraints of operating within the tight confines of an MRI scanner and operating while the machine is imaging. One project (lead by Georgia Tech and supported by MSOE) is developing an fMRI compatible force sensor for a haptic interface for rehabilitation. By applying and monitoring forces, this will allow the visualization of brain activity during therapy. The other project pursues the design and control of an MRI-compatible surgical robots for a non-invasive approach to access and apply thermal therapy to the hippocampus area of the brain for the treatment of epilepsy. Both projects take advantage of the fact that fluid power is one of the few ways (and it can be strongly argued that it is the only effective way) to perform actuation while simultaneously taking images. Other forms of actuation interfere with the imager leading to garbled images. Both projects utilize additive manufacturing support from MSOE to fabricate sensors, actuators and kinematic structures that are both (1) MRI compatible by having no metal, and (2) highly integrated and compact so the robots fit within the confines of the MRI scanner bore. Project 2G therefore aims to break two barriers identified by the Center: (1) compact integrated fluid power systems, and (2) making fluid power safe and easy to use. The results of this project will open up fluid power to new markets within medicine. Progress has included (a) a 5 DOF surgical robot that achieved a mean needle tip placement error of 1.18 mm, (b) invention of an intrinsically-safe MRI compatible pneumatic stepper actuator, (c) a pneumatically driven tele-operated platform for the rehabilitation of hemiparesis, (d) two MRI-compatible sensors: rotary displacement and force sensing. Progress in 2014 included: (1) design and testing of a RF ablation electrode and an accompanying concentric tube needle, (2) mature actuation hardware for the novel transforamenal ablation approach including the invention, fabrication, control and testing of an intrinsically safe MRI-compatible pneumatic stepper actuator, (3) observer-based control of tele-operated pneumatic systems using a force sensor to overcome pneumatic line delays, (4) modeling of pneumatic line transmission delay and attenuation, and (5) design of a repetitive facilitation exercise (RFE) using a pneumatic device. Plans for the future include further testing of both projects in MRI scanners.

EFFECTIVENESS

The effectiveness thrust addresses the technical barriers of making fluid power safe and easy to use, leak-free and quiet. The thrust also supports the Center's major goal of making fluid power ubiquitous and capable of being used anywhere.

The table below shows the effectiveness thrust projects funded in FY9 and the barriers that they address. Further details about each project can be found in the following pages and in Volume 2.

	Technical Barriers									Supported Projects and Test Beds
	Efficient Components and Systems	Efficient Control	Efficient Energy Management	Compact Power Supply	Compact Energy Storage	Compact Integration	Safe and Easy to Use	Leak-free	Quiet	
3A.1: Operator Interface Design Principles for Hydraulics	•	•					•			TB1, TB4
3A.3: Human Performance Modeling and User Centered Design	•	•					•			TB4, TB6
3B.3: Active Vibration Damping of Mobile Hydraulic Machines	•	•				•	•		•	TB1
3D.1: Leakage Reduction in Fluid Power Systems	•							•		TB1
3D.2: New Directions in Elastohydrodynamic Lubrication to Solve Fluid Power Problems						•	•			1G.1
3E.1: Pressure Ripple Energy Harvester			•		•	•	•			TB1

Effectiveness Thrust Technical Barriers

Effectiveness Projects

Project 3A.1: Operator Interface Design Principles for Hydraulics

This project will consolidate results on multi degree of freedom interfaces over the range of speeds, dimensions, numbers of interfaces, extent of automation and interface modalities found with hydraulic actuation. Experimentation via excavator simulation and simple displays has been the principle source of data up to this point. Studies performed on the Georgia Tech excavator simulator have illustrated a potential double-digit percentage improvement in efficiency and economy when using advanced hand controllers, however these studies have been inconsistent. Another goal for this project is to determine the root of these inconsistencies, providing a better understanding of how user interface drives performance. The intuitiveness of hand controllers, position versus velocity control, and the effectiveness of selected data presentation modes will be evaluated.

The project supports the strategic plan's call to make fluid power effective, safe and easy to use. The Strategic Call for Proposals prioritizes high efficiency and effective system control, both of which are central to this project. Previous work has shown higher task efficiency as measured by soil moved per unit fuel consumed and soil removed per unit time when advanced and intuitive controls are used. Reasonable questions about the application of these advanced controls to the full range of fluid power applications still remain. It is known that dynamically slow machines favor human interfaces with velocity commands whereas dynamically faster machines favor interfaces with position commands, but the boundary condition between fast and slow is not well defined. When selecting a human interface for a task, the most intuitive controls are the most efficient, but the most intuitive controls can lack ergonomics and lead to rapid operator fatigue. The transition from one type of human interface to another depends on the task, and because fluid power is being applied to a huge range of tasks with different characteristics it is valuable to understand how to select an optimal interface. Excavators, patient transfer devices and high-speed robotic arms do not share an optimal interface or control strategy. This project will quantitatively justify interfaces and controllers based on task characteristics.

Project 3A.3: Human Performance Modeling and User Centered Design

The goal of the project is to investigate human performance in complex fluid power systems where human operators interact with the machines, and to use user-centered design approach to develop human machine interface for selected fluid power systems (test beds) that are user-centered, safe, easy and comfortable to use.

This project will address the effectiveness and efficiency barrier by comprehensively assessing fluid power system operator performance, by developing a quantitative human-machine interaction model that will help excavator designers better understand the limits of cognitive and physical capabilities of human operators of fluid power systems. These quantitative models would be used to predict operator performance in an effort to develop a safe, intuitive, efficient and effective user interfaces for selected test beds. Further, this project will address the effectiveness barrier through the application of user centered design techniques/tools to improve the interfaces of emerging as well as existing fluid power systems by soliciting user needs and observing users interact with fluid power systems both in simulated laboratory environment and in real world scenarios.

Project 3B.3: Active Vibration Damping of Mobile Hydraulic Machines

The goal of the project is to develop a novel energy-efficient control methodology to reduce vibrations in hydraulic machines. The proposed control strategy has potential to replace or limit costly and energy dissipative methods currently utilized to achieve acceptable dynamical behavior in mobile fluid power applications. The novel solution would allow for a reduction of both amplitude and duration of actuators oscillation up to 70%. The solution offer also margin of energy consumption reduction. Based on an adaptive control method based on pressure feedback (using pressure sensors located in well protected locations of the machine), the proposed techniques is suitable to all mobile applications without introducing significant cost increase.

This project is related to the “control and controllability” topic, and addresses the major technical barriers of “control and energy management” and “efficient systems”. In particular, the project proposes an innovative adaptive electro-hydraulic (EH) control methodology for general application to fluid power machines that permits to reduce machine vibrations according to a general and inexpensive technique that addresses the inherent nonlinearities of the hydraulic systems and the unpredictable operating conditions of the machine (e.g. varying inertia of the load, terrain roughness, variable geometrical configuration of the booms, etc.).

The proposed control method has positive implications as concerns safety, efficiency, controllability and productivity of current FP machines. Moreover, the novel EH method will allow: a) the simplification of current hydraulic circuits, through the removal of elements normally introduced to improve system dynamical behavior; b) to enlarge the area in which fluid power technology can be conveniently applied.

Project 3D.1: Leakage Reduction in Fluid Power Systems

The objective of our most recent work is to reduce the friction of rod seals while, at the same time, preventing leakage. Over the last several years there has been substantial tribological research on reducing friction by the application of micro-patterns on mating surfaces using laser texturing and photolithography. This has been applied to such machine elements as journal bearings, piston rings and mechanical seals. The present study takes a similar approach, applied to rod seals, initially considering a pattern of micron-scale triangular cavities in the surface of the rod. A numerical model consisting of a fluid mechanics analysis, utilizing a two-dimensional Reynolds Equation, and a contact mechanics analysis, utilizing the Greenwood-Williamson model, is used to investigate the effects of the micro-pattern on seal friction and leakage, as well as on the fluid pressure and contact pressure distributions in the sealing zone, and on the film thickness distribution. Both flooded and starved lubrication conditions are considered, with the two giving very different results.

The project addresses the Center’s effectiveness thrust by providing tools and physical understanding that will allow the development of seals that will eliminate or substantially reduce leakage and friction from fluid power components such as actuators, valves and pumps. It constitutes fundamental research, which will have long term benefits. Reducing, ideally eliminating, leakage is a major barrier to expanding the benefits of fluid power to many new applications and will improve the system’s performance and lessen maintenance costs in existing applications.

Project 3D.2: New Directions in Elastohydrodynamic Lubrication to Solve Fluid Power Problems

The goal of the project is to transform elastohydrodynamic lubrication into a quantitative field, able to provide solutions to problems in fluid power. This is a basic research program intended to support applied research in fluid power. There are five thrusts to this project. Much of the work will be done concurrently since progress depends upon collaborators in laboratories scattered around the world working on different schedules. The research thrusts are:

- Extending the pressure range for shear-dependent viscosity measurement
- Demonstrating the prediction of friction from primary properties
- Rheology of degraded oil
- Accurate prediction of minimum film thickness in EHL
- Solution of Navier-Stokes for piezoviscous liquids

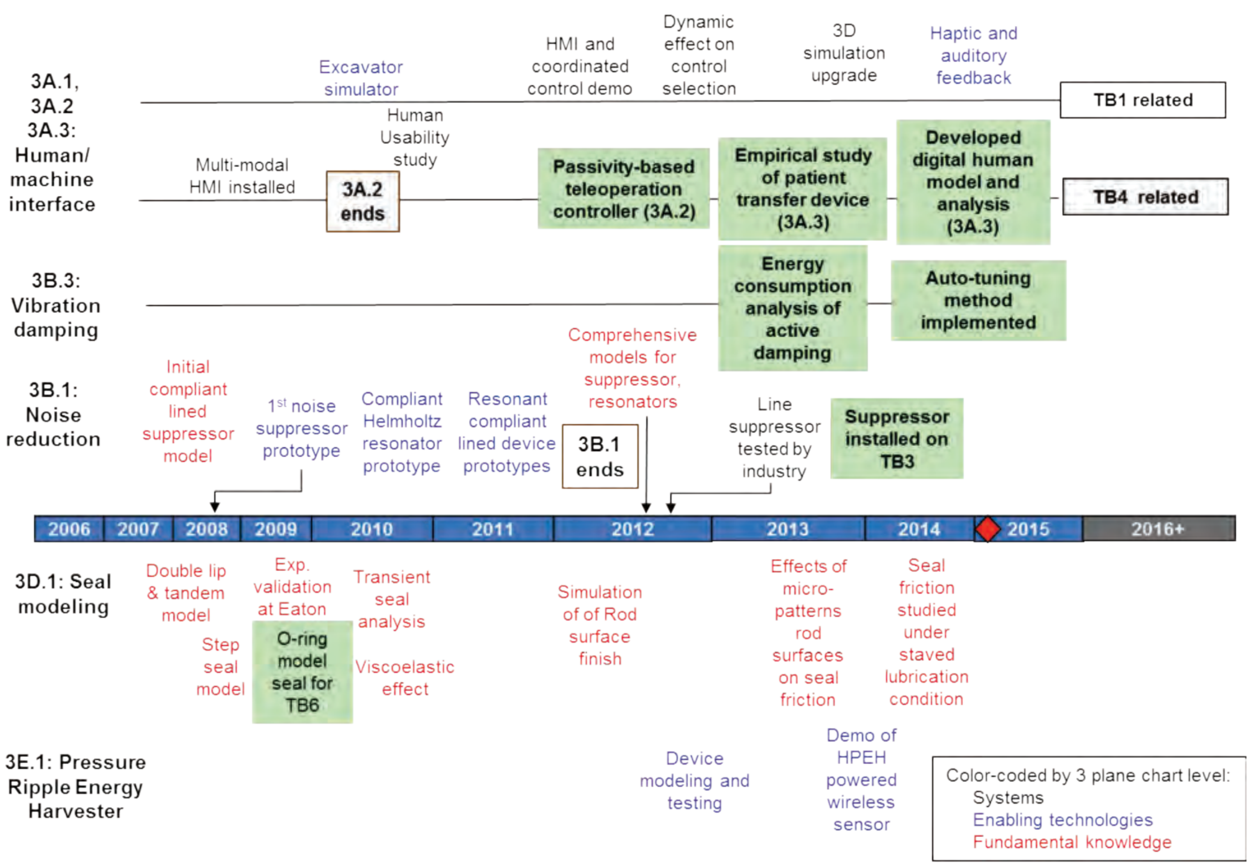
The project addresses the Center’s compactness and efficiency thrusts. More compact components must necessarily have smaller radius of curvature of the contacting elements. A clear strategy for making more compact components is also to increase the operating pressure. The resulting increase in load and decrease in radius of curvature of the sliding/rolling elements will result in diminished film thickness. The reduced film must impact the reliability. New insights into the effects of scale, load and lubricant degradation are being provided by this project.

Project 3E.1: Pressure Ripple Energy Harvester

The goal of this project is to model, develop and prototype energy harvester devices capable of producing useful power from pressure ripple in high-pressure hydraulic systems. The application of the devices is for powering sensor nodes within a fluid hydraulic system, as may be used for health monitoring or data acquisition applications. This project has fulfilled all of its initial project goals, including proof-of-concept devices with demonstrated performance for powering of wireless sensor nodes. In addition, detailed design models have been developed and validated. Current research goals include exploration of means to increase the power conversion efficiency at low hydraulic noise levels, as well as developing means to improve efficacy at high static pressures. Full funding of this project ended in May, 2014; current funding is for graduate student support, only.

The research is predominately focused in the effectiveness thrust, in that it enhances the utility and efficiency of hydraulic systems. Further, it is enabling of compact and efficient implementation of self-powered sensors and control capabilities, relevant to the Efficiency thrust. Such capability, for example, is relevant to sensing systems considered for Test Bed 1. The technology could reduce the overall system complexity, improve reliability, and reduce maintenance contact.

Effectiveness Technology Integration (Quiet, Leak-Free, Safe-and-Easy-to-Use)



Effectiveness Thrust Milestone Chart

<u>Safe and Easy to Use</u>

Safe and intuitive operation in human-machine interactive devices was addressed Project 3A.1. Project 3A.2, which graduated in 2010, investigated passified control methods to ensure safe operation. Project 3A.3 is investigating fluid power system operator performance by developing a quantitative human-machine interaction model that will help excavator designers better understand the limits of cognitive and physical capabilities of human operators of fluid power systems. Project 3B.3 for active vibration damping also enhances effectiveness of human operation by reducing undesired vibrations that worsen controllability, reduce productivity and adversely impact operator comfort and fatigue and safety of operation. These projects target test beds 1, 4 (old and new) 6.

Test Bed 1-related

A functional excavator simulator was achieved in 2010. This was used to conduct human usability study to evaluate haptic controlled excavator. An operator performance evaluation framework was developed in 2010. The developed HMI and coordinated control was demonstrated on TB1 in 2011 and showed the superiority of coordinated control over the traditional method in 2012. A new design of coordinated control interface was tested in 2012. A hypothesis of dynamic effects on optimal selection of control was also tested in 2012. The 3D simulation system has been upgraded in 2013. Hatpic and auditory feedback for operator will be tested in the near future.

Test Bed 4-related (rescue robot)

A multi-modal human-machine interface was installed in 2009. Although project 3A.2 officially ended in 2010, a passive pneumatic teleoperation and human power amplifying controller was implemented demonstrated on TB4-rescue robot in 2011-2012 by the student researcher in 3A.2.

New Test Bed 4-related (patient mover)

Energy consumption analysis of active vibration damping has been finished. Auto-tuning method has been tested to reduce vibration in 2014. Empirical study of patient transfer device (3A.3) has also been conducted in 2013. Digital human model has been developed in 2014 and applied for analyzing the patient transfer device.

Leak-free

Project 3D.1 has made significant progress on the development of numerical models to predict the performance of various kinds of seals: lip and tandem seals, step seals, seal with difference surfaces (2007-2013). Some experimental validation of the modeling has also been done. From these models, leakage regimes were identified which lead to better seal design. While the previous has focused on leakage, models for investigating the friction effect of the patterned rod surfaces have been developed in 2013. Seal friction was studied for starved lubrication condition in 2014.

Quiet

A design for a tunable compact noise attenuation device using engineered compliant linings was created in Project 3B.1. Comprehensive models have been created. These have led to designs of various types. A prototype has been evaluated by industry. 3E.1 has finished the design and testing of prototype pressure ripple energy harvesters and demonstrated HPEH powered wireless sensor.

TEST BEDS

The CCEFP test beds represent applications that were selected to align with the technical barriers facing fluid power and the Center's goals.

- Test Bed 1, mobile heavy equipment (excavator), was chosen to address efficiency and effectiveness thrusts. It also represents the largest single segment of hydraulics, mobile off-road equipment, and aligns with the Center's goal of increasing fluid power efficiency in current applications.
- Test Bed 3, the hydraulic hybrid passenger vehicle, addresses all of the Center's thrusts. In order for hydraulic hybrid passenger vehicles to be commercially successful, the efficiency of the fluid power components and systems must improve. Optimizing the control and energy management is required to improve overall system efficiency. The size and weight of the hybrid system must be reduced to succeed in the passenger car market. Finally, the expectations of a car owner are vastly different than those of the owner of off-road mobile equipment. Noise and leaks are technical barriers that must be overcome for hydraulic hybrid passenger vehicles to be viable. The test bed also addresses the Center's goals of expanding fluid power use in transportation and making fluid power ubiquitous.
- Test Beds 4 and 6, the human-scale equipment and the human-assist device test beds, were chosen as examples of future portable human-scale fluid power applications. Both of the test beds address nearly all of the technical barriers. In addition, these test beds align with the Center's goal of ubiquity by focusing on applications where fluid power's benefits can provide better performance than available with current technologies.

The test bed summary reports that follow are truncated and the references have been removed. Complete versions of the test bed summaries can be found in Volume 2. The manner in which the test beds address the nine technical barriers is shown in the chart below.

	Technical Barriers								
	Efficient Components and Systems	Efficient Control	Efficient Energy Management	Compact Power Supply	Compact Energy Storage	Compact Integration	Safe and Easy to Use	Leak-free	Quiet
Test Bed 1: Heavy Mobile Equipment	•	•	•				•	•	
Test Bed 3: Hydraulic Hybrid Passenger Vehicle	•	•	•		•	•	•	•	•
Test Bed 4: Human-Scale Mobile Equipment	•		•	•	•	•	•	•	•
Test Bed 6: Human Assist Devices	•	•	•	•	•	•	•	•	•
Test Bed α: Wind Power Generation	•	•	•		•			•	
Test Bed β: Prescision Pneumatics	•	•	•	•	•	•	•	•	•

Technical Barriers Addressed by Test Beds

Test Bed 1: Heavy Mobile Equipment (High-Efficiency Compact Excavator)

Research Team

Project Leader:	Monika Ivantysynova, Purdue University, School of Mechanical Engineering, Dept. of Agricultural & Biological Engineering
Other Faculty:	Andrew Alleyne, UIUC Wayne Book, Georgia Tech Paul Michael, MSOE Kim Stelson, Minnesota
Test Bed Manager/ Staff:	Anthony Franklin
Graduate Student:	Enrique Busquets
Industrial Partners:	Bobcat, Caterpillar, Parker Hannifin, Moog, Husco, Sauer Danfoss, Sun Hydraulics.

1. Statement of Test Bed Goals

The compact excavator test bed was a demonstrator of throttle-less hydraulic actuation technology since the inception of the center through spring 2012. This technology, called displacement control (DC) or pump-controlled actuation (PCA), promises fuel savings for various multi-actuator machines used widely in the construction, agriculture and forestry industries. Following predictions based on system simulations, significant fuel savings have been demonstrated on the test bed over the standard excavator system.

Over the past few years, efforts have been focused toward transition of the test bed becoming a demonstrator of a novel hydraulic hybrid configuration with pump switching. 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, capture of swing braking energy and 50% engine downsizing. The pump switching architecture introduces a distributing manifold that acts as a logic element to minimize the installed pump power while maximizing the number of actuators available to the operator. This architecture leverages fuel savings above those demonstrated with the non-hybrid DC excavator prototype and the reduction of production costs and improved reliability.

2. Test Bed Role in Support of Strategic Plan

The compact excavator test-bed primarily addresses the efficiency thrust of the center. The prime role of the test-bed is to be a demonstrator of energy savings that are possible in multi-actuator machines, through efficient system architectures and through advanced power management strategies. Through project 1A.2 work was developed to evaluate and ultimately implement 1) throttle-less DC actuation, 2) a novel highly efficient hydraulic hybrid swing drive and 3) pump switching, a reliable and cost effective solution for the reduction of the installed pump power. In addition, the developments of project 1A.2 led to the theoretical development, simulation and formulation of appropriate control concepts for each of the aforementioned proposed technologies. The test bed has also been used for the demonstration of a novel human-machine interface as part of project 3A.1 at Georgia Tech. The test bed is well positioned for testing of energy-efficient fluids researched at MSOE (project 1G.1), and for evaluation of high efficiency, virtually variable displacement pump/motors that utilize high-speed on-off valves (projects 1E.3 and 1E.6), at Purdue University. With the transmission 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 accumulator (project 2C.2).

3. Project/Test Bed Description

The current state-of-the-art in hydraulic drive and actuation technology involves the use of different forms of resistance control through the utilization of valves. Most mobile applications use load-sensing (LS), negative flow control (NFC), positive flow control (PFC) architectures or variations of these architectures. In those systems one or two hydraulically controlled variable displacement pumps provide the required flow to all actuators by adjusting the system pressure to the highest required pressure of all actuators. Control valves throttle flow from the operating pressure to the desired actuator pressure and meter flow in accordance with respective operator inputs. This leads to large throttling losses across the control valves supplying all actuators other than the actuator operating at maximum pressure (in a typical cycle, only one or two actuators operate at high pressures, with the others at low or medium pressures). Further, energy from braking or lowering of actuators is either wasted or recovered very inefficiently, through these architectures.

Displacement controlled (DC) actuation is a highly efficient throttle-less actuation with simultaneous utilization of energy recovery without energy storage. The basic circuit for linear single rod cylinders was introduced by Rahmfeld & Ivantysynova (1998). One variable displacement pump/motor is used per working actuator in a closed-circuit, and throttling valves are entirely eliminated. The only control element is the pump displacement, and the unit automatically moves over-center to allow energy recovery. The initial challenge was to demonstrate that pump control could compete with the performance of valve controlled systems with respect to bandwidth and accuracy. Another challenge was to define the maximum required pumps in multi-actuator machines by introducing pump switching architectures and new control concepts. This complete new hydraulic actuation technology has been demonstrated in the past on a wheel loader where measurements showed 20% higher fuel efficiency. As a first result of the CCEFP research a four pump DC system with multiple switching valves was implemented for the eight actuator mini-excavator test-bed. 40% fuel savings were demonstrated through independent, side-by-side testing at a Caterpillar facility over the standard machine in August 2010. The technology offers several new energy efficient features to be introduced to mobile machines. In an affiliated project, energy efficient active vibration damping of the boom and machine cabin has been demonstrated on a skid-steer loader. Competing throttle-less actuation technologies are open-circuit DC actuation and hydraulic transformers. Open-circuit DC actuation is a feasible alternative, however it involves the use of several logic valves per actuator and accompanying control laws, which greatly complicates the actuator control. The INNAS Hydraulic Transformer (IHT) concept is not yet a proven technology that has been demonstrated on mobile multi-actuator machines.

The DC hydraulic hybrid prototype captures the swing drive braking energy in a hydraulic accumulator. Through the use of a secondary-controlled variable displacement motor for the swing drive, both the energy recovery concept and the manipulation of the excavator cabin motion are possible. The energy stored in the accumulator may be re-used either for reducing the load on the engine or for powering the swing at a later stage. The proposed system architecture does not require any additional units compared to the DC non-hybrid prototype, and energy from the boom, stick and bucket can be recovered through the DC circuits. The typical cyclical operation of these machines, together with added energy storage capability leads to the idea that engine downsizing is possible with appropriate power management. In such scenario, peak power requirements would be met by assistance from the accumulator. On the test-bed, the engine will not be downsized, however through the use of appropriate power management, engine load will be limited to 50% of peak power in order to demonstrate the feasibility of the concept in a functioning machine.

Caterpillar has released a hydraulic hybrid version of a 37-t excavator (336E H) and has announced the release of a hydraulic hybrid front shovel. The 336E H excavator uses a parallel hybrid architecture, wherein an extra pump/motor is added to the engine shaft, in parallel to the pumps supplying the working actuators. The additional pump is responsible for charging and discharging the accumulator. Caterpillar has claimed 25% fuel savings over the 336E, it is claimed that swing braking energy is captured. However, the addition of another pump in the Caterpillar system will introduce additional power losses to the system. This is not the case in the in CCEFP series-parallel hybrid DC architecture. Also, due to the fact that all remaining functions are still valve-controlled, it is not possible to recover energy from other working functions like boom, arm or bucket in the current 336E-H Caterpillar machine.

Achievements Prior to Reporting Period

- Four variable displacement pumps were installed on test bed 1 along with associated sensors and electronic control hardware to retrofit the prototype with DC actuation and control laws for pump displacement, actuator position and actuator velocity control were developed and implemented.

- The DC hydraulic system was demonstrated by video at the CCEFP annual meeting and in person to a delegation from Caterpillar on 2009.
- Simulation and measurement results on test bed 1 determined that up to 50% of the cooling power capacity in the system could be reduced.
- Productivity and fuel test for test bed 1 with DC hydraulics was conducted in cooperation with Caterpillar, Inc.; test bed 1 consumed 40% less fuel on average than the standard machine while moving the same amount of dirt and productivity was increased by 16.6%, which lead to a fuel efficiency (tons/kg) improvement of 69%.
- A proposed optimal power management algorithm from project 1A.2 was evaluated using a pipe-laying cycle. Results showed 56.4% fuel efficiency improvement over the non-optimally managed.
- In April 2011, test bed 1 was evaluated for fine actuator control to the satisfaction of a team of Bobcat expert operators, test and system engineers in Bismarck, ND.
- Through project 1A.2, a feasibility study predicted that the novel series-parallel hybrid system could be limited to half of the maximum engine power, suggesting that the engine size could be reduced without sacrificing the productivity of the machine for the truck loading cycle.
- Through 1A.2 in 2011, a conservative power management strategy demonstrated that the proposed test bed 1 hybrid configuration together with downsized engine, can achieve 52% fuel savings compared to the standard machine (> 20% over the prototype DC excavator).
- Also through 1A.2, optimal power management strategies were developed to achieve up to 27% fuel savings over the non-hybrid DC excavator.
- Optimal sizing studies using dynamic programming were undertaken to evaluate various possible unit and accumulator sizes as well as accumulator pre-charge pressures.
- The hydraulic hybrid swing was successfully implemented on test bed 1.
- Control strategies were implemented with the goal of demonstrating the hydraulic hybrid functionality.

<u>Achievements During Reporting Period</u>

<u>*Hydraulic Hybrid Actuator Level Control*</u>

Since the conception of secondary-controlled drives, many advances in the control of the actuator position, velocity and torque have been developed. However, every approach so far assumes a constant pressure at the working port of the secondary unit. Efforts in this area for test bed 1 focus on the synthesis of a robust controller which achieves maximum actuator performance (good tracking of the cab velocity) while minimizing losses by actively controlling the secondary unit working pressure. The proposed controller design was carried out using the Robust Control Toolbox in MATLAB. Simulation of the proposed controller promised improved tracking for the actuator level control over a manually tuned PID controller. In reference to Fig. 1 and 2, measurements of the pressure show greatly improved tracking for various inertia loads and commanded speeds. However, the speed tracking is only improved in certain areas displaying overshoots when decelerating. For illustration purposes, Fig. 3 and show the commanded and measured pressures and cabin speeds for a manually tuned PID controller.

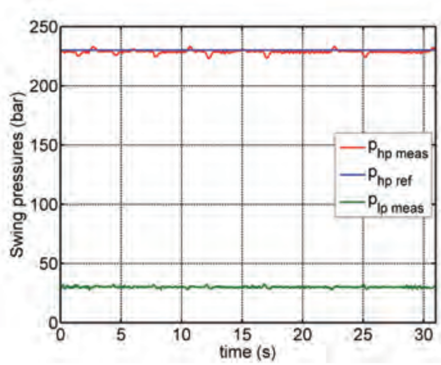


Fig. 1: Proposed controller pressure tracking

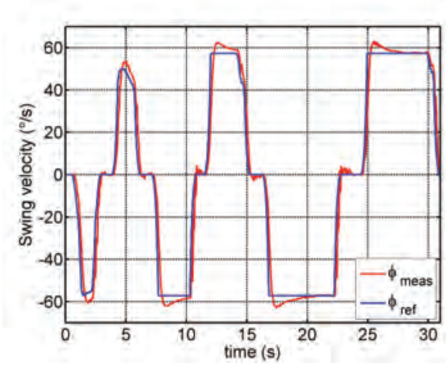


Fig. 2: Proposed controller cab speed tracking

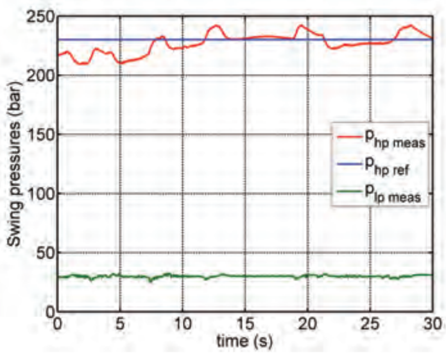


Fig. 3: PID controller pressure tracking

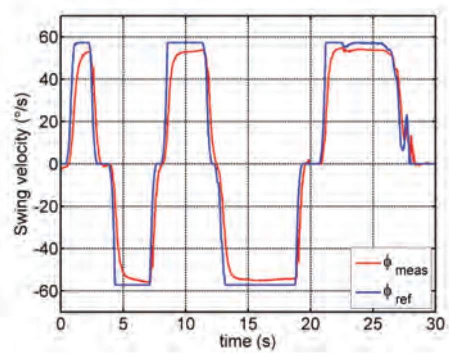


Fig. 4: PID controller cab speed tracking

Pump Switching

With the developments from project 1A.2, the concept of pump switching was realized in test bed 1. Pump switching has the potential to minimize the number of pumps in a DC hydraulic system. However, this parameter will depend upon machine operation and operator demands. In the case of test bed 1, the limitation is imposed by the main purpose of an excavator: digging. This limitation exists since experienced operators use the swing, boom, arm and bucket simultaneously. The distributing manifold has been designed to distribute the flow from the hydraulic units to all of the actuators. Therefore, the coupling of a well-designed manifold and proper controls lead to the maximization of the number of actuator combinations which an operator may use. To demonstrate the operability of the actuators in test bed 1, the hydraulic manifold was manufactured by Sun Hydraulics and installed in the prototype. The aforementioned control concepts were implemented and studied for test bed 1. Measurements of pump switching for the boom actuator are presented under a large load to show the ability of the control algorithms to prevent undesired actuator transients. The intention of the obtained measurements is to present the most challenging operation which is to allow the valve to open while the operator commands very small increments in motion. In all measurements, an exaggerated miscalibration of the swash plate was imposed to force the wrong pilot-operated check valve to open.

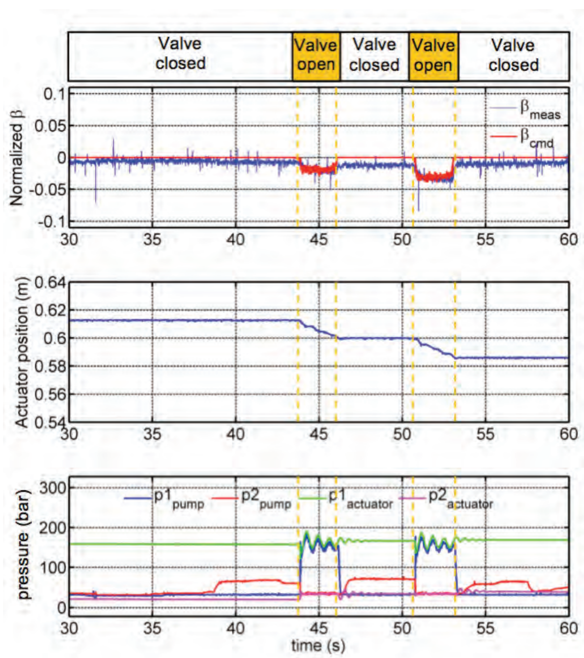


Fig. 5: Pump switching without control using the boom actuator under a high load

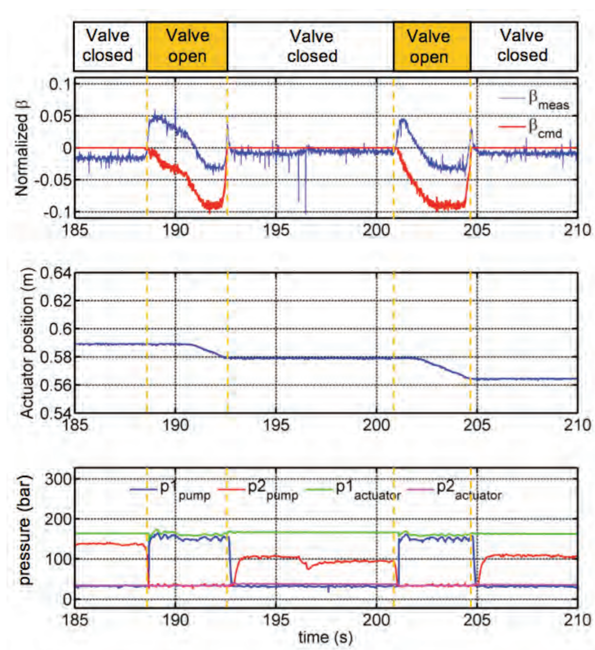


Fig. 6: Pump switching with control using the boom actuator under a high load

Electronic Anti-stall Controller

One of the often overlooked challenges of fluid power systems is that in most cases hydraulic drives are extremely powerful relative to their primary movers. If not addressed properly, this condition can degrade performance, controllability, efficiency and even lead to complete system shutdown. To prevent engine overloading and its undesired effects, several hydraulic and electro-hydraulic anti-stall system have been proposed and commercialized. The main challenge for DC actuation is the one pump per actuator requirement. This condition complicates the conception and implementation of an anti-stall apparatus. For this reason, we have proposed for the first time an electronic anti-stall control for DC actuation. Similar to the majority of anti-stall controllers, the proposed scheme is enabled based on the error between the engine speed measurement and reference value. However, the operation of the DC actuation as well as its nonlinear behavior are taken into account. Since the hydraulic units in DC actuation may operate as pumps or motors they can contribute to loading or aid in unloading the engine.

The advantage of the proposed approach is that the displacement of the hydraulic units operating as motors is not affected by the anti-stall controller, maximizing their torque, while the displacements of the units operating as pumps are penalized depending on their torque level and the available torque from the engine. To deal with the nonlinearities in the system, a manually tuned gain scheduler takes into account the error between the measured and reference engine speeds and each units' differential pressure. The commanded unit displacements are limited according to the gain-scheduler. To show the validity of the controller approach, the strategy was implemented in test bed 1. An aggressive cycle was measured to show the controller working at extreme operating conditions. In reference to Fig. 7, it can be observed that the engine speed error is maintained relatively small.

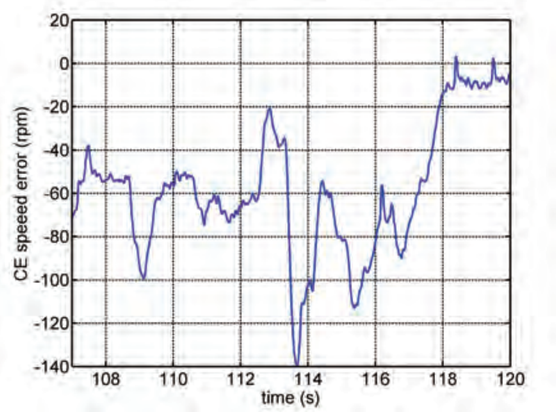


Fig. 7: Engine speed error

<u>Planned Achievements following the reporting period</u>

- Synthesize smart controllers for pump switching to both optimize the entire system operability and increase DC system reliability through control redundancy
- Derive and implement advanced controls for the power management of the hydraulic hybrid swing drive.
- Improve the anti-stall control algorithm capabilities through the formulation of an algorithm that optimizes the gain values of the now manually tuned anti-stall gain schedule.

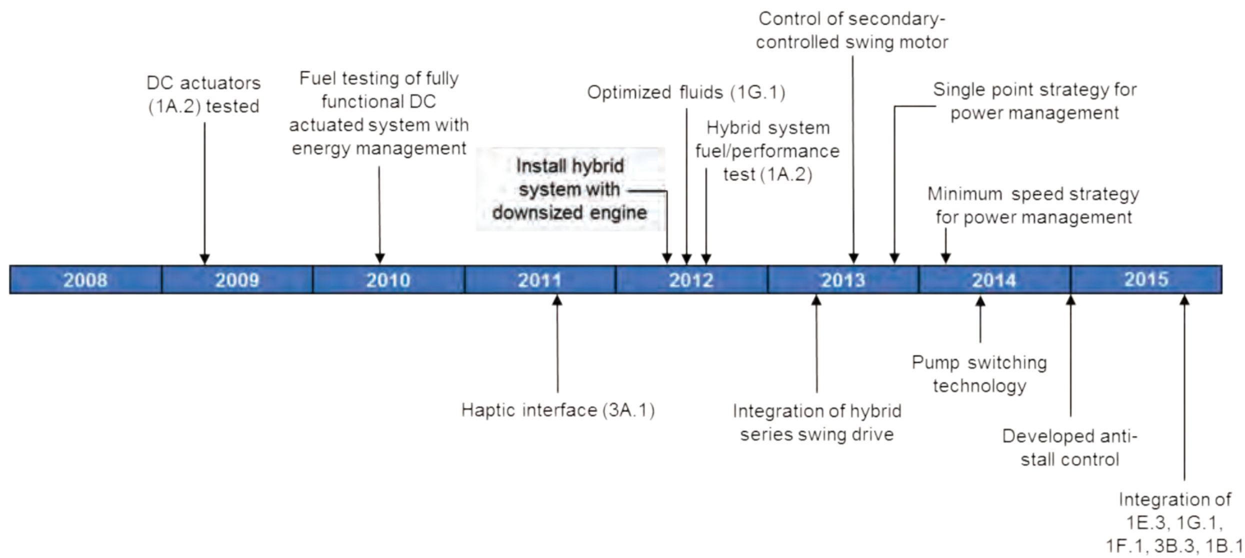
Member company benefits

The results gained from test bed 1 are directly transferable to industry and have already offered benefits to member companies. Below are some of these benefits:

- Test bed 1 was actively evaluated and tested by industry members (Caterpillar, Bobcat, Parker-Hannifin and CNH) during its time as a DC, non-hybrid prototype excavator. In the future, it can be tested and evaluated in its hybrid configuration. This saves them much time and money compared to building their own prototypes in order to evaluate the potential of DC actuation as well as that of the hybrid DC architecture.

- The results of this test bed have shown that up to 40% fuel savings can be achieved which would clearly be a benefit to OEM companies within the center.
- The improved efficiencies and potential for reduced engine power made possible by the hybrid DC excavator architecture being developed in this project will help OEMs meet upcoming regulations under the TIER emissions standards, together with providing the resulting monetary benefits.

Test Bed 1 Technology Integration



Test Bed 1 Milestone Chart

The excavator test bed has been serving as a platform for developing displacement control (DC) actuation since inception of the Center. DC actuation was first demonstrated in 2009. Fuel savings of 40% was demonstrated in independent testing by Caterpillar in 2010. The multi-modal human-machine interface developed in (3A.1) was implemented on TB1 in 2011. Since 2012, TB1 began focusing on demonstrating hybrid architecture (2A.1). Investigation of hybrid series swing drive was finished in 2013. Various power management strategies have been investigated. The pump switching technology (2A.1) has be tested in 2014 and the prognostic system (2A.1) will be tested in 2015.

In the next few years, several other projects will be installed and tested on TB1:

- A variable displacement gear pump to reduce throttling loss in the cooling system will replace the fixed displacement pump and be tested in 2015. (1F.1)
- The effects of optimized hydraulic fluid and non-optimized hydraulic fluid will be tested in 2015. (1G.1)
- The high efficiency digital displacement pump will be tested in 2015. (1E.3)
- Implementation of adaptive control strategies for active vibration control in 2015. (3B.3)
- A high efficiency pump based on optimized gap surfaces will be tested in 2016. (1B.1)

Test Bed 3: Hydraulic Hybrid Passenger Vehicle

Research Team

Project Leader:	Perry Y. Li, Mechanical Engineering, University of Minnesota
Other Faculty:	Thomas R. Chase, Mechanical Engineering, University of Minnesota
Graduate Students:	Kai-Loon Cheong, Tan Cheng
Industrial Partners:	Bosch-Rexroth, Eaton, Parker, Danfoss, and others

1. Statement of Test Bed Goals

The overall goal of this project is to realize hydraulic hybrid power trains for the passenger vehicle segment which demonstrate both excellent fuel economy and good performance. As a test bed project, it also drives and integrates associated projects by identifying the technological barriers to achieving that goal. The design specifications for the vehicle include: (i) fuel economy of 70 mpg under the federal drive cycles; (ii) an acceleration rate of 0-60 mph in 8 seconds; (iii) the ability to climb a continuous road elevation of 8%; (iv) exhaust emissions meeting California standards; and (v) size, weight, noise, vibration and harshness comparable to similar passenger vehicles on the market. Power trains produced in the scope of this project must demonstrate advantages over electric hybrids to be competitive.

2. Test Bed Role in Support of Strategic Plan

Test Bed 3 (TB3) directly supports goal 2: improving the efficiency of transportation. Efficiency is achieved by utilizing hydraulic assist to enable operating the engine at or near its “sweet spot” and regenerating brake energy. The power trains integrate high efficiency components, hydraulic fluids and energy management algorithms (thrust 1), compact energy storage (thrust 2) and methodologies for achieving quiet operation (thrust 3) from related CCEFP projects.

3. Test Bed Description

A. Description and explanation of research approach

The high power density of hydraulics makes them an attractive technology for hybrid vehicles, since both fuel economy and high performance may be achievable. Hydraulic hybrids provide an intriguing alternative to electric hybrids because the large battery required for electric hybrids can be eliminated. A few hydraulic hybrid vehicles have been developed for heavy, frequent stop-and-go applications such as garbage or delivery trucks. However, hydraulic hybrids have not yet reached the much larger passenger vehicle market. In order to succeed in this market, hydraulic hybrid drive trains must overcome limitations in component efficiency, energy storage density, and noise. These barriers represent worthwhile challenges that stretch the envelopes of existing fluid power technologies.

TB3 focuses on power split architectures, which combine the positive aspects of the series and parallel drive train. They are not as well studied as the simpler architectures. Two hydraulic hybrid passenger vehicles are being developed in the scope of this test bed, each of which offers unique research benefits. The “Generation 1” vehicle (Figure 1) was built in-house using the platform of a utility vehicle (a Polaris “Ranger”) connected to an in-house built hydrostatic dynamometer. The vehicle has been outfitted with a modular power train. This enables experimenting with different pump, motor and energy storage technologies, including those developed in complementary CCEFP projects.

The “Generation 2” vehicle is being developed in partnership with Folsom Technologies International (FTI). It is built on the platform of a Ford F-150 pickup truck, which has refined vehicle dynamics capable of highway speeds. Its power train utilizes a prototype continuously variable power split hydraulic transmission developed by FTI. Adding hydraulic accumulators to the CVT enables hybrid operation. The power train is built as a compact, integrated, self-contained package. However, the integrated package prevents changing out the hydraulic pump/motors or instrumenting them individually. Development for the last two years has focused on the Generation 1 vehicle, although development of the Generation 2 vehicle has continued as resources permit. The Generation 2 vehicle is housed at the Folsom facility in Albany, NY.

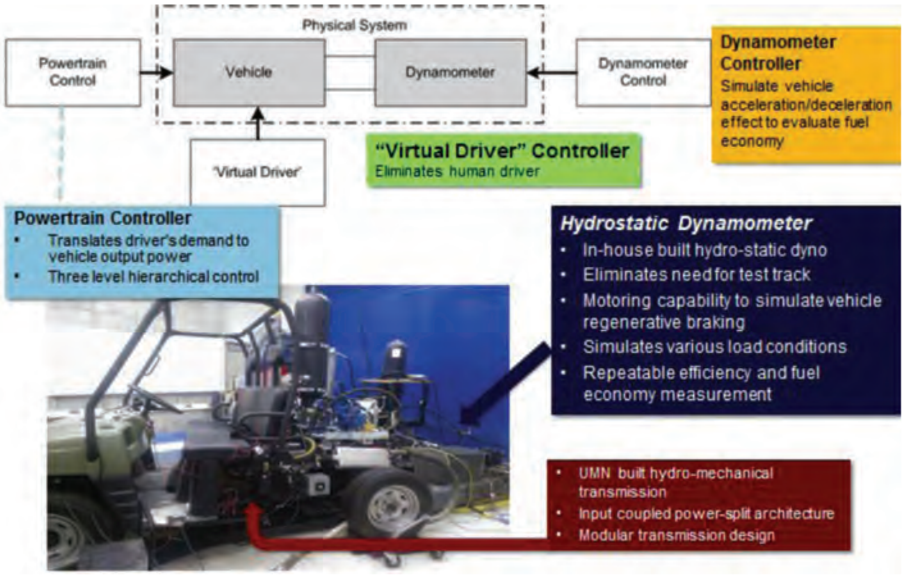


Figure 1: Overview of Test Bed 3 HHPV Generation 1 with hydrostatic dynamometer.

Achievements

Achievements are separated according to the two platforms: the Generation 1 vehicle and Generation 2 vehicle. Within each category, achievements in previous years are briefly summarized first, followed by more detailed descriptions of achievements in the past year (2014).

<u>Achievements Applicable to the Generation 1 Vehicle</u>

Recent years' major achievements:

- *Drive train rebuild*: The first hydraulic hybrid transmission was completely rebuilt in 2011-2012 to use only gears to transmit power to and from the hydraulic pump/motors. The all-gear design improved the power capacity, the efficiency and the reliability of the power train.
- *Dynamometer*: The vehicle was coupled to a hydrostatic dynamometer in 2012, eliminating the need to drive the vehicle on a test track. The dynamometer was designed and constructed in house to enable it to motor as well as load the vehicle, thereby enabling it to simulate braking events.
- *New engine installation and characterization*: The vehicle's engine was discovered to be inadequate to take the vehicle through all planned drive cycles, so it was replaced with larger and more efficient engine in 2013. The new engine was characterized using the dynamometer described above.
- *Powertrain and dynamometer control systems*: Three controllers have been designed and implemented on the vehicle-dynamometer system (see Fig. 1). The first, the "powertrain controller", is integrated with the hybrid vehicle itself. It utilizes a three-level hierarchical strategy, which was described in previous years. The second is the dynamometer controller. This controller also simulates the inertia of the vehicle, which requires monitoring the torque applied to the drive shaft. The third, described as the "virtual driver" controller, interfaces with both the dynamometer and the vehicle's throttle controller. The virtual driver controller replaces an actual driver. It makes it possible to track arbitrary drive cycles repeatably, which is necessary to gather reliable fuel efficiency data.

Major achievements in year 2014:

- *Clutch system redesign*: Now that we are able to program actual drive cycles, we learned that the transmission occasionally and briefly transmits torque to the vehicle's engine, rather than vice versa. The electric clutch that we formerly used to couple the engine to the transmission only had the ability to transmit torque in one direction. Therefore, instances of reverse torque transmission would damage the clutch. A new hydraulic clutch, with two way torque transmission capability, was purchased and installed. A small electrically driven hydraulic pump, originally intended for use on a convertible top, was adapted to enable engaging the clutch with an electric signal. This architecture eliminates the need to throttle hydraulic fluid from the main hydraulic system to power the clutch. The new clutch system now enables us to simulate complete drive cycles.

- *Sensors upgrade on vehicle*: Several sensors were added to the vehicle to enable better quantifying drive cycle efficiency. A wireless torque sensor was installed on the transmission input shaft to directly measure engine torque. At the suggestion of one of our industry mentors, pressure and temperature sensors were installed at the inlet and outlet ports of the two hydraulic pump motors to improve the assessment of their efficiency, particularly while experimenting with alternative hydraulic fluids.
- *Dynamometer controller improvement*: The dynamometer was previously modeled as a second order system. Further study of system identification results revealed that it is better modeled as a third order system. This improvement increased the bandwidth of the dynamometer controller from 6 rad/s to about 15 rad/s.
- *Energy management strategy implementation*: The top level of the three level vehicle controller was programmed to implement a rule based energy management algorithm developed in related Project 1A.1. Results for the urban and highway drive cycles are shown in Figure 3. (Preliminary results from the highway drive cycle were reported in Year 8.) As noted in "Dynamometer Hardware Upgrades", the vehicle inertia was artificially reduced to enable completing these drive cycles with an undersized hydraulic power unit available for the dynamometer at the time of testing. This is the first time that the HHPV has been tested in hybrid mode using an urban drive cycle. Unfortunately, the results showed little improvement in fuel economy over CVT mode. The likely reason is that the algorithm used was not designed to fit the Generation I vehicle. Improvement is expected for future hybrid algorithms such as Mild Hybrid and Lagrange multiplier.

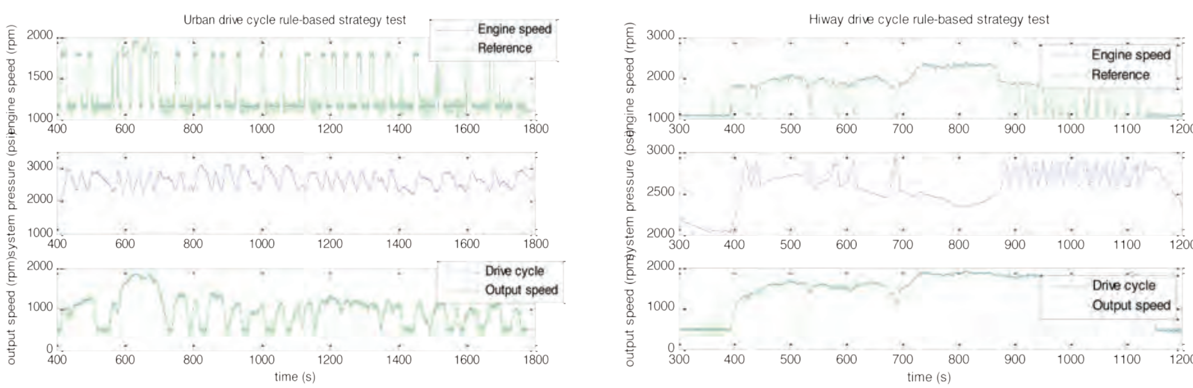


Figure 2: Hybrid powertrain operated with Rule-based strategy in urban (left) and highway (right) drive cycles

- *Dynamometer Hardware Upgrades*: Two improvements on the dynamometer were completed in December 2014. First, the dynamometer has not been able to simulate the full inertia of the Generation I vehicle due to an undersized power supply. The power supply was increased from 5.6 kW to 15 kW to overcome this problem. Second, the charge pump for the dynamometer was formerly attached in parallel with the main pump/motors, which are driven by the vehicle's drive shaft. As a result, the drive shaft could not be run at low speed, as charge pressure would be lost. As a consequence, note that the output shaft speed is not allowed to drop below 400 RPM in Fig. 2. This problem was overcome by installing a separate 750 W electric motor to drive the dynamometer charge pump exclusively. This modification also removes a parasitic power loss on the dynamometer, further increasing its power capacity.

Achievements Applicable to the Generation 2

Recent years' achievements:

- *Transmission Characterization:* A method has been developed to determine the efficiency map for the FTI transmission under various hybrid operating conditions given limited data. This map is necessary for proper design of the vehicle operating strategy.
- *Effect of hydraulic oil*: The transmission efficiency depends on the hydraulic oil used. It has been demonstrated that replacing the low viscosity (5 cSt) Automatic Transmission Fluid (ATF) with a higher viscosity (15 cSt) fluid results in improved efficiency, especially at low transmission ratios.
- *Hardware preparation:* The FTI transmission has been re-installed on the Ford F-150 at Folsom. The signal conditioning and data acquisition system is installed on the vehicle. Hardware-in-the-loop testing has been completed at UMN.

Major achievements in year 2014:

- Visit #1: The control computer was interfaced with the vehicle. Access was established with the engine and transmission control inputs and sensors.
- Visit #2: System identification was performed on the drivetrain.
- Visit #3: The low level portion of the 3-level hierarchical vehicle controller was implemented. A free-spinning test of the CVT was performed; e.g., the wheels were raised off of the ground. Figure 3 illustrates that the controller maintains the engine speed at 900 rpm as the transmission ratio is changed by varying the pump/motor displacements.

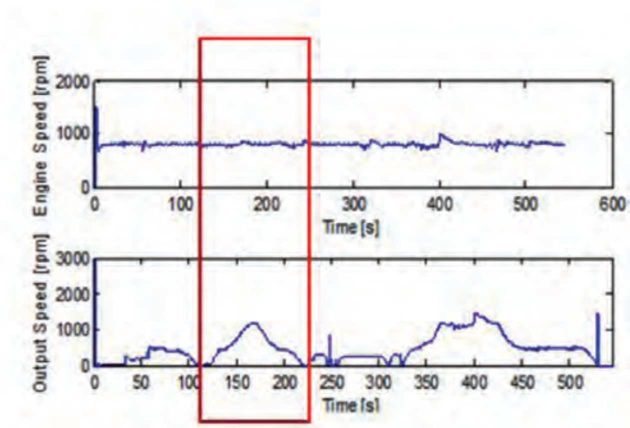


Figure 3: CVT free-spinning test

Plans

Plans for the Generation 1 Vehicle

Plans for the Generation 1 vehicle will focus on core project integration. It is noted that several of events from the Year 8 plan have been re-scheduled to Year 9. The reason is that power to the fourth floor lab space where the vehicle was housed was discontinued on short notice in August 2014 due to building remodeling, and power for operating the dynamometer in its new lab space was not made available until late December 2014. Nevertheless, two benefits resulted from the move. First, we were able to specify power in the new lab to accommodate the new 15 kW dynamometer power supply described earlier. Second, the new space is on the first floor and has a garage door, so the vehicle can be easily removed from the building for road demonstrations. The Year 9 plans are described in order below.

1. Additional high level hybrid energy management control strategies will be tested. The mild hybrid mode is now being implemented, which will be followed by the modified Lagrange multiplier strategy. The more complex Stochastic Dynamic Programming (SPD) and Model Predictive Control (MPC) algorithms developed in Project 1A.1 will be implemented and tested in Fall 2015.

2. For Project 1G.1 (Energy Efficient Fluids), a synthetic biodegradable ester will be utilized as the hydraulic fluid, which is expected to exhibit higher efficiency at low speeds [10]. The new oil will be compared with a baseline shear stable high viscosity index hydraulic fluid in Spring-Summer 2015. The modified Lagrange hybrid control strategy will be used if it shows improvement over CVT control.

3. A pulse width modulated virtually variable displacement pump/motor (VVDPM) designed in Project 1E.1 will be evaluated using torque and speed data provided by the Gen I vehicle.

Simulations have been performed to optimize the gear ratios for the pulse width modulated pump/motor [8]. The VVDPM will be evaluated on a test bench using the torque-speed data in a hardware-in-the-loop configuration. Performance will be compared with the baseline bent-axis unit (summer 2015).

4. A conventional accumulator is currently used on the low pressure side of the vehicle. When its pressure rises, vehicle efficiency declines, since the differential pressure across the pump/motors decreases. Strain energy accumulators being developed by Project 2C.2 introduce the potential for maintaining the low pressure at a constant low level. We are planning to replace the low pressure accumulator with a prototype provided by Project 2C.2, and we will measure the change in efficiency associated with this replacement (December 2015-January 2016).

<u>Plans for the Generation 2 Vehicle</u>

Much of the controller development that has been completed for the Generation 1 vehicle will be adapted to the Generation 2 transmission, and fine-tuned for the differences in architectures. After the Generation 2 vehicle is fully functional, the continuous variable transmission (CVT) strategy and a hybrid strategy will be tested.

1. Visit #1: Implement two high level control strategies: CVT and mild hybrid (regenerative braking, launch assist, CVT).
2. Visit #2: Implement full hybrid operation and prepare vehicle for dynamometer testing.

Milestones and Deliverables

Generation I:

- Task 1: Implement the mild hybrid and modified Lagrange multiplier method developed and compare their effectiveness. [4/15]
- Task 2: Baseline Generation I vehicle performance by running it through the EPA urban drive cycle in a hybrid mode using mineral oil based hydraulic fluid. Compare performance of biodegradable synthetic hydraulic oil using identical drive cycle and mode. [8/15]
- Task 3: Evaluate the 4 quadrant Virtually Variable Displacement Pump/Motor (VVDPM) developed in Project 1E.1 under a hardware-in-the-loop test (1E.1) [6/15]
- Task 4: Test efficiency gain attributable to installing a strain energy accumulator (2C.2) [1/16]

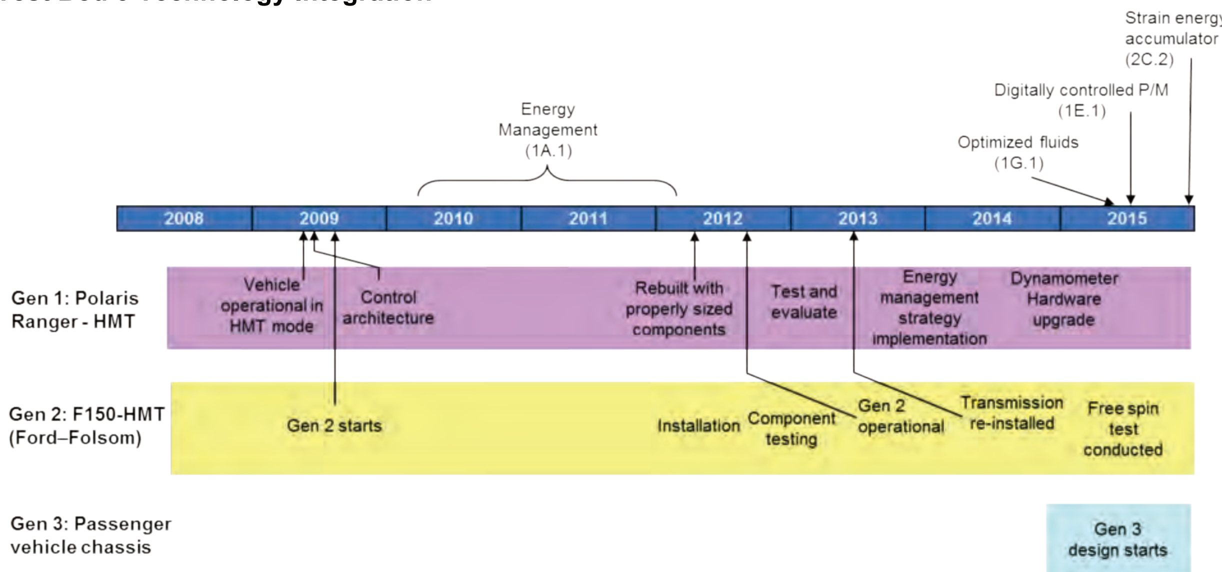
Generation II:

- Demonstrate CVT control strategy in Generation 2 vehicle [6/15]
- Demonstrate mild hybrid control strategy in Generation 2 vehicle [12/15]

B. Member company benefits

Development of practical hydraulic hybrid passenger vehicles creates a new and lucrative market for hydraulic products. In addition, development of the HHPV enables member companies to gain experience in a potential market segment where they have not traditionally worked which requires very high efficiency at relatively low power. Finally, the test bed provides an ideal application for testing the efficiency of alternative hydraulic fluids intended for use in power trains.

Test Bed 3 Technology Integration



Test Bed 3 Milestone Chart

The hydraulic hybrid passenger vehicle test bed consists of two platforms. The Gen 1 vehicle is a utility vehicle chassis with a UMN designed and custom built hybridized input coupled hydro-mechanical transmission (HMT). The Gen 2 vehicle is a Ford F150 pickup equipped with an output coupled HMT provided by Folsom Technologies.

The initial HMT architecture for the Gen 1 platform is capable of independent wheel-torque control and used over-sized available off-the-shelf components. Design, analysis and control approaches were developed by 2009. The Gen 1 vehicle underwent major mechanical redesign to increase robustness in 2010. Also in 2010, component were redesigned and optimally sized and a custom planetary mechanical transmission was designed. The redesigned drive-train was constructed and installed in 2011. In 2012, a hydraulic dynamometer was designed and constructed in-house to enable repeatable, lab-based vehicle testing and control tuning. Several hardware components had to be repaired or replaced in 2012, including the engine. The efficiency map of the new engine was characterized on the dynamometer in 2012. CVT operation was tested on the hydraulic dynamometer in 2013. Various energy management strategies have been implemented. The dynamometer hardware has also been updated to support the vehicle testing.

In the next few years, several other projects will be installed and tested on TB1:

- The effect of two hydraulic fluids on fuel economy will be tested in 2015. (1G.1)
- Energy management control algorithms that have been designed will be tested in Fall 2015. (1A.1)
- The rotary spool-valve based virtually variable displacement pump/motor will replace the bent-axis “speeder” P/M and undergo testing in summer 2015. (1E.1)
- A strain-energy storage prototype will be installed and tested in January 2016. (2C.2)

Because of the lack of vehicle testing and maintenance facilities at the University of Minnesota, the decision was made in 2012 that the Gen 2 platform will reside at the facility of our partner, Folsom Technologies, in New York. The Folsom transmission was damaged during testing and has undergone repairs in the past year. The transmission has been re-characterized and installed on the F150 in 2013. Free spin tests have been conducted in 2014. A control approach similar to Gen 1 will be implemented and tested in the future.

A Gen 3 platform on a passenger vehicle chassis is desirable to demonstrate the potential of the hydraulic hybrid technologies. However, the development of the new test bed depends on the availability of funds and an industry partner.

Test Bed 4: Human-Scale Equipment (Patient Transfer Device)

Research Team

Project Leader:	Wayne J. Book, Mechanical Engineering, Georgia Tech
Research Engineer:	James Huggins, Mechanical Engineering, Georgia Tech
Graduate Student:	Heather Humphreys, Mechanical Engineering, Georgia Tech
Undergraduate Student:	Zack Siegel, Mechanical Engineering, Georgia Tech
Industrial Partners:	Parker Hannifin, Eaton

1. Statement of Test Bed Goals

The high level goal of Test Bed 4 is to explore ways to expand and improve the use of fluid power to needs at the human scale and associated new application areas. Many applications in this power range interact with humans; the patient transfer assist device provides an opportunity for us to explore how fluid power can be utilized with humans in the workspace. We have identified a significant market need for an improved, cost effective assist device for transferring mobility limited patients, especially heavier patients. This device is designed to meet this growing need by providing a way for caregivers to move patients without injury to the patient or themselves. It also provides a human scale system for testing integrations of various CCEFP subsystem projects/components.

To benefit from the power and force density of fluid power, effective human interfaces and control algorithms are very important. It must be safe for humans in its workspace, allow for simple and intuitive operation of multiple degrees of freedom (DOFs) by a single caregiver, have smooth motion without vibration or oscillation, and be highly maneuverable. Related and client CCEFP projects include passivity based control (3A.2), control of vibration (3B.3), multi-modal human machine interfaces (3A.1), user-centered design (3A.3), the hydraulic transformer (1E.5), and potentially others. The research includes developing methods to allow for intuitive collaborative manipulation, managing external interaction forces with a powerful machine operating in a relatively delicate environment, and compensation for nonlinear and non-ideal characteristics resulting from lower-cost components.

2. Test Bed Role in Support of Strategic Plan

The CCEFP seeks to make fluid power ubiquitous. As such the power of hydraulics must be adapted to uses in the delicate situations which are epitomized by patient care. Affordable, quality care of mobility limited individuals is currently hampered by the need for multiple caregivers to perform transfers of patients that may occur a dozen times in a day. Obese, even moderately heavy patients are especially difficult to transfer. The needs for the patient transfer assist device application exemplify some primary CCEFP goals, such as the need for a safe and effective operator interface, a very compact and mobile design, and minimal noise and leakage, all in a multi-DOF system. This test bed provides an opportunity to explore how fluid power can be used in non-traditional environments such as homes and clinical institutions, with humans in the workspace. It also provides a system in which to test features needed for these fluid power applications. Contrary to prior concerns, the research is consistent with the goals of the center in that it demonstrates expansion of fluid power technology to a smaller than typical scale, in a more delicate environment. It addresses barriers that arise in these new applications, such as control with low-cost components with non-ideal characteristics, management of forces in any undesirable environmental interactions, and physical collaboration with humans.

3. Test Bed Description

Overview

A significant market need has been identified for an improved mobile assist device to aid in transferring mobility limited people, particularly bariatric patients. With the increasing aging population and the increasing number of bariatric patients, the number of mobility limited patients is significantly increasing. Institutions have recognized the risks of injury to caregivers and most are implementing “no lift policies” which require the use of an assist device to lift the weight of a patient. However, current market lift devices are antiquated and insufficient for many patient and caretaker needs; transfers often require multiple personnel and as much as 10-20 minutes. Only a few projects have addressed the problem of patient transfers, and most do not consider bariatric patients. One example of a prototype patient transfer and rehabilitation device was developed by NIST. This test bed concept stemmed from a related project with our collaborators at the Quality of Life Technology NSF ERC, which developed a wheelchair-mounted device for transferring patients. However, using electrical actuation, they were unable to achieve the desired lifting power. Hydraulic actuation has the advantage of providing large force capability in a compact package, with the power source located at the base of the device. This is an ongoing test bed; currently it has two degrees of freedom fully functional. The next stage of the research focuses on various control techniques, operator interface design, and modeling and dynamic simulation.

Challenges & Technology Advancement Barriers

One challenge is to develop a multi-DOF device that is compact, untethered and highly maneuverable, while also powerful enough to maneuver up to 1000 lb payload. Another primary challenge is the development of a control strategy to allow a single caregiver to control all degrees of freedom of this powerful lift device in an intuitive, safe, simple manner, while simultaneously maneuvering and fine-tuning the complex patient payload. The machine itself needs to be untethered, mobile, and capable of maneuvering a heavy payload through complex motions; hydraulic actuation provides the needed compact power source, and it allows for the power source to be located at the base of the device. These requirements directed us to an onboard battery power supply and electric motors driving hydraulic pumps, in an efficient pump controlled architecture to eliminate valve losses.

The control and caretaker interface design objectives are unique and challenging aspects and primary areas for continued work. In this operator interface, the caretaker and machine collaborate to maneuver the patient; the caretaker interacts directly with the patient, fine-tuning position and orientation, placing limbs, etc., while simultaneously controlling the lift device. In order for a single caregiver to perform transfers quickly and safely, the caretaker needs to remain near the patient and within reach of the input device. Key components of this control and interface research include (a) safe operation of a powerful hydraulic machine with humans in the workspace and subsequent management of forces exerted by the machine, (b) lower level electro-hydraulic pump control in multiple degrees of freedom, and (c) intuitive collaborative manipulation using an assistive device. Additional challenges involve management of the slow and nonlinear plant dynamics.

C. Achievements

Achievements in previous years

At the start of the project, a substantial needs assessment was completed, involving individual interviews, a focus group, and a benchmark operator study with current market patient lift devices. The assessments included patients who use current market lifts, engineers and salespeople in the patient lift industry, home caretakers, nurses, assisted living facility administrators, and physical therapists. The study shed light on a number of shortcomings of current market lifts. We learned that the new design needs to be much more maneuverable in tight spaces, such as transfers into cars and inside bathrooms, providing accessibility to more locations. The device needs to allow for a single caregiver to perform even complex transfers; often only one caregiver is available. Heavier or bariatric patients are particularly difficult for caretakers to maneuver; the device needs to provide forces sufficient to handle bariatric patients. Furthermore, the benchmark operator study demonstrated that the transfer operations often involve inadvertent small collisions with the environment. It is desirable for these unwanted interaction forces to be managed, considering the necessary high force capabilities of the machine.

Based on the information from the needs assessment, a design for the first prototype was developed. A design review meeting was held, including researchers from the assistive device industry, fluid power researchers, engineers from the current patient lift industry, and human factors researchers. It was determined that hydraulic actuation of multiple degrees of freedom would be beneficial. The first two degrees of freedom of the machine were fabricated and integrated, a main lifting scissor mechanism and a boom extension. The machine uses an electrohydraulic pump controlled architecture, intended to provide better efficiency than valve-controlled systems by eliminating throttling losses. The system includes a servo drive, reversible DC electric motor, small gear pump, and hydraulic actuator for each degree of freedom. The control input is the reference current for the servo drive. The operator input is measured from a force sensing handle mounted near the patient, providing intuitive coordinated control; the operator simply pushes on the machine in the desired direction of motion, and it moves the patient accordingly.

Additionally, some initial testing was performed on a pre-prototype patient transfer assist device, which used a valve-controlled vertical lifting cylinder to actuate a boom which lifted the patient sling. A force sensing handle was mounted to the boom, which provided the operator input. A passivity-based human power amplifier controller was implemented on the pre-prototype. This control approach uses feedback of both motion and actuator force, with the goal of acting as a mechanical tool to amplify the human input force, within passivity constraints. Preliminary operator experiments were performed using the passivity based human power amplifier controller.

Achievements in the past year

System Integration & Hardware

Two additional degrees of freedom have been added, the differential drive wheels. For the purpose of safety in testing controller designs, the wheels are currently mounted on a separate cart. The wheels are actuated by low speed high torque hydraulic motors. The wheel cart uses the same actuation system architecture as the first two degrees of freedom, with a servo drive, reversible DC electric motor, and hydraulic motor, for each wheel. The cart uses a separate onboard National Instruments Single Board Rio controller, which is similar to the controller used on the main lift and extension; when the wheels are integrated into the full machine, the control code will be easily portable. The cart also has a separate set of batteries and a force/torque sensing handle for the operator input (Figure 2).

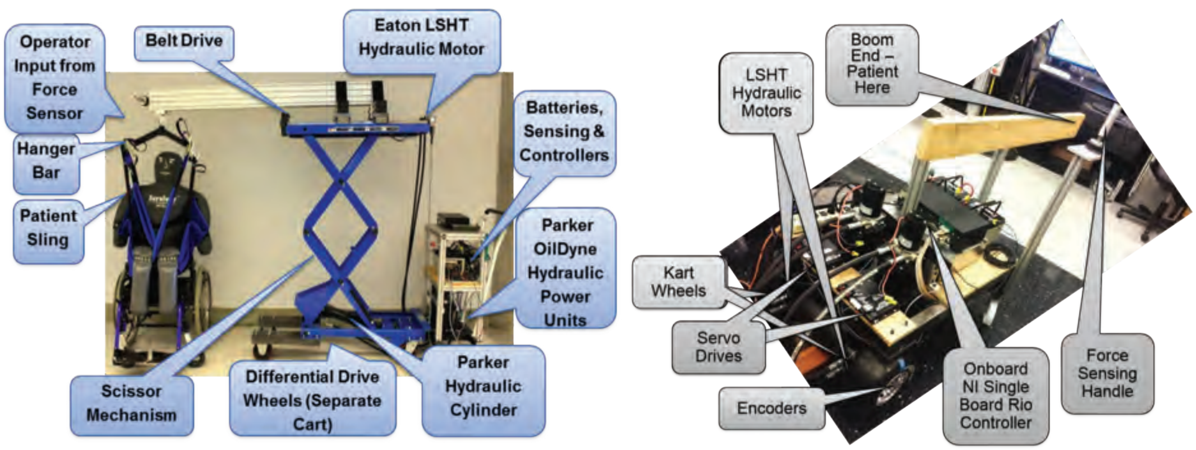


Figure 2. First prototype patient transfer assist device; left: main lifting and boom extension, right: differential drive wheels on separate testing cart

The operator input force maps to a reference patient velocity, and the kinematics calculations for conversion from patient motion to wheel motion are performed on the controller. Wheel position feedback is obtained from encoders, and feedback rate control is implemented on the controller. The cart is fully functional and ready for testing of more advanced control architectures, such as obstacle avoidance. Additional updates have also been made to the overall electrical system, including addition of a breakout board and electrical box to handle all sensing, including pressures on each side of each actuator, motor currents, actuator positions, operator input forces, and other system forces.

Dynamic System Modeling

A model has been created to simulate the mechanical dynamics of the main lifting scissor mechanism, boom extension, and actuation mechanisms, as well as a variable patient payload, in MATLAB. A gray box model based on system identification by spectral analysis, roughly based on the form of a first principles based model, has been developed for the actuation systems, with input reference motor current and output actuator motion. Further investigation is in process to capture significant nonlinear or non-ideal features of the actuation systems, such as stiction, deadband, and other characteristics.

Control and Operator Interface

In order to allow for this powerful machine to operate safely in a relatively delicate environment with humans in the workspace, and to reduce the caretaker mental workload, it is desirable to manage any undesirable interaction forces. For the main lifting and boom extension, some interaction with the caretaker and patient is necessary. Therefore, it is desirable to develop controllers which manage both force and motion. A substantial literature study has been performed on various types of interaction controllers, particularly those that are well-suited for hydraulic actuation. Several forms of interaction control will be tested on the boom extension.

The first form of interaction control to be implemented on the hardware system is an impedance control [9], currently implemented in a mechanical dynamics simulation on the scissor lift and boom extension, and in the hardware system on the boom extension, shown in Figure 3. The controller uses a low level force control based on pressure measurements from the hydraulic motor. The required estimate of the external interaction force is estimated from pressure measurements and knowledge of the system dynamic properties, such as inertia and friction/damping.

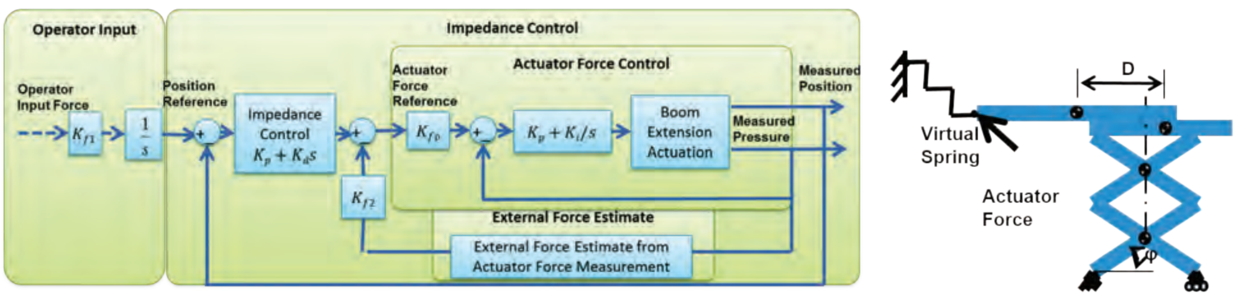


Figure 1. Interaction control; left: current impedance control implementation on boom extension, right: interaction concept of virtual spring in task space

The architecture shown in Figure 3 has been tested on the boom extension hardware system. Preliminary experiments demonstrate that the motion of the machine under closed loop control can be significantly affected by small external forces (less than 15 lb_f), exerted by a human.

D. Plans

Plans for the next year

System Integration and Modeling

Once controller testing for the wheels is complete, the differential drive wheels will be integrated into the full patient transfer assist device system. The machine and electronics were designed to allow for integration with the additional actuators, sensors, and hydraulics. Four degrees of freedom, the wheels, the vertical lift, and the horizontal boom extension, will be controlled from the same operator input force sensing handle. Management of the redundancy between the boom extension and the wheeled base will be determined. An investigation on this base redundancy management, along with tipping stability, will be performed. Basic models of the hydraulic actuation system and mechanical dynamics for the boom and lift have been created. Models for the differential drive wheels will be added and integrated into the full system model. Also, further characterization of nonlinearities and other non-ideal features of the pump controlled actuation systems will be added, and the full system will be integrated in simulation.

Operator Interface and Control Design

The current focus for the control design is on interaction control, to manage any undesirable external interaction forces. It was apparent from the benchmark operator testing that unintentional interactions between parts of the machine and the environment are common, and with such large force capability, management of such forces is needed. First, a few different types of interaction control will be implemented on the horizontal boom extension, along with any needed compensation for nonlinearities or other non-ideal hardware system features. These include forms of the currently implemented impedance control (with low level force control), an admittance-based human power amplifier (with low level position control), and a passivity-based human power amplifier. The most suitable forms of interaction control will also be implemented on the vertical lifting degree of freedom. Obstacle avoidance algorithms based on ultrasonic sensing will be implemented on the wheeled base. The system will be integrated to provide coordinated control of all degrees of freedom of the machine from a single force sensing handle. The design of the caretaker physical interface will be improved, based on input from NCAT, including determining an appropriate ergonomic location for the input handle.

Operator Testing

Once the system integration is complete, a set of operator experiments will be performed. The experiments will include tests similar to those from the benchmark study, which included several transfer operations between a bed, a wheelchair, a chair and the floor, as well as a time study and survey. It will also include experiments to evaluate the performance of the obstacle avoidance / interaction control. Results will be evaluated by statistical methods, including ANOVAs, and the results will be presented. Improved or alternative caretaker physical interface designs will also be tested.

CCEFP Project Integration

Collaboration continues with NCAT on project 3A.3 on their modeling of the caretaker physical and mental interaction with the machine. CAD models of the prototype patient transfer assist device have been provided and are being used in their simulations. They are also providing input on the operator testing, evaluation, and interface design. A form of vibration control similar to that used in project 3B.3 with Dr. Vacca may provide a different method to compensate for an instability problem encountered in this test bed hardware system resulting from an overrunning load condition; they have provided some guidance toward our understanding and solution of this issue, and investigation on viability of implementation on Test Bed 4 will be pursued further. The graduated passivity-based human power amplifier controller developed in project 3A.2 was implemented on a pre-prototype of this test bed, and it continues to be a candidate controller and will be tested on the current prototype hardware. Finally, initial investigation and exchange of information has begun related to simulation of integration of a hydraulic transformer, project 1E.5, into Test Bed 4.

Longer Term Vision

In later years, this test bed can provide a platform in which to test additional small scale subsystem and component technologies and operator interface designs, as they further develop. Alternative hydraulic system architectures may be tested. This system is also a good candidate for testing regeneration.

Expected milestones and deliverables

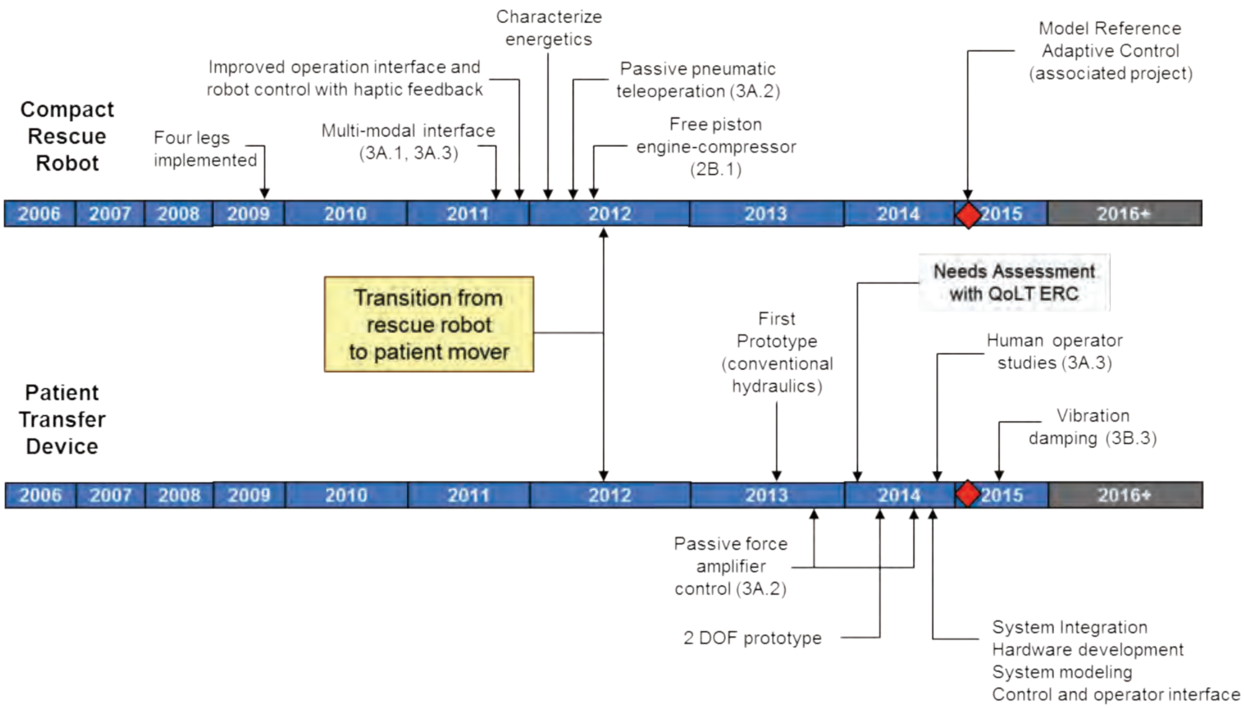
- Preliminary testing with control strategies implemented in simulation and hardware completed [Month 10]
- First round of human operator studies completed [Month 13]
- Preliminary testing with additional actuated degrees of freedom completed [Month 15]
- Preliminary testing with alternative operator and patient interface designs completed [Month 19]
- Results of testing with other CCEFP component projects [Month 22]
- Final testing *and reporting** completed [Month 24]

**Note: added after proposal*

E. <u>Member company benefits</u>

This project provides several potential benefits to member companies. It exemplifies a significant market need where fluid power technology can be utilized, to expand the use of fluid power in home and healthcare applications. This has potential to combat any negative perceptions of fluid power in these areas (e.g. noisy, leaky, unsafe, etc.), paving a way for further expansion into these domains. It also provides an opportunity to develop more effective operator interface concepts for multiple degrees of freedom that work well with humans in the workspace. Furthermore, it is expected to demonstrate methods for effective small scale closed loop electro-hydraulic pump control from electric motors.

Test Bed 4 Technology Integration



Test Bed 4 Milestone Chart

Test Bed 4 (TB4) was originally targeted as a rescue robot platform with the goal of demonstrating portable power supplies, compact components, intuitive human-machine interface and control advances. Passive pneumatic teleoperation control (3A.2) was successfully implemented on TB4 in (2012). The Free-piston engine-compressor (2B.1) was also installed in (2102) and demonstrated a low-weight device fully capable of being carried by the crawler.

In summer 2012, TB4 transitioned to a patient mover platform, in collaboration with the Quality of Life Technology (QoLT) ERC. The fluid powered patient transfer test bed affords opportunities to investigate the use of fluid power at the human scale where the high power density of fluid power is required. Specifically, applications in this area will require the safe interaction of fluid power machines with humans in the workspace, and will also afford a representative test bed for human-machine interfaces that are intuitive and safe for controlling multiple degrees of freedom. The test bed also provides a proving ground for inherently safe control methodologies as applied to fluid power. In addition to the design and construction of the platform, several projects will demonstrate the requirements above, including:

- (3A.1) Multi-model human machine interfaces
- (3A.2) Passive force amplifier control for inherently safe human-machine interaction

- (3A.3) Human centered design and operator studies for intuitive operation of multiple degrees of freedom
- (3B.3) Active vibration damping for smooth control that limits exposure of forces to the patient
- (1E.5) Hydraulic transformers for efficient operation

The test bed, and the demonstration of the above projects on the test bed, will serve to move fluid power into new application areas and new markets that are not traditionally fluid power: homes and clinical institutions. Other research areas of the CCEFP will also potentially contribute to the success of the application area of patient transfer such as noise mitigation and component integration.

Test Bed 6: Human Assist Devices (Fluid Powered Ankle-Foot-Orthoses)

Research Team

Project Leader:	Elizabeth Hsiao-Wecksler, MechSE, UIUC
Other Faculty:	Will Durfee, Mechanical Engineering, University of Minnesota Geza Kogler, Applied Physiology, Georgia Tech
Graduate Students:	UIUC: Morgan Boes, Mazharul Islam, Ziming Wang, Matt Petrucci (affiliated project using PPAFO on persons with Parkinson's disease) UMN: Jicheng Xia, Brett Neubauer
Undergraduate Students:	UIUC: Katie Neville, Chenzhang Xiao; Tim Anderson, Minnesota State Mankato (CCEFP REU); UMN: Faith Bradley, UIUC (CCEFP REU), Jon Nath (UMN)
Industrial Partner:	Parker Hannifin

1. Statement of Test Bed Goals

The goal of this test bed is to drive the development of enabling fluid power technologies by:

(1) Miniaturizing fluid power systems for use in novel, human-scale, untethered devices that operate in the 10 to 100 W range.

(2) Determining 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 (TB6) 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.

2. Project Role in Support of Strategic Plan

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. This 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.

3. Test Bed Description

A. Description and explanation of research approach

<u>Problem Statement</u>

In the US alone, individuals who suffer from or have been affected by stroke (4.7M), polio (1M), multiple sclerosis (400K), cerebral palsy (100K) or acute trauma could benefit from a portable, powered, daily wear lower limb orthoses. For individuals with impaired ankle function, current solutions are passive braces that provide only motion control and joint stability and lack the ability to actively modulate motion control during gait and cannot produce propulsion torque and power.

<u>Challenges</u>

The ideal AFO should be adaptable to accommodate a variety of functional deficits created by injury or pathology, while simultaneously being compact and light weight to minimize energetic impact to the wearer. These requirements illustrate the great technological challenges facing the development of non-tethered, powered AFOs. The core challenges that must be met to realize such a device are: (A) a compact power source capable of day scale operation, (B) compact and efficient actuators and transmission lines capable of providing desired assistive force, (C) component integration for reduced size and weight, and (D) control schemes that accomplish functional tasks during gait and effectively manage the human machine interface (HMI). Therefore, the development of light, compact, efficient, powered, un-tethered AFO systems has the potential to yield significant advancements in orthotic control mechanisms and clinical treatment strategies.

State-of-the-Art

Passive AFO designs are successfully used as daily wear devices because of the simplicity, compactness, and durability of the designs, but lack adaptability due to limited functionality. To date, powered AFOs have not been commercialized and exist as research laboratory devices constructed from mostly off-the-shelf components. The size and power requirements of these components have resulted in systems that require tethered power supplies, control electronics, or both.

Research Approach

We are following a roadmap for developing portable fluid powered AFO devices with increasing complexity and performance requirements. In 2008, the design and construction of an energy-harvesting AFO that selectively restricted joint motion using a pneumatically-driven locking mechanism was completed. Using a systems engineering approach, the fluid powered AFO system has been divided into four subsystems that align with our core system challenges: power supply, actuator/valving, structural shell, and control system (electronics, sensors, and HMI). The subsystems have target specifications that must be met to realize a fully functional device. The power supply must weigh < 500 g, produce at least 20 W of power, run continuously for ~1 hour, and be acceptable for use near the human body. The actuator and valving must weigh < 400g and provide a minimum of 10 Nm of assistive torque at a reasonable efficiency. The structural shell must weigh under 500 g, be wearable within a standard pair of slacks (fit inside a cylinder with 18 cm OD), and operate in direct contact with the body. The control system must control the deceleration of the foot at the start of stance, permit free ankle plantarflexion up to mid stance, generate a propulsive torque at terminal stance, and block plantarflexion during swing to prevent foot drop; all in a robust and user friendly manner. To achieve our goals we have pursued two parallel paths: a portable pneumatic AFO (the PPAFO) and an untethered hydraulic AFO (the HAFO). We report on each below.

B. Achievements

Portable Pneumatic AFO (PPAFO)

In 2010, the first generation PPAFO demonstrated device feasibility and was an improvement over state-of-the-art passive and active systems because it provided subject-specific motion control and torque assistance without tethered power supply or electronics. The device provided modest dorsiflexion (toes-up) and plantarflexion (toes-down) torque actuation at the ankle. Two U.S. patent applications on the PPAFO were filed with CCEFP students and faculty from UIUC, UMN, MSOE and GT as co-inventors.

Since then, we improved the efficiency, compactness, control, usability, and applications of the PPAFO. The hardware includes an OTS pneumatic rotary actuator located at the ankle joint, a canister of compressed CO_2 at the waist (a placeholder for a future compact power source), and a waist-worn microcontroller (Figure 1d). The Gen 1.0 PPAFO could generate up to 12 Nm at 100 psig with run times less than 30 minutes with a 20 oz. bottle (Figure 1a). Theoretical and experimental component and system efficiencies of the PPAFO system suggested that the exhaust gas from the higher pressure plantarflexion actuation (100 psig) could be captured into an accumulator and recycled to power the lower pressure dorsiflexion actuation (30 psig). Working with students at Vanderbilt on Project 2C.2 (strain energy accumulator), we constructed a pneumatic elastomeric accumulator for use with the regenerative pneumatic circuit that was tested during walking tests and we investigated the effect of two control algorithms on fuel efficiency. By increasing the net work output, a more intelligent, state estimation controller improved fuel efficiency by 72% compared to a basic controller with the regenerative circuit. Using the state estimation controller and the regenerative pneumatic circuit, the run time for a 9 oz bottle was expanded from original 15 to 19 minutes.

For the 2012 Gen 2.0 PPAFO, we developed a lighter and simpler structural shell that allows for swapping of modular system components (Figure 1b). The shell has no metal vertical struts and no medial support. The weight of the PPAFO went from 1.86 kg to 1.60 kg. Multiple sized (S, M, L) foot and shank shells were fabricated to support testing on different sized test subjects. To reduce the size and increase the torque of pneumatic actuation, we have sponsored Mechanical Engineering capstone design teams at Bradley University from fall 2011 to spring 2014 as a CCEFP E&O capstone project. The 2014 team delivered a design with dual cylinders and gear train that achieves 40Nm @ 110 psig. We are currently integrating this actuator with the Gen 2.0 shells to create the Gen 3.0 design (Figure 1c).

To control the PPAFO in varied walking environments (level ground, stairs, ramps), we examined different actuation-timing control strategies, solenoid vs. proportional control, and recognition and control for different gait modes. Our initial controller for level ground walking was a simple direct event threshold-based control using just the heel and toe sensors. To accommodate impaired gait, we developed a model-based state estimator controller that added the angle sensor. We examined how work and fuel use were affected by the controllers and inclusion of a regenerative circuit using the elastomeric accumulator. A simulation and bench-top study highlighted that proportional valve control has better tracking and efficiency compared to solenoid valves; however due to the large size of commercial proportional vales, we have not implemented this on the PPAFO, but it does highlight technological barriers to compact fluid-powered orthoses. In 2011, we began work in recognition and control for different gait modes using a 6DOF inertial measurement unit (IMU). Progress in 2012 and 2013 resulted in success rates of identifying level ground, stairs, or ramps of 97-99%. We determined that only stair or ramp descent require a different controller than level ground or stair/ramp ascent, and differential gait mode control has been implemented. In Y9, we worked on improved control algorithms that use modified fractional time and Bayesian regularized artificial neural networks for estimating walking state.

In 2013, in collaboration with researchers at the Rehabilitation Institute of Chicago, we began testing the Gen 2.0 PPAFO compared to tibial stimulators and passive AFOs in post-stroke and multiple sclerosis (MS) subjects. At the end of Y9 we nearly completed a 20-person study on MS participants. Results suggest that walking with the PPAFO reduces stride length and velocity, but improves joint kinematics perhaps leading to less stress on compensating joints for ankle impairment. In an associated project with the Movement Disorders Center at the University of Minnesota, we are investigating the use of the PPAFO as a gait initiation device for people with Parkinson's disease (PD). A pilot study on healthy young adults provided insight into the feasibility of this application, and an on-going study with people with PD began in 2013. Preliminary results suggest that modest mechanical assistance at the ankle could enhance diminished or absent force production and lateral weight shift while preparing for the start of a step in people with PD and symptoms of freezing of gait.

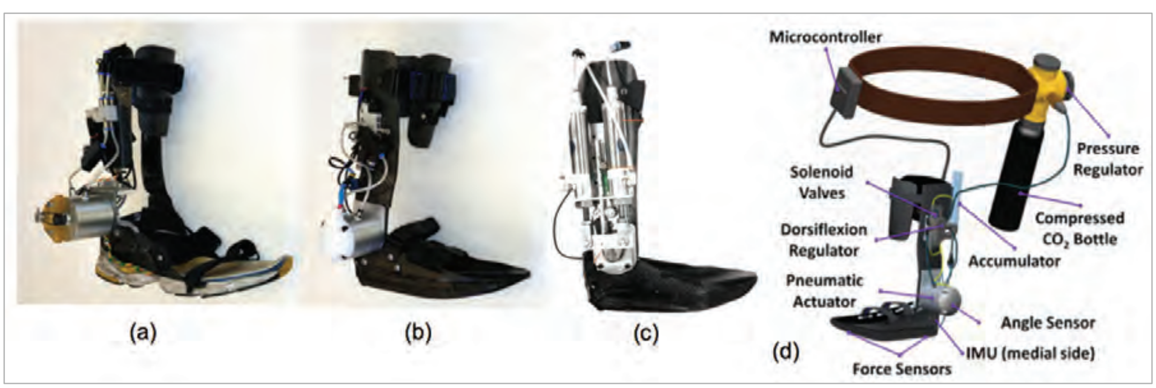


Figure 1: Three generations of the PPAFO (a) 1.0, (b) 2.0, (c) 3.0. (d) CAD rendering of Gen 2.0 system.

Untethered Hydraulic AFO (HAFO)

The research objective for the HAFO test bed is to understand the limits of small-scale hydraulics in the 10-100W range. The motivation is the need for small, untethered wearable robots. The rationale for using hydraulics is that the higher pressures that can be attained with hydraulics enables high-torque exoskeletons. From an analysis of small-scale system, we determined that the hydraulic pressure must be over 500 psi for high power-to-weight and chose 2,000 psi as the nominal pressure for the HAFO. The key design requirements driving the test bed HAFO are: (1) 90 Nm torque, (2) 70 deg range of motion, (3) 100 deg/sec velocity, (4) fits under pants, (5) less than 1 Kg mass at the ankle, (6) 3,000 steps between recharge, (7) no tether. In Year 9 we completed the design and assembly of a wearable HAFO and met all of the key design requirements except requirement 6 that we have yet to test.

The configuration of the HAFO is: Battery ⇨ DC Motor ⇨ Pump ⇨ Hose ⇨ Cylinder. The system layout and prototype is shown in Figure 2. Performance bench testing of the prototype showed the system can reach the 90 Nm and 100 deg/s target and has about a 3 Hz bandwidth.

C. Plans, Milestones and Deliverables for Next Year

PPAFO

Complete longevity assessment of PPAFO with additional healthy test subjects to verify robust operation. Perform clinical trials on use of PPAFO on post-stroke, multiple sclerosis, and Parkinson's populations. Investigate new control schemes for state estimation and gait mode recognition. Implement new higher torque output pneumatic actuation system on Gen 3.0 PPAFO.

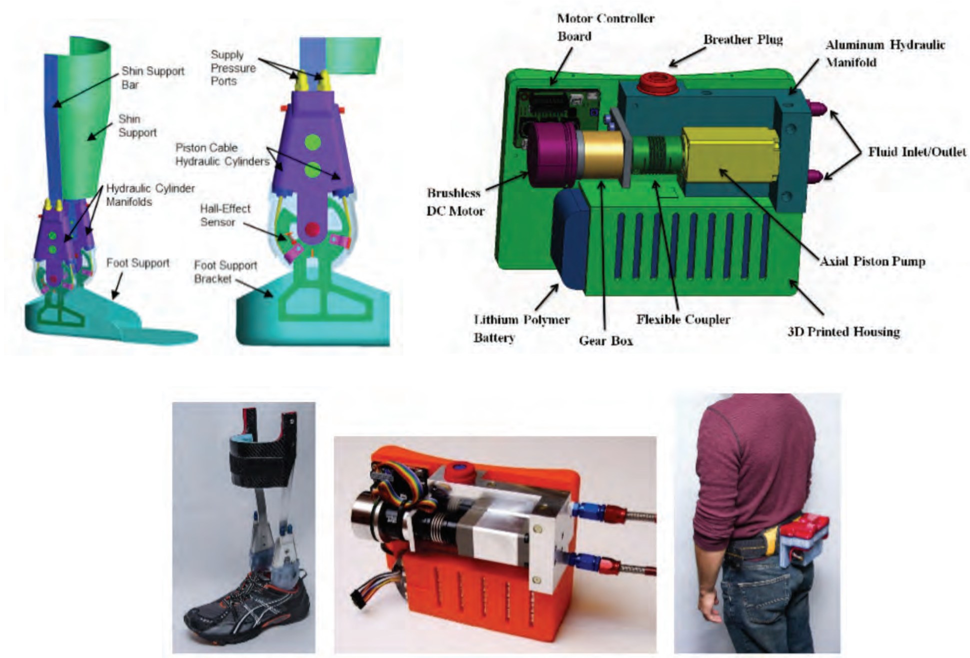


Figure 2: HAFO layout and prototype.

HAFO

Complete bench testing of the HAFO prototype. Complete walking testing of prototype. Develop new controllers. On the analysis side, we have begun to develop a comprehensive suite of design tools for small-scale hydraulic systems. Using static physics models of piston pumps, hoses and cylinders, we are able to predict the weight and efficiency of a system for a chosen operating point. During Y10 we will validate these models and will add in models for control valves.

D. Plans, Milestones and Deliverables for Next Five Years

PPAFO

Demonstrate the PPAFO on different patient populations (MS, PD, stroke) and seek external funding to support extended clinical research. To achieve these goals, we will conduct the following tasks:

Task 1: Improve torque to weight and torque to size performance, and a proportional MEMS valve. Integrate MEMS valve and higher torque actuation system. Milestones: Investigate control of Gen 3.0 PPAFO [June 2015]; Integrate MEMS proportional valve into PPAFO [December 2015].

Task 2: For a walking assistance application, design and implement control, including neural network state estimation and gait mode recognition. Milestones: ANN integration (computer driven) completed [June 2015]; Gait mode recognition and actuation without one-step delay completed [August 2015]; Concepts for energy harvesting completed [December 2015].

Task 3: For a seated rehabilitation therapy application, we will work with clinical stroke collaborators to identify testing protocols. Pressure and air flow control for torque and rotational velocity control will be examined to allow proper operation of the PPAFO. A post-stroke therapy system will be demonstrated. Milestones: Identify therapy requirements [June 2015]; Initial integration of clinician and patient user interfaces with PPAFO [September 2015]; Torque and rotational velocity control completed [March 2016]; Demonstration of post-stroke therapy [May 2016]

HAFO

Task 1: Create suite of design tools for small hydraulic systems that predicts size, weight and efficiency.

Task 2: Examine selected fluid power circuit and control architectures for small hydraulic systems.

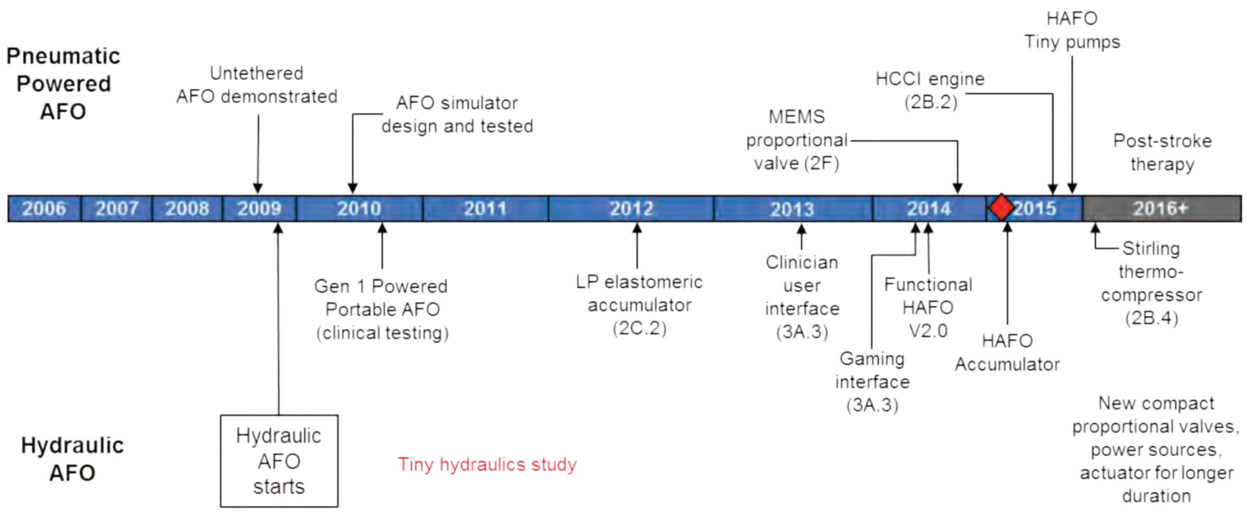
Task 3: Implement the HAFO in a child-size version for a research project involving children with cerebral palsy.

Task 4: Seek external funding to support application studies.

E. Member company benefits

New technologies that miniaturize components such as power sources, actuators, and valves will be developed. New design tools that simplify the process of small hydraulic systems. This could spawn new markets for miniature fluid power systems.

Test Bed 6 Technology Integration



Test Bed 6 Milestone Chart

The role of the Fluid Power Assisted Ankle Foot Orthosis (AFO) test bed is to represent human assistive devices of the 10W-100W range. Initially, the AFO is targeted to use pneumatics. In 2009, the potential of tiny hydraulics to achieve the required compactness was recognized. Currently, both a pneumatic and a hydraulic AFO are under development.

The pneumatic powered AFO (PPAFO) platform has demonstrated un-tethered operation and has been tested in clinical settings (2010). The needs for specialized components in this test bed have given rise to new projects such as a compact MEMS pneumatic valve, and portable power sources. A strain energy accumulator (2C.2) was installed in (2012) to recapture energy of the exhaust gas to improve overall efficiency. Several projects will be integrated and demonstrated in the next few years.

- (3A.3) A clinician-centered user interface was implemented in (2013), a rehabilitation game interface for patients will be implemented next.
- (2F) The compact MEMS proportional pneumatic valve will be tested in (2015)
- (2B.2) The micro HCCI free-piston engine-compressor will be tested as a power source in (2015)
- (2B.4) The controlled Stirling thermo-compressor will be tested as a power source in (2016)

The hydraulic version of the AFO is being investigated to understand the capabilities and limits of small-scale hydraulics. Custom design of hydraulic components is required at this scale and work is currently underway along this direction by using a physics-based modeling approach. A first prototype hydraulic AFO (HAFO) is expected in (2015), integration of MEMS valves in (2015), creation of a suite of design tools for small hydraulic systems in (2015), implementation of the HAFO for children with cerebral palsy in (2015) and demonstration of post-stroke therapy in (2016).

3. UNIVERSITY AND PRE-COLLEGE EDUCATION PROGRAM

The mission of the Education and Outreach 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 Program is a general public that is aware of the importance of fluid power and the impact of fluid power on their lives; students of all ages who are motivated to understand fluid power and can create new knowledge and innovation; 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 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 program leaders for new audiences; and to leverage and coordinate the accomplishments of individual projects to facilitate the progress and successes of complimentary projects.

The objectives of the Education and Outreach Program are to:

1 Motivate a diverse cohort of 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.
3 Infuse new fluid power research and innovative, evaluated, fluid power curricula and programs into informal, K-12, and college level course offerings.
4 Create a culture that integrates research and education for undergraduate and graduate students across all 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.

Organization: The EO program is divided into four thrusts, each of which meet one or more of these six objectives.

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

The objectives of the CCEFP diversity strategic plan:

1. The Center aims to provide a welcoming and inclusively environment for all persons, especially those who are underrepresented in engineering, to work synergistically, educate and learn enthusiastically, and mature professionally.
2. The Center aims to facilitate and maintain a student body that is abundantly diverse and reflective of the greater domestic community.
3. The Center aims to change the face of the fluid power industry by providing opportunities to diverse students and authentically engaging these populations in workforce development.
4. The Center aims to reach, recruit, and retain graduate students, staff, and faculty that reflect the gender, racial, and ethnic composition of our country.

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, industry engagement, and evaluation. 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 this industry's intellectual capital.

The CCEFP Workforce Development figure is a snapshot of the CCEFP education project portfolio showing the target objectives for each project. The project reports in Volume 2 provide detailed information on each project.

Thrusts, Projects and Program Objectives	Promote STEM learning	Promote awareness of fluid power	Fluid power dissemi-nation	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	x	x		x		x
Thrust B: Outreach Bringing fluid power education to K-12 students, with a focus on middle and high school outreach						
B.1 Research Experiences for Teachers (RET)	x	x	x	x		
B.3B Portable Fluid Power Demonstrator and Curriculum	x	x	x	x		
B.7 NFPA Fluid Power Challenge Competition	x	x			x	x
Thrust C: College Education Bringing fluid power education to undergraduate and graduate students						
C.1 Research Experiences for Undergraduates (REU)	x	x		x	x	
C.4 Fluid Power in Engineering Courses, Curriculum and Capstones	x	x	x	x	x	x
C.4A Capstone Senior Design Project: A Third-Generation Pneumatic Rotary Actuator Driven by Planetary Gear Train	x	x	x	x	x	x
C.4B Parker Hannifin Chainless Challenge	x	x	x	x	x	x
C.8 Student Leadership Council (SLC)	x	x		x	x	x
Thrust D: Industry Engagement Making connections between CCEFP and industry						
D.1 Fluid Power Scholars	x	x		x	x	x
D.2 Industry Student Networking	x	x		x	x	x
D.5 CCEFP Webcasts Series	x	x		x	x	x
Thrust E: Evaluation Measuring CCEFP program effectiveness	x	x	x	x	x	x

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

- **Industry Student Connection** - A deliberate focus of the E&O program is to foster industry and student connections by leveraging existing meetings and events to build upon networking opportunities, both for employment as well as research collaboration. These connections and networking opportunities exist during meetings, events and other leveraged moments. (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 hundreds of students to this technology each year. The University of Minnesota recently offered the first Massive-Open-Online-Course (MOOC) in Fluid Power, a significant achievement in undergraduate curriculum. In addition, 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. 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, a positive outcome from industry's point of view. To date, more than 170 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.
- **REU Fluid Power Boot Camp** – Twenty-two enthusiastic REU students conducted research in CCEFP labs at the Center's seven universities during the summer of 2014. REU students participated in the Center's fourth Fluid Power Boot Camp for REUs at Purdue University, May 2014. To date, 170 REU students have participated in Center research. (Project C.1)
- **CCEFP-GEM Partnership** - 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. This rich collaboration offers nothing but benefits to the GEM Fellow, the ERC, the Industry member, and the GEM Consortium.
- **Science Museum of Minnesota** - The fluid power exhibits at the Science Museum of Minnesota are now in a special area of the physical exhibit floor, named the Experimental Gallery, and have educated thousands of museum visitors of all ages about fluid power. The Science Museum of Minnesota has indicated that the fluid power exhibits will likely remain a permanent feature in the Museum's Experiment Gallery. The SMM also advises fluid power capstone projects at the University of Minnesota. (Project A.1)
- **SLC Travel and Project Grants** - 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 and Project Grants Program has been highly successful, providing over 24 travel grants to CCEFP graduate students. This program has proven to be very popular among students and faculty. (Project C.8).
- **CCEFP Webcast Series** – An expansion of the Center's popular webcast series includes special topics discussions led by industry experts as well as invitations to associated and affiliated research projects. (Project D.5)
- **Fluid Power Challenge** - The Fluid Power Challenge, marketed through the National Fluid Power Association, is a hands-on engineering design competition for eighth grade students, utilizing hydraulics and pneumatics. The CCEFP committed to coordinating three events in the 2014/2015 school year, at U of MN, GeorgiaTech and Purdue at Kokomo. The NFPA provided additional funding to launch the new events at GT and PU. At the end of the school year, over 400 students would have been through the event through CCEFP schools, including MSOE. (Project B.7)
- **External Evaluation** - Quality Evaluation Designs (QED) is the CCEFP's external evaluator of Education and Outreach projects. The overall goal of the QED external evaluation is to collect data that have the potential to promote sustainability of E&O beyond NSF funding of CCEFP. To do this, QED will pursue the following objectives: to anticipate in the evaluation design a new

administrative/organizational CCEFP structure that supports and integrates E&O goals and objectives, to identify current and potential stakeholders who could sustain E&O goals and/or programs during and after the current funding cycle, and to collect data and draft reports that address the value-added of E&O to CCEFP goals and programs. (Thrust E)

- **Fluid Power Scholars** - The Fluid Power Scholars Program is in its sixth year. It is a sponsorship program of interns to attend a short-course on fluid power. To date, 40 high-performing undergraduate engineering students completed a fluid power boot camp followed by a full-time summer internships at CCEFP member companies. Since 2010, 75% of Scholars have been hired into the fluid power industry. The FPS program went through a revamp in 2014 and with new system; the program has reached max capacity for 2015, by recruiting a full roster of corporate supporters. (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:

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 7 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.

A Y9 highlight of significant achievement: Professors James Van de Ven and William Durfee successfully offered 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. 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 offered during the fall of 2014, over 8,000 registered for the course.

Professor Jim Van de Ven, CCEFP Education Director, continues to lead efforts to develop undergraduate and graduate fluid power curriculum. A full report can be found in Volume II, EO Project C.4. Preliminary plans and actions for fluid power curriculum design and dissemination include:

- Continue to encourage the incorporation of fluid power content into existing courses and to develop new lecture and lab courses in fluid power.
- Continue to work on mini-books, developing problem sets, video lectures and lecture slides.
- Promote the Fluid Power OpenCourseWare site and create awareness
- Encourage completion of on-going projects.
- Utilize multiple modes to increase digital repository content.

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. Long-term, this project will be a collaborative activity with the National Fluid Power Association (NFPA).

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, a win-win from industry's point of view. 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 170 REU students have participated in the program--more than many traditional REU site programs.

The REU Site Award will expire after the summer 2015 program. The CCEFP will continue to apply for supplemental grants and funding sources to support the REU program. The CCEFP desires for the REU Program to continue after the Center's Year 10. However, without additional supplemental funding, the chances of sustainability are slim, given the significant financial investment needed to support the program in full.

Fluid Power Scholars Program: The Fluid Power Scholars program compliments the REU program. The program was launched in 2010 and is underway for 2015. Over 40 Fluid Power Scholars have been named since the program inception, and we are pleased to announce it has reached capacity for 2015. 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. 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.

Essentially, 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 CCEFP and NFPA workforce development initiatives.

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 seven years ago.

Student Leadership Council Travel and Grant Programs: The Student Leadership Council is an independent board of the CCEFP. The Education and Outreach program sponsors the activities of the SLC. The SLC has launched a successful travel and project grant program used to support student travel between CCEFP institutions and to companies engaged in the fluid power industry. The travel grant program will foster greater communication between the research institutions as well as between students and industry partners. The SLC issues calls for proposals on a revolving basis and the CCEFP expects to continue meeting these needs of the students.

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* 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.	*Finalist, 3MT Competition* Purdue University 3MT ('3-Minute Thesis') 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.

The Center is not surprised that the ratio of Graduate to Undergraduate students who are involved with the CCEFP has reached a value of 1.8 during the current reporting period (table 3b). This result is due to the decreasing number of undergraduate students involved with CCEFP programs, namely some of the undergraduate outreach programming that has been sunsetted as the Center entered into Y9 and Y10. This ratio, however, is still within the appropriate and recommended range. The Center understands a large number of undergraduate students involved with the CCEFP brings visibility to the Center in an important demographic, future graduate students and future practitioners in the area of fluid power.

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 hope and expect that the OpenCourseWare site will grow in content and use, and in particular, that universities outside the CCEFP will use and find value in the materials. We expect the Fluid Power MOOC to generate much interest in fluid power training and dissemination. Through the REU program, the Fluid Power Scholars program, and the requirement of each research project to include at least one non-graduate research student, significant numbers of undergraduate students will gain fluid power experience during the summer and the academic year. In the future, the CCEFP expects to have a focused effort in curriculum module design, implementation and dissemination of the OpenCourseWare site. A partnership with the NFPA is expected to help drive this initiative.

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. Moreso, in Y10, the program will change its name to Workforce Development as we begin to partner, formally, with the National Fluid Power Association.

In the future, the CCEFP proposes to expand the internship program to include vocational and technical colleges and to broadly engage graduate students in corporate internship positions. The Center proposes to continue the highly successful REU program, having secured an external grants, the NSF REU Site award, for support. Industry-sponsored capstone projects in fluid power will be a joint matchmaking effort between CCEFP and NFPA. 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. A fluid power training program designed and offered through the CCEFP and NFPA workforce development program is proposed, targeting students seeking employment, industry seeking qualified students, engineers seeking the latest in fluid power research, and the academic community seeking project support. There is so much to be gained from collaboration and cooperation within the fluid power industry.

CCEFP E&O 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. It is anticipated that a cooperative program would reside in both CCEFP and NFPA, with oversight from appropriate governing boards. Rather than work independently on workforce development goals, the two organizations would be collaborative in the approach. Together, the program would be responsible to meet yearly objectives and would find greater success together than individually. It is proposed that the NFPA Foundation Board be the final authority on fluid power education goals and objectives. It is anticipated an Education Strategy Committee be formed, inclusive of academia, practitioners and educators. Areas of expertise, technical ability, and existing infrastructure will be a major factor in determining the ways in which CCEFP and NFPA will coordinate logistics. 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.

3.2 PRE-COLLEGE PROGRAM

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
CCEFP hosts four NFPA 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. Offered at the University of Minnesota in 2009, 2012, 2013 and 2014, the Fluid Power Challenge has reach more than 400 8th grade students in metropolitan and out-state Minnesota communities. New in 2014, the CCEFP, with sponsorship from the NFPA, hosted two additional events at Georgia Institute of Technology and Purdue University at Kokomo. The Milwaukee School of Engineering has traditionally hosted this event, before the CCEFP adopted it as its primary outreach program. The CCEFP expects to continue to host the Fluid Power Challenge, as it is cornerstone of the National Fluid Power Association. CCEFP hopes to expand its offerings to other CCEFP site locations in the future.

Research Experiences for Teachers Program: In the recent reporting year, four RET teacher participants conducted research in the CCEFP laboratories of Purdue University and North Carolina A&T State University. The CCEFP has sponsored 42 RET projects to date, and many teachers have been repeat participants. In 2014, the RETs from NCAT were community college faculty members. Additionally, one 2014 RET teams at Purdue University continued to work on the Fluid Power Demonstrator Kit and Curriculum under the guidance of Professor John Lumkes (Project B.2). The RET effort at Purdue is one of a kind. The CCEFP is the only 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. In Y10, the CCEFP RET program will be offered for the last time. The CCEFP and NFPA believe that greater outreach impacts can be made through the Fluid Power Challenge Competition.

CCEFP Joins NFPA as an Exhibitor at the International Manufacturing Technology Show in Chicago, IL: The CCEFP and the National Fluid Power Association (NFPA) co-exhibited at the Smartforce Student Summit during the International Manufacturing Technology (IMTS) Show 2014 in Chicago, IL, September 8 - 13. The IMTS supports the next generation "smartforce" entering the manufacturing technology industry who will keep the U.S. in its global manufacturing leadership position. In the future, the CCEFP will participate alongside NFPA during other select exhibiting opportunities, for example, the ITEEA STEM Showcase, Milwaukee, WI, March 2015.

Priorities for the Future
With the CCEFP now in its ninth year, planning and implementation of E&O 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, the pre-college program will be a joint effort between the CCEFP and NFPA to partner on pre-college fluid power outreach and engagement. To do this, the CCEFP and NFPA will leverage existing and established national partnerships, to expose the general public, teachers, and students to fluid power and its importance in our lives. The CCEFP will serve as a supporter role rather than a lead role in pre-college outreach. The NFPA has the necessary communication infrastructure and industry support, whereas the CCEFP has relationships with educational organizations. Between the CCEFP and NFPA, a solid and structured public and pre-college outreach and engagement program would be highly successful, due to the individual investments of each partner.

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 fifty 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, if not more, important 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/Student Networking: 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 Y9, the CCEFP expanded its bridge between industry and students. Examples include:

- Fluid Power Capstone Courses
  - Promote industry support of undergraduate capstone projects.
- Fluid Power Scholars Program
  - Highly successful sponsorship program of incoming corporate interns.
- CCEFP Webcast Series
  - Popular on-line research seminar series on CCEFP progress, and affiliated research, presented by students and special topics by industry guests.
- Industry Engagement Committee / IEC Summits
  - The NFPA Pascal Society's IEC Summits are held twice a year at one of the CCEFP institutions. Students present research updates to the IEC audience and the attendees give immediate feedback on the research progress.
- Fluid Power Innovation and Research Conference (FPIRC)
  - The CCEFP hosted its first annual FPIRC event at Vanderbilt University, October 2014. FPIRC has replaced the CCEFP Annual Meeting. The vision of FPIRC is to become the premier fluid power technical conference in the United States.
- CCEFP Student Retreats hosted by Industry
  - The 2012 summer retreat was hosted by Sauer-Danfoss in Ames, Iowa.
  - The 2013 summer retreat was hosted by Caterpillar, Inc. in Joliet, Illinois.
- NSF and GEM Consortium
  - NSF adopts CCEFP's innovative approach to recruitment of underrepresented students in engineering through the National GEM Consortium.

An ongoing portfolio of accomplishments:

- FPIRC, formerly CCEFP Annual Meeting: The CCEFP hosted its first annual FPIRC event at Vanderbilt University, October 2014. FPIRC has replaced the CCEFP Annual Meeting. 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 Chicago, IL in October 2015 and

Minneapolis, MN in October 16. 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, social activities, etc. It was a grand success!

- The Student Leadership Council (SLC) hosts a Research Webcast every other week. Students and faculty from CCEFP institutions participate, along with industry supporters. These webcasts are intended to keep everyone in the Center informed about research progress, give and receive suggestions, and generally promote inter-university collaboration as well as cooperation between academia and industry. These webcasts are well attended, with an average of 73 participants per week. All are welcome and invited to tune in.
- IEC 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.
- Resume Exchanges: Held at each CCEFP FPIRC (formerly Annual Meetings) in 2011, 2012, 2013, and 2014. 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.
- 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, 42+ 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, and 2014 (at UMN, GT and PU). Over 600 8th grade students 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.
- CCEFP Wins Runner-Up 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.

4. Plans, Milestones and Deliverables

- Holding retreats at company facilities will provide students the chance to interact with practicing engineers and will facilitate opportunities for knowledge transfer.
- All FPIRC research poster sessions will continue to include a competition, with industry representatives as judges. Future FPIRC events will include half of the technical program being industry presenters.
- Resume exchange, Industry Kiosks and Corporate Sponsorship will continue at future CCEFP 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.
- Industry sponsorships of Fluid Power Challenge Competitions will be encouraged as a way of getting middle and high school students interested in fluid power.
- A workforce development steering committee will be formed between NFPA and CCEFP to design a new mutual workforce development strategic plan.
- The Student Leadership Council will continue, serving as the student voice to the CCEFP.

Priorities for the Future

The CCEFP will continue to develop networking opportunities for students and industry, connect industry to the OpenCourseWare project, the fluid power MOOC, and develop versions of the hands-on workshops suitable for new engineering employees not familiar with fluid power and non-engineering employees, further engaging industry in education initiatives. The Center will expand the content of the CCEFP Webcast 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. To do so, the CCEFP and NFPA will continue to provide online modes of research dissemination by way of an online seminar series presented by researchers in the Center.

Education Activities Matrix

	REU / Undergraduate	Pre-College / RET / Teacher	College Education / Course Materials: New/Ongoing Courses	Industry / Practitioner Education / Outreach	General Community
University of Minnesota	✓	✓	✓	✓	✓
GeorgiaTech	✓	✓	✓	✓	✓
MSOE	✓	✓	✓	✓	
NCAT	✓	✓	✓	✓	✓
Purdue	✓	✓	✓	✓	✓
UIUC	✓		✓	✓	✓
Vanderbilt	✓		✓	✓	

✓ = In Place ★ = Future Year

As mentioned in section 3.1, the Center is not surprised that the ratio of Graduate to Undergraduate students who are involved with the CCEFP has reached a value of 1.8 during the current reporting period (table 3b). This result is due to the decreasing number of undergraduate students involved with CCEFP programs, namely some of the undergraduate outreach programming that has been sunsetted as the Center entered into Y9 and Y10. This ratio, however, is still within the appropriate and recommended range. The Center understands a large number of undergraduate students involved with the CCEFP brings visibility to the Center in an important demographic, future graduate students and future practitioners in the area of fluid power.

4. INDUSTRIAL/PRACTITIONER COLLABORATION, TECHNOLOGY TRANSFER AND NEW BUSINESS DEVELOPMENT

The CCEFP implemented a major change in its sustainability strategy in this reporting year. The key aspect of this change from an industry perspective was a switch from our existing industry membership agreement organizational format to an industry gifting structure called the Pascal Society. All changes were discussed extensively with NSF at last year's site visit. The successful implementation was made possible in large part by an even closer collaboration with the National Fluid Power Association (NFPA), an industry consortium alliance which represents much of the fluid power industry. While the NFPA has always been active in the CCEFP, during the past year they became committed to helping the Center achieve sustainability. As an outcome our two organizations have reached a formal agreement to collaborate much more closely in the areas of fund raising and sharing of administrative costs through synergistic leveraging of each organization's strengths. Greater detail of the new Pascal Society and the increased industry collaboration through NFPA will be describe here in subsequent paragraphs as well as in section 5.3.

4.1 VISION, GOALS, AND STRATEGY

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 implements its new sustainability strategy. However, because the CCEFP enjoys such broad industry representation, it can be challenging to achieve the necessary level of engagement to ensure each member's continued, long-term commitment. To improve this engagement we have initiated efforts that leverage the already well-established industry communications network and numerous media outlets of the NFPA. A mutually developed Engagement Strategy with the NFPA is currently underway. Besides the obvious industry engagement avenues, this strategy will include programs that will engage all critical stakeholders (Industry, PIs, Students, general public, etc.) of the Center. Table 4.1 shows a summary of engagement activities that are either currently underway or planned for future implementation.

Table 4.1: CCEFP Communication Methods

Method	Frequency	Content	Audience
NFPA Annual Conference	1x per year	Business potential	CEOs
IFPE Conference	1x per 3 years	General	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

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 4.1). This allows for interested parties to save these dates early in the year to avoid potential conflicts. Simple modifications such as this, along with much better event planning and promotion, resulted in a 50% increase in attendance at our most recent FPIRC conference. Our goal is to increase attendance by another 50% at the FPIRC15 Conference scheduled for this fall.

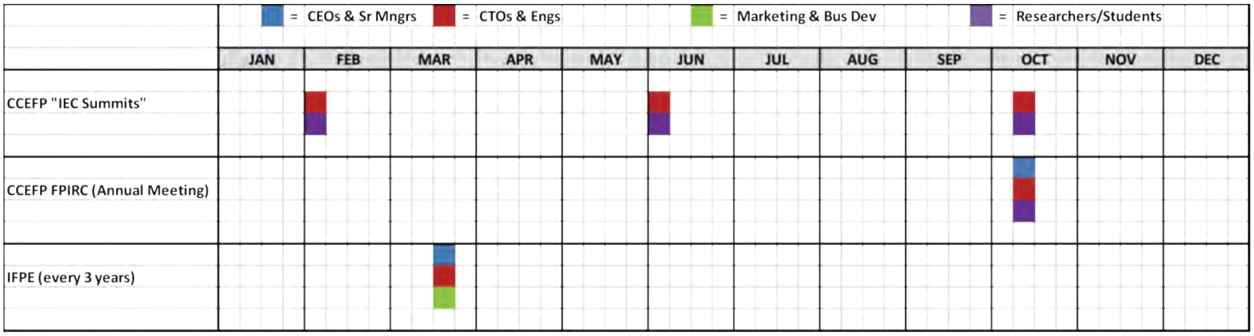


Figure 4.1: CCEFP Event Cadence Document

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. Again, the NFPA will play a pivotal role in connecting us with CEOs of industry members. This will benefit the center by positioning us to gain greater support from these members as we focus on long term sustainability. Progress is already being realized in this area as the NFPA Executive Board with be attending the CCEFP 2015 Annual Meeting, which has been renamed the Fluid Power Innovation and Research Conference or FPIRC15 for short. The CCEFP is well positioned to achieve its vision of making FPIRC the premier fluid power research conference in North America.

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 is made possible by combining individual company donations into a single award, administered by the CCEFP, which is meant 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 Executive Committee – Comprised of C-suite executives focused on the Center's overall research strategy and securing the resources we need to accomplish it—both academic and government.
- CCEFP Industry Engagement Committee – Industry CTOs working actively to help select and guide the research projects in the way that best benefits industry.
- NFPA Roadmap Committee – Industry experienced engineers working to identify the broad areas of pre-competitive research need that will advance our industry.

The interaction of these committees is shown pictorially in Figure 4.2

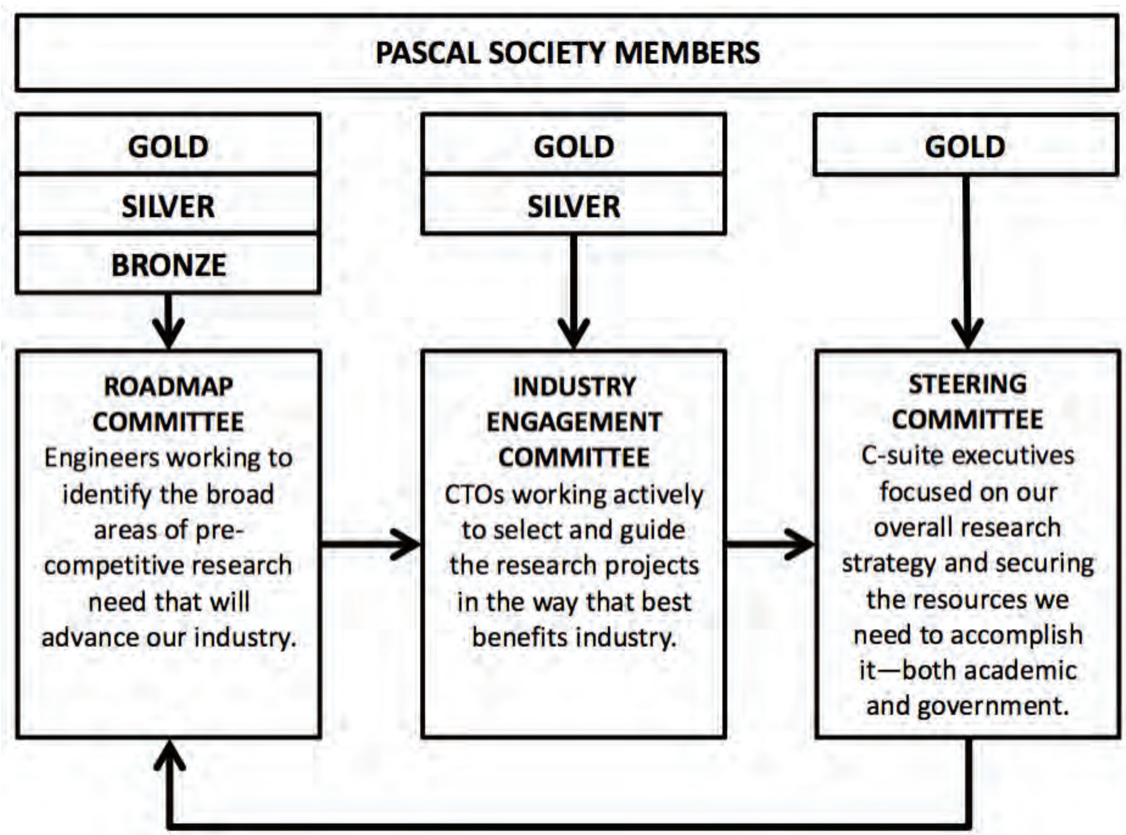


Figure 4.2: CCEFP Industry Committees

The boards to which an individual company can nominate representatives is determined by the organization's sales and support level as shown in Table 4.2.

Table 4.2: CCEFP Giving Levels for Industry Supporters

		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/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 will assume the role of fund raising with support from key CCEFP member staff. In exchange for this support the Center will cease to invoice its members. Each year this gifting contract will be reviewed with another year of funding agreed upon and guaranteed for the year after the current two year contract. This will allow sufficient notice for planning purposes. We will continue to invite all companies to become supporters of the CCEFP. Our plan calls for 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 5.3.

4.2 SPONSORSHIP

As previously described the CCEFP strategically decided to migrate its industry supporters from a formal membership agreement to a gifting society. Our primary objective to date has been to transition all existing members to the new Pascal Society model. We are happy to report that this has been largely accomplished. This transition has resulted in some new industry supporters and our next task at hand is to continue increasing industry support by recruiting other NFPA members. Our current industry supporters are shown in Table 4.3. We also intend to strategically reach out to non-NFPA industry members that we feel would be well aligned with our research efforts. In the process of identifying these strategic partners, we have identified gaps that are leading us to pursue other relationships. A review of our industrial membership identifies these opportunities:

- Most of our members are in the hydraulics sector of the fluid power market. Yet industry uses significant pneumatic power. We have begun a project to understand that industry base and recruit as appropriate. Our research indicates there is potential for significant energy savings in this arena. Several of our industry members are interested in pneumatic based medical applications. Since designating a co-Deputy Director dedicated to pneumatics we have seen a dramatic increase in high quality research proposals. Several such projects are funded for the FY9/10 budget cycle.

- We need to continue to focus strategically on recruiting OEMs and system integrators. Examples of these include automotive manufacturers, off-road heavy equipment manufacturers and medical providers. Recruiting the integrators will likely have a secondary effect of creating more interest by their suppliers in the CCEFP. Many of our current members indicate that this is a benefit of being a member. We have seen a substantial increase in construction OEMs joining the Center in the past few years, several of which are global manufacturers.

- Our membership is not well represented by government agencies. We are working to recruit support from the Departments of Defense and Energy. The recently published DOE report on estimating the impact of fluid power on energy, emissions and economics is an excellent leverage point for these discussions.

- We have continued our efforts to understand the significant impact of fluid filtration on fluid power with promising results. One of our newer members, Pall Corporation, is focused in this area. Another leading filtration provider, Donaldson Corporation, recently indicated that they will be joining the Center. We are currently developing an accompanying research agenda with the Center for Filtration and through leveraging our existing members' network. This will likely lead to additional recruiting opportunities.

- The wind energy market remains a strategic focus for the CCEFP as evidenced by test bed alpha. A critical maintenance concern is the transmission of mechanical power from the turbine to the generator. Fluid power offers some potential advantages over tradition approaches.

Table 4.3: CCEFP Industry Supporters

GOLD		
• Bimba Manufacturing	• Danfoss Power Solutions	• Hydra-Power Systems
• Caterpillar	• Eaton Corporation	• Pall Corporation
• Daman Products Company	• Enfield Technologies	• Parker Hannifin
SILVER		
• Afton Chemical	• Gates Corporation	• Netshape Technologies
• Bobcat	• HYDAC/Schroeder Industries	• Poclain Hydraulics
• CNH	• Hydraquip	• Quality Control Corporation
• Deltrol Fluid Products	• Linde Hydraulics	• Simerics
• Donaldson Company	• Lubrizol	• Trelleborg Sealing Solutions
• Evonik Oil Additives	• MICO	• Woodward HRT
• Fluid Power World Magazine	• Moog	
BRONZE		
• Bosch Rexroth	• HUSCO International	• ROSS Controls
• Concentric AB	• Idemitsu Kosan	• SMC USA
• Delta Computer Systems	• JCB	• Sun Hydraulics
• Festo Corporation	• Kaman Industrial Technologies	• The Toro Company
• FORCE America/Valve Division	• Main Manufacturing Products	• Walvoil Fluid Power
• G.W. Lisk Company	• Master Pneumatic	• White Drive Products
• HECO Gear	• Muncie Power Products	• Womack Machine Supply
• Hitachi	• National Tube Supply	
• Hoowaki	• Nexen	

Membership Agreement

As already discussed, the CCEFP has transitioned from a Membership Agreement (MA) to a giving society. The Grant Agreement (GA) and associated CCEFP Operating Procedures (COPs) shown in Appendix III 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. Despite our initial concerns we are pleased to report that industry has readily 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.

Intellectual Property

The process for handling ERC generated intellectual property (IP) has changed with the new sustainability approach. The recommended process is as follows:

- The PI makes an invention disclosure to the technology transfer office (or similar entity) at their respective University.
- The technology transfer office provides the disclosure(s) to the CCEFP Industry Liaison Officer (ILO).
- The ILO works with the PI to create a non-confidential overview of the invention which is distributed to any interested industry party even if they do not directly support the Center. With this overview is a notice of a web-meeting in which the PI will provide additional details about the invention. Any company can attend the web-meeting of which the primary purpose is to determine if they have an interest in pursuing licensing of the affiliated IP. The other participants in the web-meeting are representatives from the inventing university's technology transfer office.
- Interested companies are encouraged to contact the participating technology transfer officer to further advance discussions.

Industrial Advisory Board

With the introduction of the Pascal Society, the Industrial Advisory Board (IAB) has been 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 listed in Appendix III. 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 is a monthly IEC conference call 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 IEC meetings are held on site 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 are held during the evenings and are an excellent venue to get to know one another better. All 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. A recent improvement has been to include industry feedback via an electronic survey that is completed by attendees after each research project presentation.

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.

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.

The CCEFP produced 4 invention disclosures being filed this past year. 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 4.4 summarizes the CCEFP invention disclosures and current status since the Center started in 2006**.**

Table 4.4: ERC Intellectual Property

IP File number at the Home University	Home University	IP Title	Provisional Application Date	Patent Application Date	Patent Number	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	GT	Multiple Disclosures for Acoustic Management	not yet filed	not yet filed	NA	Archive/Waived Title

5345	GT	Multiple Disclosures for Acoustic Management	not yet filed	not yet filed	NA	Archive/Waived Title
5346	GT	Multiple Disclosures for Acoustic Management	not yet filed	not yet filed	NA	Archive/Waived Title
5347	GT	Multiple Disclosures for Acoustic Management	not yet filed	not yet filed	NA	Archive/Waived Title
5348	GT	Multiple Disclosures for Acoustic Management	not yet filed	not yet filed	NA	Archive/Waived Title
5350	GT	Multiple Disclosures for Acoustic Management	not yet filed	not yet filed	NA	Archive/Waived Title
5408	GT	Multiple Disclosures for Acoustic Management	not yet filed	not yet filed	NA	Archive/Waived Title
5480	GT	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	GT	Multiple Disclosures for Acoustic Management	not yet filed	not yet filed	N/A	Archive/Waived Title
5568	GT	Multiple Disclosures for Acoustic Management	not yet filed	not yet filed	N/A	Archive/Waived Title
5569	GT	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	GT	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	GT	A Modelica Library for Hydraulic Components and Systems	N/A	N/A	N/A	Archive/Waived Title

5182	GT	A Flow Control Circuit with Dynamic Compensations	2/28/2012	61/604,214	N/A	Archive/Waived Title
5652	GT	MRI Compatible Force Sensor	4/26/2011	61/479,214	N/A	Archive/Waived Title
4574-PR-08	GT	Hydraulic Rod Seal with Saw Tooth Sealing Surface Pattern	11/26/2008	61/118,080	N/A	Archive/Waived Title
4574-PR-10	GT	Hydraulic Rod Seal with Saw Tooth Sealing Surface Pattern	11/24/2009	61/263,894	N/A	Archive/Waived Title

Communications

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 4.3). 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.

Figure 4.3: Research Project Summary Sheet

Technology Impact

Some of the more impactful CCEFP technologies are mapped in the Impact vs. Maturity chart below (Figure 4.4). 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

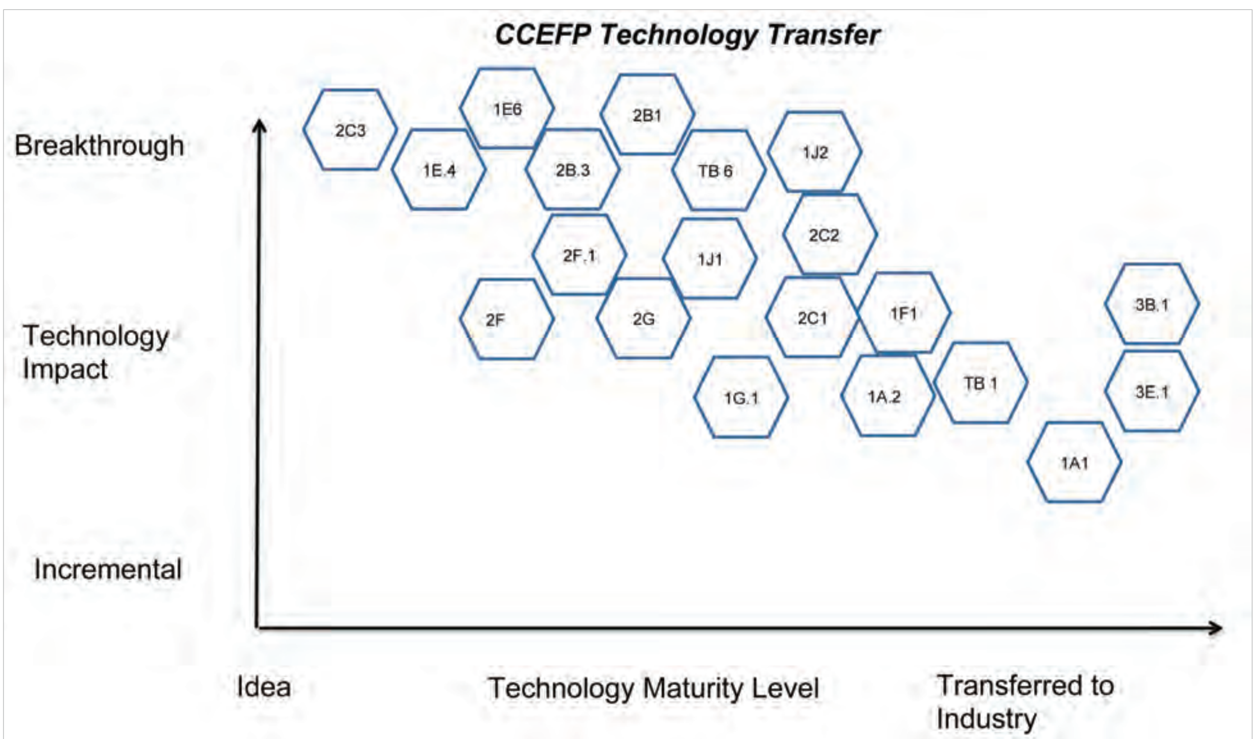


Figure 4.4: Center Technology Transfer Chart

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. Also, 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.

4.5 FUTURE PLANS

The SWOT 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.

CCEFP Industry leaders also recognize that even if their organization doesn’t 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. New this year is our plan to leverage the NFPA communication network to highlight student profiles to industry. 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.

The CCEFP is aggressively pursuing long term sustainability. To do so, industry must play a major role. It is imperative that we capture a significant portion of industry’s mind share. The best way to do so is through active and meaningful engagement. Once an industry member becomes intimately involved with the Center and truly understands the value it provides they can't help but become a strong advocate. The CCEFP is actively working with the National Fluid Power Association to improve our industry engagement as part of our Pascal Society sustainability plan. Going forward the CCEFP-NFPA-industry partnership will be the critical cornerstone of our long term sustainability strategy as described in section 5.3. Raising awareness at the senior management CEO level will encourage industry CTOs to actively engage the CCEFP. CTOs will encourage their managers who will support their engineers' participation and so on. To facilitate this need a comprehensive Engagement Strategy is under development and will be finalized by Q2 2015. The activity table shown below lists the many tactical efforts being planned or currently underway. Items in blue are a priority for the upcoming year.

Table 4.5: CCEFP Engagement Program Tactical Implementation

Action or Tool	Timeframe	What it's meant to do	Audience	Team Lead	Action Items	Current Barriers
Action: CCEFP Engagement Strategic Plan and/or Statement of Purpose	By end of 2014	CCEFP strategy, objectives and tactical plan. Plan includes all audiences of industry, government, academia and media. CCEFP to incorporate NFPA's goals into strategic plan, and vice versa	CCEFP and NFPA admin.	Burger Haney	Underway. Padilla review.	CCEFP strategy is in a state of design and implementation. NFPA goals need to be incorporated.
Action: Mktg/Promo/ Comm. CCEFP & NFPA Working Agreement	Early 2015	Agreement between CCEFP and NFPA so that together (or separately) the organizations can offer products and services to key audiences. Apply this knowledge to identify the best approaches for marketing the value each organization brings to respective members and prospects.	CCEFP and NFPA admin.	Burger	Working session to be scheduled with NFPA, Padilla to facilitate?	Need to finalize how we will work together via formal agreement. WHO communicates WHAT and WHEN
Action: Database of Contacts and Shared and individual list-serves	On-going	Comprehensive database of individuals deep and wide within Industry, Pascal, government agencies and representatives and audience specific to CCEFP. Not limited to IEC or corporate representatives. Within industry, include HR, marketing, engineering managers, VPs, CTOs, etc. Within government, who, what and where? Build our reach. Be certain to indicate role. Others? Current, existing and prospective academics. Professional networks and those in prospective areas of fluid power application.	CCEFP and NFPA admin.	Wissbaum Haney Lanke	CCEFP to work with Lanke on process and anticipated steps to move forward. Separately, CCEFP to data mine internally those who should be engaged in the Center. Build our marketing lists, independent of NFPA. Deb to be recruited to own the project. Lisa to investigate CRM options. Create an internal system to identify, collect and send contact data from CCEFP to NFPA.	To be determined.
Action:	By end of	Cadence document of all regularly	CCEFP and	Burger	Underway.	Barrier is to keep the

Communications Cadence Calendar	2014	occurring comm/mark/promotion activities. Follow strictly. Publicize to community, present to leadership.	NFPA admin.	Haney		schedule alive. Must remain a priority and we must stay accountable.
Action: CCEFP Engagement Campaign	By end of 2014	Engagement campaign within CCEFP community. A call-to-action by KAS on Jan. 14 webcast.	CCEFP admin. and community.	Burger	Underway.	
Action: Special Marketing Promotions: Recruitment, Informational. Research, Workforce Development,	As needed	Sell new or existing members on the Center's value and / or Pascal Society and why it's important to raise membership to sustain Center's vision. Two points of value: Pascal Society. Center's Value. Define roles of creating, delivering message, dependent on the "type" of "member". i.e.: CCEFP does not deliver Pascal messages to existing members. A concern is how to draw a clear line between IEC-specific communication and general communication to IEC. Materials should be relevant to markets outside of the traditional industry: medical, aerospace, automotive, government.	Industry. Government. Existing and prospective industry members. Prospective government agencies.	NFPA Burger	Inquire with NFPA, consult with Gust, plan meeting with NFPA to scope out opportunities.	NFPA has graphic design expertise, CCEFP does not. Assistance by NFPA is requested.
Action: Sustainability Strategies: Government agencies and how to effectively create targeted messages	As needed.	Two audiences exist under the CCEFP sustainability plan: Industry and Government. Learn how to best educate and communicate to government representatives in organizations of which the Center intends to leverage. DOE, DOD, NSF, etc. Idea: create a "leave-behind" specific to the visit. What does this look like?	Primary: government	Haney Wissbaum Bohlmann	Inquire with Padilla, consult with Brad. Who else may be knowledgeab le in this arena? Lisa to gather information on campus experts. Consult with Drew R.	Many unknowns.
Action: Research and Technical Content Recruitment	Monthly	Protocols to regularly recruit articles from CCEFP research community. What are the "hot" items? Repurpose and refresh highlights from annual reports. Consider utilizing the updates and webcast presentations for promotions / communications. Use as e-blasts, and post to Twitter, FB, LinkedIn, etc. Target for transition is July 1, 2015. Carefully keep individual brands, but incorporate CCEFP into NFPA's brand. CCEFP is a "product" of NFPA. Submit "something" once per week to NFPA. Build directory of content.	Industry, Academia, Government, CCEFP community	Burger Haney	Plan schedule.	Barrier is content identification and recruitment. Engagement campaign aims to overcome barrier. Need all CCEFP staff employed.
Action: Faculty, Student and Alumni Profile Recruitment	Monthly	Protocols to regularly identify and recruit current or former students to highlight as human interest stories. Objective is to demonstrate the human capital value of the CCEFP. NFPA to repurpose. Post as e-blasts. Get student videos, offer incentive. Create a program for collecting student profile text and videos. July 1, 2015	Industry, Academia, Government, CCEFP community	Haney Burger	Plan schedule.	Barrier is content identification and recruitment. Engagement campaign aims to overcome barrier. Need all CCEFP staff employed.
Tool: Webcasts	Bi-weekly	Webcast of research, administrative and special topic presentations	Industry, Academia,	Burger	New this year, invite	Need assistance in identifying associated

		conducted by the CCEFP. Regular research dissemination, industry guest presenters, State of the CCEFP, others as needed.	Government, CCEFP community		associated projects to present.	projects most likely to present.
Tool: Project Summary Sheets	Yearly, aligned with AR	Refresh, have accurate. Require it as part of the award process. Has been identified as a need when communicating with industry and assisting projects in moving into sponsored support. Need a vehicle to market each project. Used mostly in industrial recruitment.	Industry, Academia, Government, CCEFP community	Haney Bohlmann Wissbaum	Plan underway to recruit updated project summaries simultaneously with Y9 annual report recruitment.	Cooperation by PIs.
Tool: Trade Press	Frequently	A system to answer the trade press request for articles and editorials out of the CCEFP. Form a working relationship with the trade press. Replace with press release?? Proactive approach. Quarterly press release. Editorials? Leaks, Need a Consortium	Industry, Academia, Government, CCEFP community	All Gust Bohlmann Stelson Co-DDs	Develop a process. Create an inventory of editorials and topics to provide to trade press, on request. Journalist student?	
Tool: e-Blasts (more than one) e-Alert (one item)	1 x - 2 x per month	One newsworthy item, technical, workforce, student faculty highlight. Minimal in length. Each staff person (and Joe K.?) responsible for writing once / every three months and contributing, in part, to e-blast messages. NFPA will repurpose this information.	Industry, Academia, Government, CCEFP community	Haney	Launch campaign, set schedule, get a bank of content, schedule across staff to write articles. Get buy-in and commitment from CCEFP community.	All CCEFP staff are expected to contribute. Need buy-in and support. No exceptions to established deadlines.
Tool: e-Newsletter	Quarterly or 2x/Year	An electronic summary of previous e-blasts, announcements and news items. NFPA will repurpose this information.	Industry, Academia, Government, CCEFP community	Haney	Launch campaign, set schedule, get a bank of content, schedule across staff to write articles. Get buy-in and commitment from CCEFP community	Barrier is content identification and recruitment. Engagement campaign aims to overcome barrier. Need all CCEFP staff employed.
Tool: Videos	Occasional	Formal and informal program. Wide Angle Studios productions. Informal student generated project videos with financial incentives.	Industry, Academia, Government, CCEFP community	Haney (formal) Burger (informal)	Haney: Wide Angle to complete FPIRC14 video. Next video underway. Burger: Launch a video program for students.	Budget for professional videos. Need to utilize across the Center to get most impact. Student videos may not be consistent in look, theme and will vary in production and professionalism.
Tool: Website (regular updates, primary source of public information, banners, calendars)	Daily and Weekly	Re-invent. New focus will be “news” orientated. Comprehensive information. All information posted to blogs, e-blasts, newsletters, annual reports, twitter, Facebook, are also reflected on ccefp.org. In	Open to all	Haney	Ideas: Re-invent. Focus of the revamped site is NEWS.	Create a site that is a destination and is purposeful.

		Y9.5, begin conversations about .org upgrade and rebuild in prep for Y11 post-NSF CCEFP.				
Tool: Twitter	Weekly	Repurpose press releases, research articles, highlights and student profiles. Retweet information. Post important announcements, events. NFPA will repurpose this information.	Open to all, general audiences	Burger Haney	Underway. Need to build Twitter audience.	Need CCEFP community to engage in social media.
Tool: Facebook	Weekly	Repurpose press releases, research articles, highlights and student profiles. Retweet information. Post important announcements, events. NFPA will repurpose this information.	Open to all, general audiences	Burger Haney	Underway. Need to build FB audience.	Need CCEFP community to engage in social media.
Tool: YouTube	Variable	Face of FP videos (NFPA). Research videos. Promotional Videos. Student project videos? NFPA will repurpose this information.	Open to all, general audiences	Burger Haney	Promote materials	
Tool: LinkedIn	Variable	Repurpose press releases, articles, blogs. Continue to put effort here. LinkedIn has a great network, but it a difficult tool to manage.	Open to all, general audiences	Burger Haney	Underway. Need to build LinkedIn audience.	Need CCEFP community to engage in social media.
Tool: Press Releases	As needed	Events. Innovation. News. Awards. Patent notifications. What's worthy of a press release? NFPA will repurpose this information.	Trade Press, PRLog.org		Learn how to create press releases. Padilla to advise.	Create a system to learn of press release type information.
Annual Report to NFPA	Post-NSF	Determine data and specs.	NFPA Board	Lanke Stelson Wissbaum		

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5. INFRASTRUCTURE

5.1 CONFIGURATION AND LEADERSHIP EFFORT

The “Institutions Executing the ERC's Research, Technology Transfer, and Education Programs” are shown in Table 6. “Location of Lead, Core Partner, and All Domestic Collaborating Institutions” is shown in Figure 6a. “Country of Citizenship of ERC Foreign Personnel for the Center for Compact and Efficient Fluid Power” is shown in Figure 6c. The table and the figures are located at the end of this section.

The CCEFP institutional configuration is well-aligned with its vision and goals. The CCEFP lead and core universities: the University of Minnesota (lead), Georgia Institute of Technology, Purdue University, University of Illinois at Urbana-Champaign and Vanderbilt University represents the majority of fluid power university researchers in the United States. Each university has been carefully chosen because its expertise is essential to realize the CCEFP vision.

The collaborating institutions were also carefully chosen. North Carolina A&T State University (NCAT) is the leading producer of African-American engineering graduates at both the undergraduate and graduate levels. The human factors researchers in the Industrial Engineering Department at NCAT provide necessary expertise to realize the CCEFP vision, and complement the abilities of the other researchers. Milwaukee School of Engineering (MSOE) has an unusually strong emphasis on fluid power in its mechanical engineering curriculum. MSOE graduates are prominent in the engineering workforce of the fluid power industry. The school emphasizes undergraduate engineering education, but also has a small graduate program, and effectively uses both undergraduate and graduate students in fluid power research. Inside CCEFP, we refer to NCAT and MSOE as the Center’s “outreach” universities.

Inspection of the strategic plan will show that eliminating any of these seven institutions would cause major gaps that would reduce the effectiveness of the CCEFP. Having a total of seven universities in the CCEFP increases the management challenge, but has been found to be manageable.

The domestic location of lead, core partner, outreach, REU, Fluid Power Scholar (FPS), and RET participating institutions are shown in Figure 6a. While the lead university and core partners remain unchanged from Y8, a number of changes occurred in other categories. The number of collaborating universities grew from 12 to 14. 4 of the 12 collaborating universities remain from Y8 and 10 additional were added. 11 non-ERC institutions provided REU students. The only institution that was a carryover from Y8 was Yale University, so 10 new non-ERC institutions were added. Institutions outside of the CCEFP network which are represented in the 2013 REU and FPS program include:

- Arizona State University
- Auburn University
- Clemson University
- Columbia University
- Iowa State University
- Kirkwood Community College
- Macalester College
- Mankato State University
- Minneapolis Community and Technical College
- Missouri University
- Morgan State University
- National Fluid Power Association
- Philadelphia University
- Quality Evaluation Designs
- St. John’s University
- University of Florida
- University of Hartford
- University of Rochester
- University of Wisconsin - Madison
- University of Wisconsin - Milwaukee

20 REU students, 40% women and 35% underrepresented racial or ethnic minority status and 9 Fluid Power Scholar students, 11% of underrepresented gender, racial or ethnic minority status participated in the program. Continuous efforts are made to recruit REU students through targeted institution-based and

specific local student chapters, offices and programs that promote diversity in the sciences in addition to NSF Diversity Programs, National GEM Consortium, LSAMP and MSI partners of the Center.

The CCEFP's Director has demonstrated effective leadership in guiding and managing the CCEFP by successful implementation of key management tools in strategic planning, project selection, budgeting, progress tracking and communication. The strategic plan has gone through several iterations and now effectively identifies the Center's goals and their links to the research, education and outreach programs that are designed with which they are associated. Since the CCEFP's launch in June 2006, projects have been both terminated and initiated and two test beds have been terminated and one test bed redirected to reflect the evolving strategic plan. Research on two associated test beds continues with a combination of University, federal and industry funding. These test beds extend the range of our research from 4 to 6 orders of magnitude of energy output. The appropriate management structure is in place to manage these processes. A total of 21 research projects were funded for Years 7-8. To assure adequate funding for each project as NSF funds decrease, this was reduced to 15 projects in Years 9-10. An effective budgeting process has been implemented where resource allocations and project efforts are closely coupled. The practice of reallocating unspent funds to other projects has been reinstated with the refinement that the funds can be kept if adequately justified. This change is necessary since tighter budget control is needed as we approach the end of NSF funding. An effective progress tracking process has already been implemented, and research, education and outreach projects are being re-directed as a result of progress tracking process. Lastly, an effective communications plan for both internal and external communication has been implemented.

The other members of the leadership team are also highly effective, and are becoming more effective as our processes become more refined. The Administrative Director greatly improved the budgeting process. The AD also oversaw the successful implementation of a Center-wide database, which is a repository for information on the Center, its research, its people, and its impact. The development and launch were very challenging, but the AD provided strong leadership to make the database a reality. The Industrial Liaison Officer's strong leadership skills and strategic vision will be a great asset as the CCEFP makes a transition to the post-NSF era. The Education Director communicates and strategizes with the Education and Outreach Director on education and outreach programs at all levels. They have increased engagement with the Student Leadership Council (SLC), and opened a channel of two-way communications, which provides student feedback to CCEFP management and helps facilitate the SLC's initiation and implementation of Center projects.

The main stakeholders in the CCEFP are the universities and their researchers, industry and the government. The Management Committee (MC) has a representative and alternate representative from the lead and each core and outreach university. The MC meets monthly and has the responsibility for day-to-day CCEFP management. The MC is also responsible for being the interface to university administration since it has representatives from each university.

Three additional committees formed in 2014 are the Sustainability Working Group (SWG), Industry Relations Committee (IRC) and the Government Relations Committee (GRC). The SWG membership is the Center Director, both Co-Deputy Directors, the Industrial Liaison Officer and the Sustainability Director. The group meets weekly and is responsible for overseeing the Center's sustainability strategy and tactics. The IRC's role is technology transfer to industry and linking industry and the Center's PIs through associated projects. The GRC is focused on doing what is required to procure large, multi-university research grants to help ensure the Center's sustainability. The committees meet monthly. The combination of the MC, IRC and GRC assures that university, industry and government issues are being addressed. These committees will play key roles as the CCEFP transitions to the post-NSF era.

In 2014, CCEFP underwent a major transformation through an alliance with the US fluid power industry's largest trade organization, National Fluid Power Association (NFPA). Under this alliance, NFPA effectively took control of procuring industry funding for the Center's pre-competitive research through its 501(c)(3) non-profit foundation. The details of the transformation are provided in several areas of this report including section 4 and section 5.3.

The SLC updated its SWOT analysis in January 2015. The SWOT analysis and CCEFP leadership response are provided below.

Y9 CCEFP SLC SWOT

The Year 9 Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis of the CCEFP was based on the results of emailed responses from active student members of the Center. While the previous method of using a survey allowed for statistical information regarding SLC pre-selected topics, the method this year allowed for a conversation between SLC members and student members to occur. Due to this, ideas that may otherwise have been missed or overlooked can now be brought to the attention of the SLC executive committee and CCEFP.

Outline of SWOT Responses

An outline of the SLC SWOT analysis is shown below. The order of topics does *not* reflect importance or severity. However, topics are numbered to facilitate referencing in the following discussion section.

Strengths

1. Facilitating a community environment (encouraging student participation)
2. Webcasts
    a. Presentation of research progress
    b. Large group of audiences from both industry and academia
    c. Educational webcast regarding opportunities for commercialization and start-up resources have been provided and emphasized during Y9
3. Communication & engagement of industry with students and projects (especially at in person events, such as Annual Meeting and Industry Engagement Committee Summit).
    a. Industry members seem excited about projects' usefulness.
    b. Resume transfer and meeting with Industry made available at annual meetings
    c. Encouragement of Industry Champions
4. Outreach and education efforts (Fluid Power project, MOOC, REU program [including boot camp], travel grants and project grants)
5. Emerging applications: utilizing and developing fluid power research in growing markets (e.g. medical devices [e.g. TB6], wind turbine [1J.1], Hybrid vehicle [TB3], etc.)
6. Offering a path to fluid power jobs
7. Providing support for students near graduation whose projects ended (funding extensions)

Weaknesses

1. Start-up development and project commercialization
    a. Disconnect between students and Center regarding interest in pursuing start-ups (especially considering career goals, student debt and job opportunities post-graduation)
    b. Benefits to students pursuing startups is not emphasized - typically viewed as a benefit to the Center. Market opportunities, tasks required, and intellectual property rights are not clear.
    c. Source of funding for startups is not particularly clear.
        i. Clear summary of funding sources not readily available and funding allocation purpose not clearly defined (requires searching through webcasts or contacting CCEFP Industrial Liaison directly). If it is available, it is not clearly advertised to students. Note: there was a webcast presentation, however occurred when students were on summer break, so some are unaware of this information

2. Engaging and energizing students (once they are present, and following when they are at their home university).
3. Providing new graduate students (especially on associated projects or schools with a smaller CCEFP student base) with an introduction to the CCEFP policies, resources and organization
4. Information transfer between SLC past officers and present or newly elected officers. Finding new student officers.

Opportunities

1. 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
   b. Provide an internal forum for discussion between center members to transfer ideas, solve problems, provide support, etc.
   c. 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
2. Change the idea of fluid power into something that is considered cutting edge and exciting.
   a. Emerging technologies are being pursued, however ensure those projects are given the support and collaboration needed to be successful.
   b. This can also help engage and energize students, via providing interesting stories (perhaps during webcasts) or opportunities where fluid power is applied or can be applied.
3. Demonstrate the value and impact of fluid power research through applications. Show when projects are being used by industry, or when customers are excited by research improvements.
4. Show that researchers in fluid power industries are appreciated and challenged.
5. Encourage students who graduated from the center to actively participate in discussions (about their current job, prospective job positions) with current students.
6. Create a more visible student tab or section on the front page of the ccefp.org website to provide new and current students with a clear path to opportunities and information regarding student related CCEFP activities and resources.
   a. Currently the SLC New Student Handbook is document based (rather than online) and poorly distributed.
   b. The CCEFP organization website has lots of information, however information is not easily found (e.g. finding student section requires going to “Get Involved” tab, which may not be clear to someone already ‘involved’ as a student on a project).

Threats

1. Difference in goals (and timelines) between academia and industry
2. Loss of learned skills (both via Center policies and Project development) due to graduation of students without overlap for incoming students
3. Varied levels of support for projects (especially a threat for large scale projects). Some projects do not receive enough support to be successful and to retain those researchers’ interest in the field.
   a. Projects are not given funding support via CCEFP when entering commercialization stage
   b. Counterexample - TB6 has lots of support from many groups working on it and appears to be successful

4. 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.” (http://www.ccefp.org/get-involved)

Discussion

Many CCEFP objectives and ideas are being pursued, however there are some opportunities and changes that could allow for further student engagement and center communication. Key elements include: website development with updated student-centered information; promoting student engagement; understanding of student priorities, time commitments, and needs. These elements should be resolved, especially with the imminent Center graduation.

It is apparent that the structure of CCEFP is evolving from a funded project based community to a community interested in changing the face of fluid power, such as Center direct funding, affiliated projects set-up between companies and university research groups, and company participation in the NFPA Pascal Society. This change can be seen in the sustainability plan (as presented during April 2, 2014 webcast https://umconnect.umn.edu/p71181893/), which includes the plan to “Allow any US university to be eligible provided they meet indirect overhead requirements.” Also, CCEFP requests (not required) affiliated projects to report to the Center annually to keep track of Center related impacts. With the expected expansion of the Center communities and connections comes a potential thinning of groups (especially student membership), which may cause student alienation and decreased participation. It may be necessary to change the definition of membership of students and faculty within the CCEFP (threat 4) to foster a community creating an accessible knowledge and resource base for those interested in changing fluid power.

While recent efforts to encourage student participation have been working (strength 1 and 2), engaging the students beyond the point of attendance or after the conference ends appears to be lacking (weakness 2 - 4). In addition, student participation may change after CCEFP graduation. Three actions could encourage student engagement: restructuring of the website to include forum discussions for students (opportunity 1); creating a website or section of the website that is clear for student participation, opportunities, and benefits (opportunity 6); and showing how research performed within CCEFP is meaningful outside of CCEFP (opportunities 2-5). In addition, this would promote collaboration between students if clear web-based paths to information and discussion were facilitated through CCEFP (opportunity 1), which in turn could help alleviate parts of threats 2 and 3.

In order to sustain a student leadership council, student engagement and awareness is key. Currently new students do not have a clear path to learn of the opportunities offered by the center other than through their advisor. A website link to this information should be established and regularly communicated to faculty. This would provide an easy step for the PIs to connect new students to the CCEFP community. The opportunities list provide ideas of how to engage students into the community beyond required participation, food availability, or monetary incentives. Creating a community where people know, trust and care about other members elicits people to help others and be engaged. There is a community established (strength 1), however engagement across this community needs improvement - especially between members at different locations. Opportunity 1 would facilitate collaboration between various locations.

The final key is to understand the student priorities, time commitments, and needs. Most graduate students focus on research, graduation requirements, and developing a portfolio to assist in post-graduation plans, with little time or energy otherwise. This is why the opportunities outlined above (specifically opportunity 1) could be crucial to helping projects succeed, alleviating loss of information transfer, and grow student engagement and trust in the Center (threat 2-3, weakness 2-4). Another important point is that graduate students have varied post-graduation plans, including consulting, industry jobs, and academia. While some students may have commercialization and startup aspirations, not all students are interested in pursuing start-up companies (weakness 1). It is possible for projects to be developed (such as via senior design development or masters student projects) to target students that are interested in pursuing startups. Assessing student interest is needed; without this, commercialization plans cannot rely heavily on current students’ willingness to take the lead on the development of a new company that most likely will have high initial costs (due to the nature of fluid power industry infrastructure) and time commitments, especially since students pursuing advanced graduate degrees have multiple career path avenues and are potentially in debt due to undergraduate education costs. It is recommended that CCEFP surveys students to determine their awareness of commercialization opportunities and gauge student interest in this endeavor. If interest is not sufficient to meet with sustainability plans, new paths or student entrepreneurship-centered projects may be required.

The goal of the SWOT analysis is to provide the CCEFP with the student perspective and ideas. We hope our suggestions and comments are useful for the betterment of the Center, and are confident the Center will continue to sustain those areas that are strong.

<u>Center Management Response</u>

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 has also identified communication and collaboration, financial independence and commercialization of fluid power as key areas of focus presently, in the near term and for long-term sustainability. We appreciate the format of this year's SWOT and wish to commend the SLC on their new approach to providing the student feedback. The discussion versus survey method has been very helpful. Lastly, the SLC's work on the webcasts has been outstanding. The Webcast Series have become a key CCEFP product.

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

Commercialization: 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. However, it is expensive and not something that can be financially supported by the CCEFP. 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". In the past year, some Center PIs have been awarded NSF PFI:AIR grants to help move their technologies toward commercialization. We will continue to communicate to industry the opportunities for commercialization of CCEFP work. New in 2015, the CCEFP is coordinating an opportunity for faculty to pitch high-TRL commercialization opportunities to an industry audience at the CCEFP IEC Summits and the Fluid Power Innovation & Research Conference (FPIRC). Additionally, Industry Relations Committee members are creating a structured process for providing resources for commercialization of technology created by the Center.

Student engagement: Tools and a guide have been created by the SLC to familiarize new and incoming students with the CCEFP. However, the problem is that no one is using it, and students don't know about it. The CCEFP management needs to communicate with faculty at the beginning of Fall Semester and asked to be notified of incoming students. Then, the SLC is armed with information on who needs to be provided information on the Center. The CCEFP management and the SLC need to work more closely on the student on-boarding process. Additionally, 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 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. Lastly, we plan on more emphasis on maintaining relationships with our graduates in our new collaboration with NFPA.

SLC administration: We encourage the SLC to re-evaluate the bylaws to be reflective of the CCEFP environment. The by-laws should be updated and rewritten to include the roles of the incoming and outgoing SLC officers and how to address the turn-over of its officers and representatives. The CCEFP commits itself to increasing the visibility of the SLC and its importance. A priority for Y10 will be to develop a sustainable way to administer itself, with the oversight of CCEFP leadership.

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.

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5.2 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 between 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.

The complete Diversity Strategic Plan can be found in Appendix IV. Progress in the current reporting period is described below.

Program highlights and activities are described below.

- **<u>A CCEFP Legacy.</u>** 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. CCEFP will help to mentor other ERCs as they investigate this opportunity, however, while CCEFP experiences a phase-down in funding and there are no additional opportunities for new research projects, the CCEFP does not anticipate a near-term opportunity to recruit another GEM-ERC Fellow. This program model is a legacy of the CCEFP.

- **A CCEFP Legacy.** 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 30% 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.
- The CCEFP has initiated a partnership with a faculty member at Rochester Institute of Technology (RIT), Larry Villasmil, who has committed to help the CCEFP recruit underrepresented students (Hispanic students in particular), as well as students with disabilities. RIT is home to the National Technical Institute for the Deaf (NTID) and is the world's largest technical college for deaf and hard of hearing students. As the program builds, so does the recruiting network. The CCEFP is considering expanding this Faculty-to-Faculty exchange / mentorship.

Table 7a shows the percentage of the Center's diversity statistics in comparison to the National Engineering Average data and average data within other ERCs. Line by line, the CCEFP tells a promising story. Following are added details.

The vast majority of respondents are US Citizens or Permanent Residents, however, the CCEFP also has a significant representation of foreign personnel whose diverse view is also significant to the broad perspective within the Center.

Women – Representation is near or above national averages in all categories. It is notable that 34% of Doctoral students are female, absolutely remarkable in such a male-dominated field. 24% of Undergrad Non-REU and 27% of Undergrad REU students are women as compared to 19% nationally. 14% of Center faculty are women, while 22% of the Center's Leadership Team is female, both up from the previous reporting year.

Racial Minorities – The CCEFP has exceeded national averages in nearly all categories. We are particularly pleased with the percentage of Doctoral students and REU students who are racial minorities, 12% and 23%, respectfully. CCEFP has traditionally been successful in recruiting racial diverse undergraduate students, however, not to be overlooked is the Center's representation of racially diverse faculty (10%) and leaders (11%).

Hispanic/Latinos – Numbers of Hispanic/Latinos and persons with disabilities remain small, but are growing within CCEFP at the graduate and undergraduate level. Hispanic/Latino students represent 9% of our REU and 10% of undergraduate researchers, 4% of our graduate students and 7% of our faculty. These numbers are incremental improvements in the recruitment of ethnically diverse participants.

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 Table 7a, 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.

The Center maintains a formal relationship with the North Star STEM Alliance, an NSF LSAMP Program headquartered at the University of Minnesota that includes 16 partner institutions across the state. This partnership includes recruiting efforts; dissemination of information about academic, research, and internship opportunities; providing resources for conferences and relevant meetings and offering support to North Star STEM Alliance student fellows and scholars. As subsequent charts indicate, these efforts are yielding positive outcomes.

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5.3 MANAGEMENT EFFORT

The CCEFP operational organization chart is shown in Figure 5.3.1:

Figure 5.3.1: CCEFP Organization Chart

Dr. Kim Stelson has been the Center director since the CCEFP was established in 2006. He reports to the Dean of the College of Science and Engineering at the University of Minnesota. Dr. Stelson is very well respected in the fluid power field and leads the center with a clear vision of developing close relationships between academia and the fluid power industry. His balanced approach to focusing on fundamental research with industrial applications has created an active industry membership.

Two Co-Deputy Directors assist the Director. Professor Zongxuan Sun focuses on hydraulics research while Professor Eric Barth focuses on pneumatics research. The role of the deputy directors is to provide technology guidance for the center. They own the strategic plan for research and oversee the test bed integration. They are active members of the Government Relations Committee (GRC) and lead working groups seeking new government funding for long term sustainability.

The other positions at the CCEFP provide the following support:

- Industrial Liaison Officer (ILO) – Conduit to Industry and responsible for business planning and development.
- Sustainability Director – Conduit to the researchers and responsible for research project management and the development of new project funding.

- Administrative Director (AD) – Responsible for operations and financial management of the center.
- Education Director – Leads the Education and Outreach activities.
- Education and Outreach (E&O) Director – Responsible for the Education and Outreach planning and execution.
- Communications Specialist – Manages all communication and tools including the CCEFP Website.

There are also several advisory boards and committees associated with the CCEFP. These committees change under the new Pascal Society structure described in section 5.5. The existing committees are summarized below.

Executive Committee (EC)

The EC is no longer active due to reorganization. Its major responsibilities will be replaced by the new Steering Committee (SC) and Industrial Engagement Committee (IEC).

Management Committee (MC)

This Committee is responsible for implementing CCEFP strategy and guiding the Center's day-to-day operations. Chaired by the CCEFP Director, its members include a faculty representative from each of the Center's seven universities. Committee meetings, most often held via conference call, are typically scheduled once a month.

Management Committee Members:

- Andrew Alleyne – University of Illinois - Urbana-Champaign
- Eric Barth – **V**anderbilt University
- Wayne Book – Georgia Institute of Technology
- Vito Gervasi – Milwaukee School of Engineering
- Monika Ivantysynova – Purdue University
- Perry Li – University of Minnesota
- Eui Park – North Carolina A&T State University
- Kim Stelson – University of Minnesota

Industrial Advisory Board (IAB)

The IAB is no longer active due to reorganization. Its major responsibilities have been replaced by the new Industrial Engagement Committee (IEC).

Scientific Advisory Board (SAB)

Members of the SAB are internationally known experts in fluid power. They represent leading engineering universities, laboratories and academies with interests in fluid power and/or have had extensive experience in hydraulics and pneumatics through their distinguished careers in industry. The SAB's periodic reviews of Center research and organization are valued throughout the CCEFP and help guide the Director in developing Center strategy. The SAB will have its final meeting at the FPIRC15 Conference in October 2015. Its responsibilities will be assumed by the Steering Committee.

The members of the Scientific Advisory Board are listed on the following page:

- Dr. Hans Aichlmayr – Lawrence Livermore National Laboratory
- Prof. Richard Burton – University of Saskatchewan
- Dr. Robert Cloutier – Stevens Institute of Technology
- Prof. Frank Fronczak – University of Wisconsin
- Mr. Steven Herzog – Evonik Additives (retired)
- Prof. Toshiharu Kagawa – Tokyo Institute of Technology
- Dr. Joseph Kovach – Parker Hannifin (retired); Komotion Technologies
- Dr. Lonnie Love – Oak Ridge National Laboratory
- Prof. Dr. Ing. Hubertus Murrenhoff – RWTH-Aachen University
- Prof. Jan-Ove Palmberg – Linkoping University
- Prof. Andrew Plummer – University of Bath
- Mr. Sohan Uppal – Eaton Corporation (retired)
- Prof. Lu Yong Xiang – Chinese Academy of Sciences (Retired)

Student Leadership Council (SLC)

The mission of the SLC is to act as a liaison between the ERC and the ERC Students; to promote collaboration between the Students at the ERC Institutions; to enhance communication between the advisors and Students of the ERC; and to encourage the study of engineering, math, and natural sciences for the future benefit of fluid power. The SLC is also responsible for preparing an annual Strengths, Weaknesses, Opportunities, Threats (SWOT) analysis and presenting it to National Science Foundation representatives.

Current SLC Officers:

- To Be Elected – President
- Sangyoon Lee – Vice President, University of Minnesota
- Ellen Skow - Secretary – Georgia Institute of Technology
- Ram Devendran - Treasurer – Purdue University

Each institution is allowed a representative on the committee:

- Brittney Jimerson – North Carolina A & T State University
- Open – University of Illinois at Urbana-Champaign
- Melih Turkseven – Georgia Institute of Technology
- Open – Milwaukee School of Engineering
- Anna Winkelmann – Vanderbilt University

MANAGEMENT OF THE CCEFP

The CCEFP key management activities include strategic planning, project selection, budgeting, organizational leadership and control. Long term sustainability planning was added in year seven and revised significantly in year eight. These key functions are summarized below.

Strategic Planning: Each year the Strategic Research and Sustainability plans are updated. These plans are used to drive the organization. Outputs from this process 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.

Research Project Selection

The process for selecting and managing research projects is shown in figure 5.3.2. The process begins with the Center Director receiving market needs input from Industry via industry research and manufacturing roadmaps. The Director then meets with the newly formed CCEFP Steering Committee (SC) to review the CCEFP Strategic Research and Sustainability plans and ensure these needs are incorporated. The Director next issues a strategic call for proposals to Center PIs citing areas of need. The Director reviews the proposals and with input from an extensive IEC evaluation, selects the funded projects.

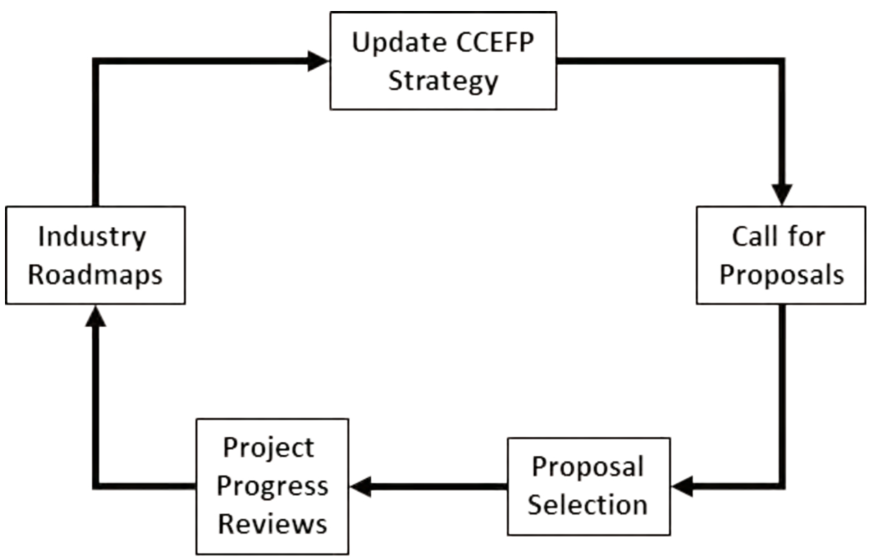


Figure 5.3.2: Project Selection and Management Process

The project selection process provides for a two-year funding cycle. This was done to allow more time to pursue higher impact research. It also provides more stability to plan graduate student funding.

The main elements of the process include a center-wide strategic call for proposals, a standardized proposal format, and an extensive evaluation procedure. The strategic call for proposals is a carefully worded summary of our strategy that identifies research needs necessary to fulfill the strategy. It is widely circulated to both existing and potential new research project leaders along with an updated standardized proposal template. Starting in year eleven it is our intention to open up this proposal process to any US university. The template is focused on the project's research approach, the research team and collaboration, strategic fit, fundamental research content, schedule, deliverables and metrics.

The CCEFP IEC enthusiastically embraces the project selection process. They will 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). An example of the review scorecard template is shown in figure 5.3.3. The review results are discussed extensively during IEC teleconferences until a final outcome is reached and sent to the Center Director.

CENTER FOR COMPACT AND EFFICIENT FLUID POWER
A National Science Foundation Engineering Research Center

Year 7-8 Proposal Scorecard

Project scores:	
Alignment:	22.0
Risk:	21.0
Reward:	20.0

Proposal number:	##
Continuation of existing project number:	NA
Project name (Main thrust):	**Example (TBD Thrust)**
Project PI:	Prof. TBD
Brief project description:	This section provides a brief project description

	Scoring Parameter	Score 1	2	3	4	5	Enter score (integers only)
Alignment	Fundamental nature of project	Largely technology development	Extension of known technology into new space.	Some level of fundamental research apparent	Largely fundamental research (extension of current or past	Largely fundamental research (novel direction)	4
Alignment	Systems approach	Little or no opportunity for demonstration on a fluid power system	A slight possibility of demonstration in a fluid power system has been established.	Provides a basis for demonstration on a fluid power system.	A clear path for demonstration on a fluid power system has been established.	Demonstration of one or more fluid power systems is planned during this project proposal time frame.	5
Alignment	Strategic fit	Strategic fit not apparent	Some level of strategic fit	Aligned with CCEFP strategy	Aligned with transformational goals of CCEFP	Strong alignment with transformational goals of CCEFP	4
Alignment	Alignment with test bed	Little or no alignment	Partial alignment, but research not consistent with main focus of test bed	Partial alignment and research is consistent with main focus of test bed	Completely aligned and consistent with scope of test bed	Completely and expands scope of test bed in a manner consistent with Center's goals	4
Alignment	Center goals focused	No or weak alignment	Slight alignment with one of the CCEFP major goals	Alignment with more than one of the CCEFP major goals	Strong alignment with one of the CCEFP major goals	Strong alignment with more than one of the CCEFP major goals	5
Risk	Project metrics	Limited definition of scope, deliverables, resources, and timeline	Some definition of scope, deliverables, resources, and timeline, but <50% defined	Scope, deliverables, resources, and timeline >50% defined	Project 80% scoped including deliverables, resource allocations, and timeline	Project completely scoped including deliverables, resource allocations, and timeline	4
Risk	Deliverables	Vague deliverables	Not completely defined and/or SMART (Specific, Measureable, Attainable, Realistic & Time-bound)	Not completely defined and/or SMART, but includes benchmarking of competitive technologies	Fully defined and SMART (specific, measureable, achievable, realistic, time bound)	Fully defined, SMART and competitive benchmarks are part of deliverables	4
Risk	Likelihood of success	Unclear	Moderate - est. 25%	Good - est. 50%	Very good - est. >67%	High - est. >80% (e.g., builds on past successes)	4
Risk	Team assessment	It is apparent that the team is missing numerous critical skillsets for project success	It is likely that the team is missing one or more critical skillsets for project success	The team is missing some critical skillsets for project success but a plan is in place to secure them	It is likely that the team possesses all critical skillsets for project success	It is apparent that the team possesses all critical skillsets for project success	5
Risk	Budget Assessment	Apparent that the budget is dramatically too high or insufficient to meet project scope or well outside of specified guidelines	The proposed budget is questionable with respect to project scope or specified guidelines	The proposed budget is adequate	The proposed budget is reasonable based on project scope and specified guidelines	It is apparent that the proposed budget is appropriate to meet project scope and within specified guidelines	4
Reward	Industry participation	No industry partners identified	Potential partners identified but not yet committed	Letter of support from industry partner	Letter of support and commitment of resources from industry partner	Letters of support and commitment of resources from multiple industry partners	4
Reward	Addressing CCEFP technical barrier(s)	Weak or no link to technical barriers	Addresses one non-transformational technical barrier	Addresses multiple non-transformational technical barrier	Transformational technical barrier addressed	Addresses multiple technical barriers including at least one transformational barrier	5
Reward	Breadth of applicability	Project's potential impact is narrow	Project's potential impact is limited to the sponsoring test bed	Project's potential impact covers more than one test bed	Potential impact benefits a broad segment of fluid power applications	Project's potential impact benefits essentially all fluid power applications	4
Reward	External support	No additional external support is likely	Nominal external support, such as in-kind donations, is possible	Some level of external support (<$50K) is expected	Government or industry sponsored research projects > $100K are likely to result from this research	Government or industry sponsored research projects > $500K are likely to result from this research	3
Reward	Original nature of project	Little or no novel contribution is likely to occur	Some novel contribution is likely to occur	Typical novel contribution is likely to occur	Novel contribution resulting in publications and/or IP is likely to occur	Novel contribution resulting in prestigious publications and/or marketable IP is likely to occur	4

Figure 5.3.3: Project Proposal Review Scorecard

For Y9-Y10, thirty research proposals were received. Because NSF funding begins to diminish during these final two years only fourteen projects were able to be funded with the available budget forecast. Non-funded proposals make up a "project funnel" for future consideration when other funding sources are made available.

The Y9-Y10 approved projects are:

1. Carbon Nanotube Reinforced Elastomeric Accumulator
2. Fluid-Powered Surgery & Rehabilitation via Compact, Integrated Systems
3. Variable Displacement External Gear Machine
4. Free-Piston Engine Hydraulic Pump

5. Energy Efficient Fluids
6. High Performance Valve Actuation Systems
7. A Novel Pressure-controlled Hydro-Mechanical Transmission
8. Operator Interface Design Principles for Hydraulics
9. MEMS Proportional Valves
10. Rheological Design for Efficient Fluid Power
11. Controlled Stirling Thermocompressor
12. New Directions in Elastohydrodynamic Lubrication
13. Soft pneumatic actuator for arm orthosis
14. Digital Pump/Motor System Integration and Control

During the past year a new streamlined process for project reviews was implemented. In this process every project is reviewed twice annually, once at the FPIRC annual conference and a second time at one of two IEC Summits. Reviews are collected electronically at the end of each project presentation. The results are summarized and presented to the Center Director and the PI of each project.

Associated Projects

There are several ways that the CCEFP pursues associated projects. The process starts with the review of our strategic research and sustainability plans. This may identify a need for research in a new area or the need to focus on a new area of technology. Once the call for proposals response is received, a gap analysis is done to identify areas that need additional focus. This gap analysis is the basis for pursuing new associated projects. New opportunities for funding are also developed by monitoring government grants opportunities and working directly with members and potential industry member to solicit support.

Budgeting and Financial Management

The budgeting process is an annual event that includes planning for research, education and outreach and center administration. The Administrative Director (AD) oversees the process. Standardized budget templates and guidelines are used to drive consistency. Regular financial reports are created by the AD and distributed to those with budget responsibility. Deviations with the approved budget are reviewed with the AD and corrective action is taken as required.

RET & REU Integration

Twenty-two REU students participated in summer 2014, the eighth year of the program: six at the University of Minnesota, three at Purdue University, two at the University of Illinois Urbana-Champaign, three at North Carolina A & T State University, two at Georgia Institute of Technology and two at the Milwaukee School of Engineering. None of these REU students had previous CCEFP REU experience. Thirteen of the 22 students were recruited from outside the CCEFP's core institutions. Over 170 undergraduate students have participated in the program since its inception.

Four teachers participated as RETs in summer 2014, the eighth year of the CCEFP RET program: two at Purdue University and two at North Carolina A&T State University. Over 40 teachers have participated in the CCEFP RET program since its inception, and several have been repeat participants. The CCEFP requires that all RET participants submit their classroom curriculum to the TeachEngineering.com website which is a repository of evaluated and reviewed curriculum modules. The CCEFP is the only ERC to have RET curriculum modules successfully accepted to the site. The three curriculum modules that have been accepted are named below; six more are under review.

- Hybrid Vehicle Design Challenge - Joel Daniels, Vanderbilt, CCEFP RET 2009
- Fun with Air-Powered Pneumatics - Jacob Givand, Jeffrey and Melissa Schreifels, University of Minnesota, CCEFP RET 2009

- Fluid Power Basics - Brian Bettag, Purdue, CCEFP RET 2009

POST DOCTORAL MENTORING

CCEFP's faculty mentors are obligated to set their post-docs on a path to develop an independent research thrust, to encourage post-docs to become lead writers or principal investigators on at least one research proposal, and to work with post-docs on the strategy and tactics of securing a permanent position. CCEFP post-docs routinely perform funded research, help teach graduate classes, mentor graduate students, and write papers and proposals that also prepare them for future employment. The post-docs at CCEFP play a very important role bridging the development of strategy for and implementation of research, dissemination of results, and teaching and mentoring of students.

COMMUNICATIONS

The CCEFP uses several formats to communicate with stakeholders including NSF, industry, the scientific and engineering communities, students of all ages, and the general public. External communication uses multiple media outlets including meetings, web casts, print media, e-mail, the World Wide Web, video and television. Under the new organization the NFPA is taking a more active role in disseminating our message to industry.

Having previously identified industry as comprised of two distinct audiences, we have continued to provide the *industry executives* with concise information affording an overall view of the research and education/outreach efforts taking place within the Center. Key among these efforts to reach industry executives are quarterly letters from the Director, monthly e-mail newsblasts, and access to member's only information via the private section of the CCEFP website. The second industry stakeholder identified are the *Industry technologists* who are provided with detailed information on a more frequent basis and of a more technical nature given their scientific interests and their role in collaborating with the research teams through the Project Champions program. CCEFP also contributes a monthly technical article to *Design World* and a Center update in the NFPA *Reporter.* Bi-weekly research project webcasts, monthly IAB teleconferences, and a quarterly newsletter are among the efforts targeted at this stakeholder group. As the Centers sustainability plan is realized and implemented, further collaborative efforts between CCEFP and NFPA will be underway. NFPA has an impressive communications strategy and infrastructure. When collaborative efforts begin, the CCEFP will evaluate its best mediums and modes for effective communication and promotion.

CCEFP efforts to further engage students and faculty have included a formal, online survey tool to provide feedback to Center leadership with regard to meetings, events, project reviews and other operations that require the participation of all members.

Communications outreach to the general public continues to be accomplished through a comprehensive, cutting-edge website presence and through online social media – Facebook, Twitter, YouTube-- and the availability of our fluid power documentary "Discovering Fluid Power" in DVD format and CCEFP promotional videos.

A brief description of key communications tools used to reach our many stakeholders follows:

Meetings and Conferences

The CCEFP has two annual meetings: the NSF Site Visit and the CCEFP Annual Meeting. The primary purpose of the Site Visit is for NSF Center review. The primary purpose of the Annual Meeting is to communicate directly with industry. The NSF Site Visits are primarily held at the University of Minnesota. The CCEFP Annual Meeting rotates among partner universities. Previous CCEFP Annual Meetings have taken place at the following locations:

- 2007 -- Georgia Institute of Technology
- 2008 -- Milwaukee School of Engineering

- 2009 -- North Carolina A&T State University
- 2010 -- Purdue University (in conjunction with the 6th Annual Fluid Power Net International Ph.D. Symposium
- 2011 -- CCEFP's Site Visit and Annual Meeting held in conjunction with the International Exposition for Power Transmission (IFPE)

  CCEFP Student Retreat at NFPA IEOC Meeting
- 2012 – CCEFP Annual Meeting at University of Illinois Urbana Champaign in conjunction with the NFPA Fluid Power Workforce Summit

  CCEFP Student Retreat at Sauer-Danfoss
- 2013 – CCEFP annual meeting co-located with the ASME/Bath symposium in Sarasota, Florida

  CCEFP Student Retreat at Caterpillar, Inc.
- 2014 – CCEFP FPIRC14 at Vanderbilt University
- 2015 – CCEFP FPIRC15 co-located with the ASME/Bath symposium in Chicago, Illinois

The 2015 Site Visit will take place at the University of Minnesota in April and the FPIRC15 will take place in Chicago in October. Beginning in 2014 the CCEFP annual meeting was renamed as the CCEFP Fluid Power Innovation and Research Conference (FPIRC) to reflect the broadened scope of the conference. Beginning in 2015 researchers from non-CCEFP universities and industry will be invited to make presentations. Our goal is to make FPIRC the premier fluid power conference in the world.

Research Project Summaries

Each research project has been summarized in its own informational and promotional sheet. These Research Project Overview sheets outline the unmet need, benefit to industry, research personnel, project achievements and technology readiness level (TRL) of each CCEFP project. Not only are these sheets informative for member industry executives and technologists, but also they are also beneficial to the recruitment of new industry partners. An improvement incorporated this year was to utilize the annual reporting process to update all project summaries. They are currently online at the CCEFP website (www.ccefp.org). An example is shown in figure 5.3.4.

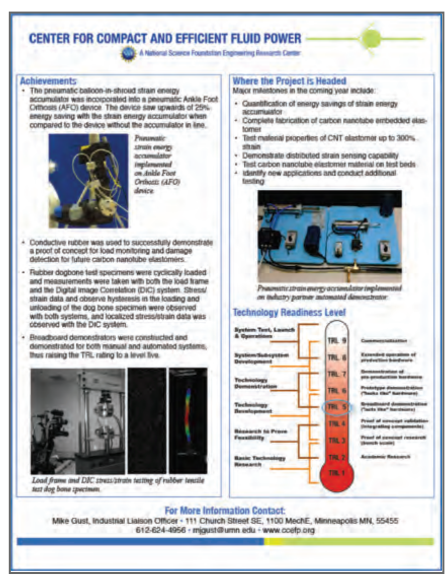


Figure 5.3.4: Research Project Summary Example (Front, left and Back, right)

Project Center Database Website

CCEFP utilizes a data collection tool in the form of the CCEFP Project Center website. While the initial goal of the site was to collect data for reporting to NSF, the site was developed in a way that provides critical project information to center researchers year round. In particular, this website allows users to see the connections between all CCEFP projects, their participants, and their resulting outputs including, presentations, publications, outreach efforts and other items. Currently the site is limited to CCEFP researchers and staff only. The creation of this website has served as a pilot for similar sites which are currently being implemented at other NSF ERCs.

Figure 5.3.5: CCEFP Project Center Home Page

Website

The CCEFP website, ccefp.org, continues to be a source for information to the public as well as for our members. The website is a means to communicate information to a wide audience and content is updated regularly. Key elements of the site include information about the Center's research and PIs, our education and outreach activities, our industry partners, as well as details on upcoming events such as the Fluid Power Innovation and Research Conference (FPIRC). A password-protected member's only section allows industry members, faculty and student access to private information not available to the general public and non-member industry companies.

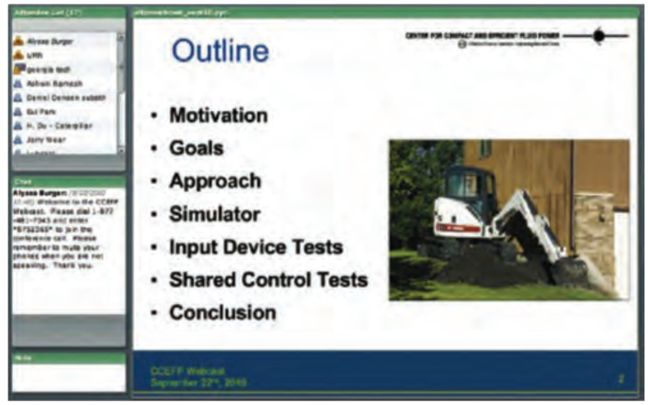
Figure 5.3.6: CCEFP Website Home Page

E-mail Newsblasts

CCEFP Newsblasts are being replaced by including CCEFP information in the weekly NFPA electronic communication. With its more than 300 members, NFPA has significantly broader reach than CCEFP.

Research Webcasts

Webcasts are a valuable form of communication and provide current information on CCEFP research projects and other topics of interest to members. The Student Leadership Council organizes a bi-weekly, one-hour webcast, each featuring three student research projects. The webcast is regularly viewed by a number of member companies, with robust interaction between the industry members and the student presenters during the Q & A portion. Archived recordings of all webcasts are available in the member's section of our website should listeners wish to watch them again or view them at a later time.



Social Networking

Outreach to students, educators, friends of fluid power and the general public is currently underway using a variety of online social media to provide information about the Center and its many efforts. Some of this category of tools currently in use includes **Facebook**, **Twitter**, **YouTube** and **TeacherTube**. CCEFP will continue to reach out to various audiences using these and other free, ubiquitous online tools whenever appropriate.

Promotional Videos

The promise of the CCEFP – the intersection between leading research institutions and the fluid power industry – has been articulated in two well-crafted promotional videos demonstrating how the Center is impacting research, innovation and workforce talent in the fluid power industry.

Changing the Way Fluid Power is Researched, Applied and Taught
(https://www.youtube.com/watch?v=09vMJ-tylOY)
and
Bringing Talent to the Fluid Power Industry
(http://www.youtube.com/watch?v=ezRYmqsad0I).

Documentary DVD

The promise of fluid power is being communicated to K-12 educators and the wider public with two half-hour public television programs, which have aired regularly on public television stations throughout the country. Additionally, the programs are available "on demand" through the Research Channel website and its cable television channels. Also of note, these programs are available for viewing on our website and are still being distributed in DVD format at no cost to those requesting one. In the year since these films were produced, there have been well over 150 requests from educators and other interested parties in the U.S. and internationally.

Trade Press

The CCEFP actively seeks out opportunities to inform the public about the Center's work in research, education and outreach. Projects and research taking place in the CCEFP are often featured in a variety of fluid power trade publications such as *Hydraulics & Pneumatics, Design News,* and *Diesel Progress* as well as several others. Publications that can be categorized under the trade press umbrella, specifically those whose readers have an interest in some aspect of fluid power, form a far-reaching network and also include those of trade associations, professional societies, specialty publications and online media. Their circulations range from approximately 2,000 to 100,000 readers. When articles about the CCEFP are carried in any of these publications, the Center is extending its network, reaching engineers and technicians in the fluid power industry and the industries it serves. By invitation, the CCEFP contributes one research update per month to the *Design World* blog: *MobileHydraulicsTips.*

STRATEGIC BUSINESS PLAN

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 vision has 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. Said another way, while great progress has been made by CCEFP across a broad, yet targeted front, 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 doing research at our seven member institutions. CCEFP has over 50 industry supporters. In addition to the $4M in ERC funding from NSF, the Center's FY8 budget includes approximately $800K in matching funds from our core member universities and approximately $700K in industry support through our partner the National Fluid Power Association. Center researchers also received more than $2M in funding from government and industry sources for associated sponsored research projects in FY9. 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 which improves the potential for licensing and/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, among other things. 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 such as pneumatics, advanced manufacturing, medical applications and wind power in the Center's research portfolio.

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 fund raising 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.
- Continue a strong focus on mobile hydraulics, but other areas of research, including research in industrial pneumatics, advanced manufacturing, bio-medical engineering and wind power will be investigated for possible future inclusion in the Center's research portfolio.
- 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. The effort has been renamed the Workforce Development Program (WDP). Increasing diversity and industry involvement are important aspects of WDP.
- 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 recently released 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

Sustainability planning has been the top priority of the CCEFP the past year. The Center Director holds a 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. Ideas are continuously vetted with internal academic and industry supporters to ensure alignment and understanding.

Based on this feedback the CCEFP has undertaken major improvements to its Sustainability Plan. The plan still calls for three major elements which 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.

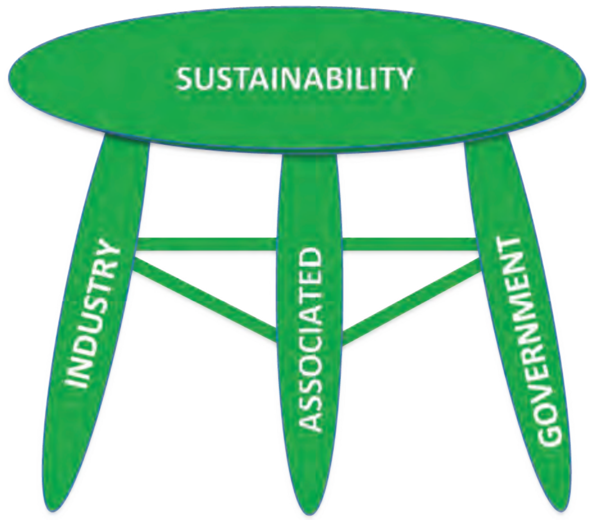


Figure 5.3.7: CCEFP's 3-Legged Stool Model for Center Sustainability

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 level for the next two years which is based upon 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 also been documented and approved. Both the Grant Agreement and the COPs are included in the appendix.

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 5.3.1.

Table 5.3.1: 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/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 on which a member is invited to serve is based on their annual giving level as defined in figure 5.3.8.

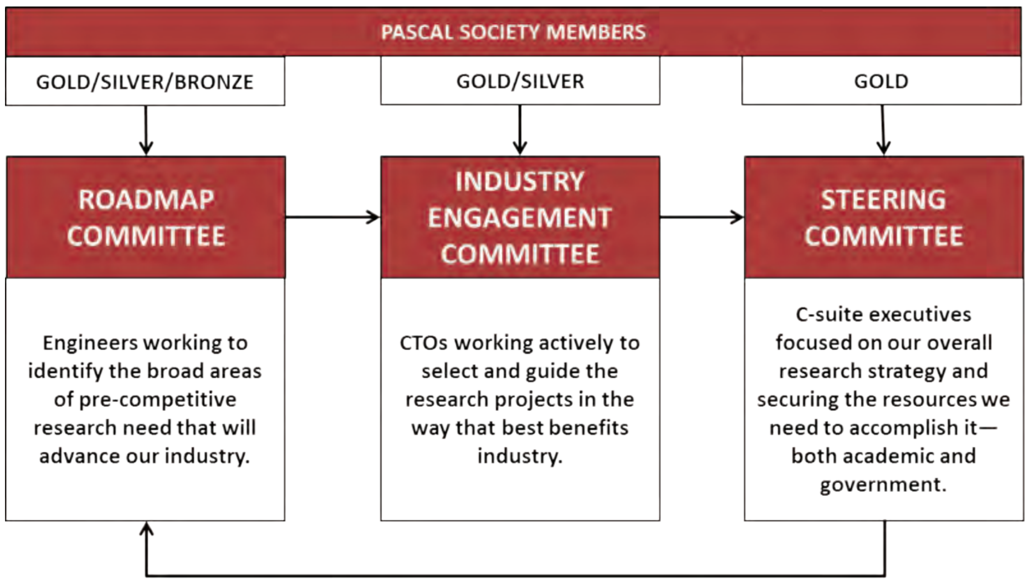


Figure 5.3.8: Pascal Society Member Representation in CCEFP Advisory Committees

Each membership level comes with a unique set of recognition benefits and participation opportunities in the committees that help determine the strategic direction and implementation of our fluid power research programs. These are defined in table 5.3.2.

	Membership Level		
Recognition Benefits and Participation Opportunities	**Gold**	**Silver**	**Bronze**
Invitation to serve on the CCEFP Steering Committee • Oversees pre-competitive research strategy	X		
Recognized individually from the podium at major NFPA events	X		
Invitation to VIP event at NFPA Annual Conference	X		
Invitation to serve on the CCEFP Industry Engagement Committee • Selects and monitors progress of research projects. • Early, frequent, face-to-face access to research results and students and notification of licensing opportunities	X	X	
Recognized collectively from the podium at major NFPA events	X	X	
Invitation to participate in CCEFP project selection process	X	X	X
Invitation to serve on the NFPA Roadmap Committee • Maintains technology roadmaps for the fluid power industry	X	X	X
Recognized in printed materials disseminated at major NFPA events	X	X	X

Table 5.3.2: Pascal Society Recognition Benefits and Participation Opportunities for Members

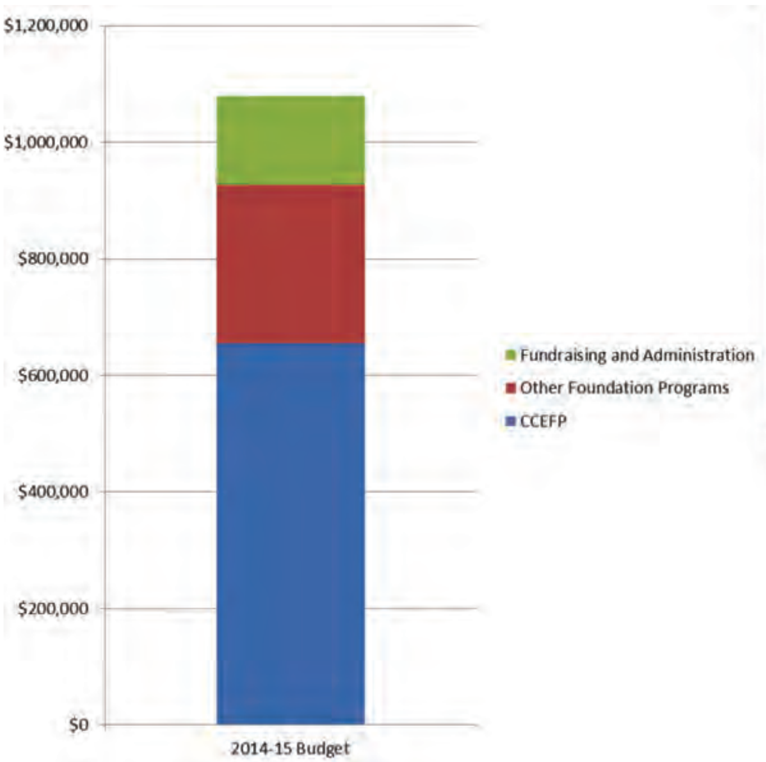
A major goal of the CCEFP and the NFPA for the past year has been to convert the existing CCEFP industry members over to the Pascal Society. This goal has been largely accomplished with fifty-four industry sponsors, listed in table 5.3.3, currently committed to supporting the Pascal Society. In recognition 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 • Caterpillar • Daman Products Company	• Danfoss Power Solutions • Eaton Corporation • Enfield Technologies	• Hydra-Power Systems • Pall Corporation • Parker Hannifin
SILVER		
• Afton Chemical • Bobcat • CNH • Deltrol Fluid Products • Donaldson Company • Evonik Oil Additives • Fluid Power World Magazine	• Gates Corporation • HYDAC/Schroeder Industries • Hydraquip • Linde Hydraulics • Lubrizol • MICO • Moog	• Netshape Technologies • Poclain Hydraulics • Quality Control Corporation • Simerics • Trelleborg Sealing Solutions • Woodward HRT
BRONZE		
• Bosch Rexroth • Concentric AB • Delta Computer Systems • Festo Corporation • FORCE America/Valve Division • G. W. Lisk Company • HECO Gear • Hitachi • Hoowaki	• HUSCO International • Idemitsu Kosan • JCB • Kaman Industrial Technologies • Main Manufacturing Products • Master Pneumatic • Muncie Power Products • National Tube Supply • Nexen	• ROSS Controls • SMC USA • Sun Hydraulics • The Toro Company • Walvoil Fluid Power • White Drive Products • Womack Machine Supply

Table 5.3.3: 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 previously and listed in section 4.5 are necessary to support this effort.

Our efforts to date have been fruitful. NFPA is making excellent progress towards it first year fund raising goal of $808,000 with $774,370 pledged to date as shown in table 5.3.9.



The NFPA is using its reserve fund to guarantee these commitments, regardless of initial fundraising success.

Status as of February 6, 2015

- 91 Pascal Society invitations issued (64 "escalator"; 27 "elevator")
- 54 Pascal Society members confirmed
- 12 invitations declined
- 25 invitations outstanding
- 91 other donors
- **Total pledged/raised = $774,370**
- 88% of overall goal

Figure 5.3.9: Pascal Society funds pledged/raised as of February 6, 2015

The Center has formed two committees that represent the other two legs of the sustainability stool. The Government Relations Committee focuses on securing large, multi-site government grants and the Industry Relations Committee is focused on increasing sponsored research. Details on these committees is provided on the following pages.

Government Relations Committee

The second leg of the stool for CCEFP sustainability is procuring large, multi-university grants. The target is to obtain $2-3M per year on an ongoing basis. The Government Relations Committee (GRC) was formed in March 2014 and meets as a committee in whole on a monthly basis.

The primary goals of the GRC are:

- To identify potential sources for large, multi-university, pre-competitive fluid power research grants
- To develop relationships with key individuals at these sources
- To create grant proposal opportunities
- To secure such grants

The GRC is led by the CCEFP Director Kim Stelson and has the following members:

- Dr. Andrew Alleyne, University of Illinois, Urbana-Champaign
- Dr. Douglas Adams, Vanderbilt University
- Dr. Thomas Kurfess, Georgia Institute of Technology
- Dr. Perry Li, University of Minnesota
- Dr. Zongxuan Sun, University of Minnesota
- Dr. Andrea Vacca, Purdue University
- Dr. Lonnie Love, SAB, Oak Ridge National Laboratory
- Eric Lanke, CEO, National Fluid Power Association
- Brad Bohlmann, CCEFP Sustainability Director

ITECS Innovative Consulting

CCEFP PIs have a broad range of expertise and interests, some of which are well aligned with the needs and interests of the sources of government grants and some that are not. In order to help define which have the best alignment with government agencies and departments, the Center engaged a consulting company. ITECS Innovative Consulting (https://itecs-innovative.com/) has a proven track record of helping both academic and commercial entities locate and procure government grant funding.

Some of the key deliverables that the Government Relations Committee gave to ITECS were to:

- 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 and implemented by ITECS is shown pictorially in figure 5.3.10.

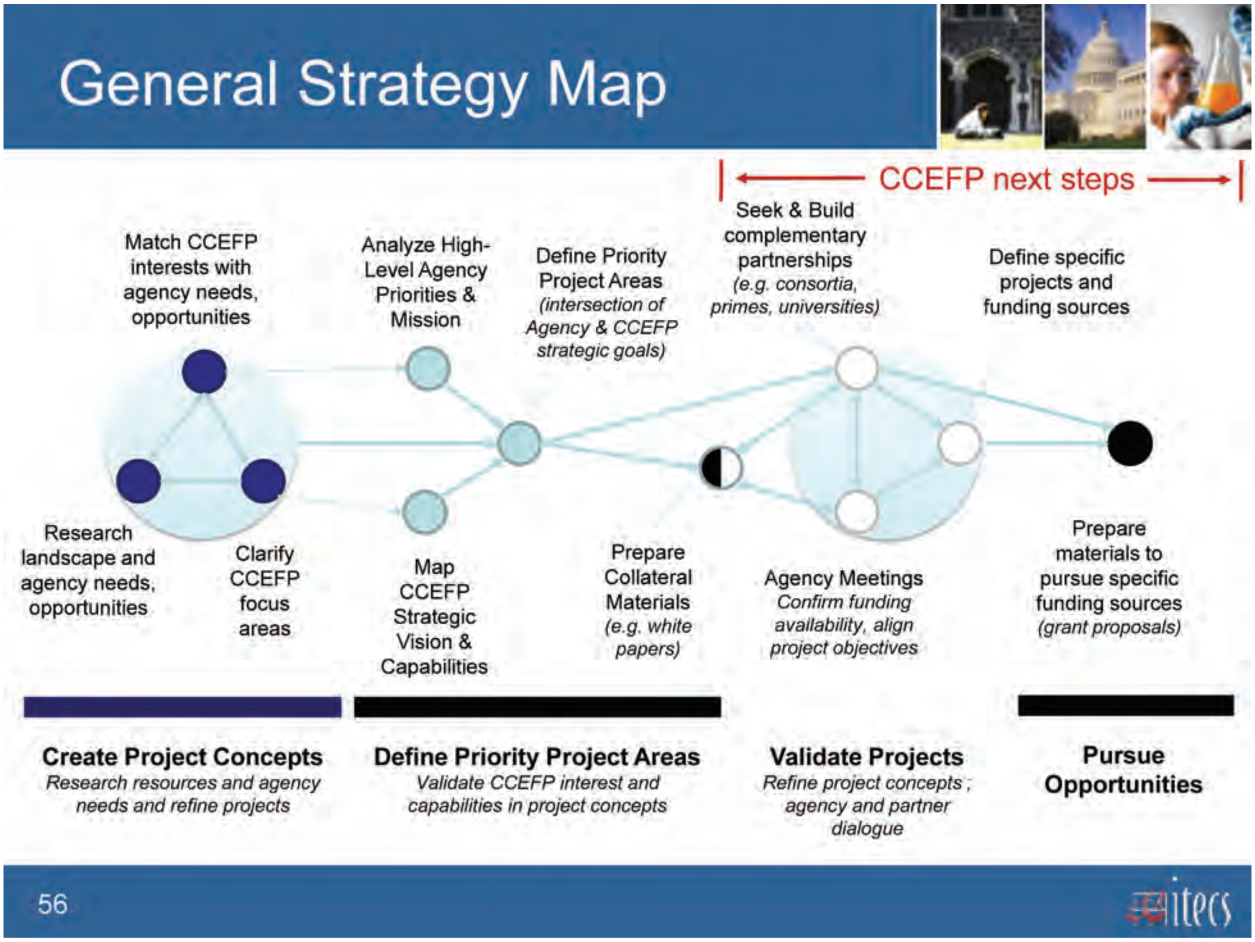


Figure 5.3.10: ITECS Innovative Consulting's Strategy Map

The first step in the process was for Center staff to provide ITECS with a list of CCEFP PIs that spanned a broad range of expertise. The number of PIs identified was 13. ITECS then did interviews with these individuals and organized the information into focus areas that were then compared with the interests and needs of grant funding sources. The agencies and department identified by ITECS 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

A pictorial representation of the ITECS recommendations is shown in figure 5.3.11.

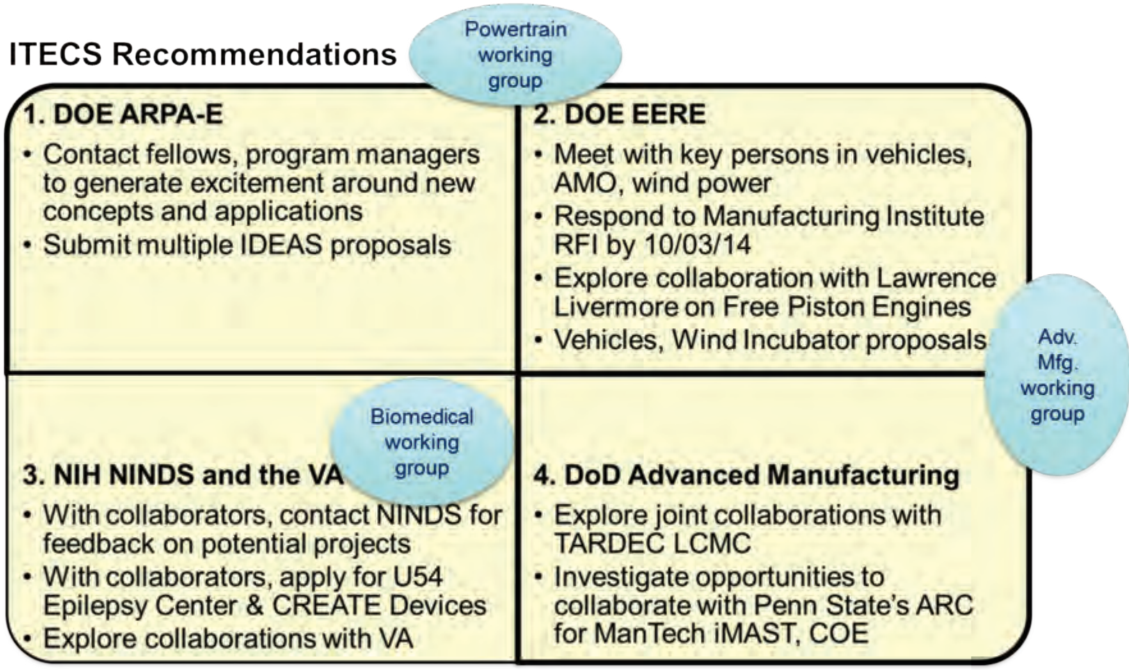


Figure 5.3.11: High level results of the ITECS government funding study

CCEFP Government Relations Committee Working Groups

The recommended funding sources and their interests fit naturally into three groups: powertrain, biomedical and advanced manufacturing. The GRC decided to form a working groups in each of these focus areas. The membership of the working groups are provided below.

Powertrain Working Group

- Prof. Zongxuan Sun, University of Minnesota (Team Lead)
- Prof. Monika Ivantysynova, Purdue University
- Paul Michael, Milwaukee School of Engineering

Biomedical/Human Scale Working Group

- Prof. Eric Barth, Vanderbilt University (Team Lead)
- Prof. Elizabeth Hsiao-Wecksler, University of Illinois Champaign-Urbana
- Prof. Jun Ueda, Georgia Tech

Advanced Manufacturing Working Group

- Prof. Tom Kurfess, Georgia Tech (Team Lead)
- Prof. Doug Adams, Vanderbilt University
- Dr. Lonnie Love, Oak Ridge National Lab
- Brad Bohlmann, University of Minnesota

The Center has limited resources so having all three working groups moving ahead at a fast pace is unrealistic. The GRC and Center management has decided to have all three working groups active, but to have the priority order for the working groups to be powertrain, biomedical, and advanced manufacturing. Our best chances of successfully acquiring grants consistent with the goals of the GRC are in the powertrain area, but both of the other topics hold promising opportunities.

Relationship Development

We have been actively working to increase awareness of the Center and its activities and cultivating relationships with mission-centric government agencies since 2012. This has been done through, among other things, attending government summits and workshops on topics of interest, responding to requests for information (RFI), submitting grant proposals, and face to face meetings with targeted government agencies. In the reporting period, the Center participated in six workshops, submitted four RFI responses, submitted two grant proposals (detailed below) and had two face to face meetings with senior DOE personnel.

Grant Proposals to Date

NSF Industry/University Cooperative Research Center Program

NSF recommends that graduating ERCs pursue the Industry/University Cooperative Research Center (I/UCRC) program. Following this lead, CCEFP applied for an I/UCRC planning grant in September 2014. We expect to hear from NSF whether or not our proposal will be funded in the near future.

CCEFP has a great deal of respect for the I/UCRC program. It pre-dates the ERC program and has facilitated academic research for more than 35 years. However, we have found that there are some policies and procedures that are not well-aligned with those of the ERC program. Given that the ERC program recommends that graduating ERCs apply to become an I/UCRC, it would be helpful if these minor conflicts could be eliminated to ease the transition from ERC to I/UCRC.

NIST Advanced Manufacturing Technology Consortia Program

CCEFP partnered with the National Fluid Power Association (NFPA) and the Association for Manufacturing Technology (AMT) to submit a proposal in response to the NIST 2013 Advanced Manufacturing Technology Consortia (AMTech) Program. The focus of this AMTech call for proposals is providing funding for advanced manufacturing technology roadmapping workshops. Our proposal was considered “fundable”, but was not one of the 19 proposals fund (out of 82 proposals received).

We took the feedback provided by the NIST reviewers and submitted an improved proposal in response to the 2014 AMTech funding opportunity announcement on October 31, 2014. We are awaiting a response from NIST regarding our proposal.

Regardless of whether our 2014 AMTech grant is funded, we intend to create a fluid power manufacturing roadmap in 2015 with our partners, NFPA and AMT. We feel that this roadmap is an critical tool to help the Center identify and prioritize the advanced manufacturing priorities of the fluid power industry.

Plans for Procuring Grant Funding

We plan to continue all of the activities listed in the Relationship Development section above. Representative examples include:

- **ARPA-E 2015 OPEN Program**: CCEFP researchers, Argonne National Lab, and two industry partners will be submitting a pre-proposal to this program to bring the free-piston engine pump closer to commercialization. If we are invited to submit a full proposal, it would be one the order of $1M over or two to three years. This is a relatively modest amount, but the exciting part is the national lab and industry interest. We visited Argonne and they want to explore establishing a long term relationship with CCEFP researchers.
- **DoD Multidisciplinary University Research Initiatives (MURI) Program**: We are exploring forming a multidisciplinary team focused on tribology, fluids and surface science that we would

propose to DoD as a potential MURI collaborative. CCEFP PIs from Georgia Tech, UIUC, Minnesota and MSOE have expressed interest. We also visiting Northwestern University to discuss their participation. They are recognized as one of the leading universities in tribology and surface science in the US. We plan to visit the Navy Research Lab this summer to enlist their support for such a MURI.

- **TARDEC Industry Days**: The Center has sent an announcement to the Industry Engagement Committee advising them that TARDEC is holding its Industry Days on March 18 & 19. At the annual Industry Days Conference, the Army reviews its 30-Year technology strategy, current research activities, and future funding priorities. Our goal is to identify the Army's requirements so CCEFP industry and academic partners can craft collaborative fluid power research white papers and proposals that align with the government's needs. CCEFP PIs and staff will attend and we hope that several of our members companies do so, as well.
- **Meeting with EERE Vehicle Technologies Office**: Center Director Stelson will lead a group that will be meeting with Pat Davis, Director of the EERE Vehicle Technologies Office. The goal of the meeting is to ask VTO to create an off-road vehicle program to provide stable annual funding focused on energy reduction technologies/research. If created, it is anticipated that fluid power would receive some fraction of the annual funding spent on off-road vehicle research. Our industry members, both component/system suppliers and OEM/integrators would like to see DOE provide research and development support to the off-road vehicle industry.

  Others who will be attending the meeting with Mr. Davis include senior personnel from Caterpillar and Parker Hannifin, NFPA's CEO, and Deputy Director Sun. The meeting is being planned for April 2015.

Industrial Relations Committee

The third and final leg of the CCEFP sustainability strategy is to increase individual PI sponsored research. Because priority was placed on implementing the Pascal Society and government sponsored research legs first, it is the least developed area of the CCEFP sustainability plan. This area is championed by the Industry Relations committee (IRC) led by the CCEFP ILO Mike Gust. The IRC has the following members:

- Prof. Monika Ivantysynova, Purdue University
- Prof. Eric Barth, Vanderbilt University
- Prof. Will Durfee, University of Minnesota
- Prof. Ken Cunefare, Georgia Institute of Technology
- Paul Michael, Milwaukee School of Engineering
- Dr. Joe Kovach, retired CTO of Parker Hannifin
- Sohan Uppal, retired CTO of Eaton's Fluid Power Group

The primary goals of the IRC are to double the amount of industry sponsored research and triple the number of industry funded PIs over the next three years. Secondary goals include raising the awareness and the value of the CCEFP to industry, broadening the engaged industry audience to higher management levels, facilitating the transfer of pre-competitive research findings to industry for commercialization, and, in instances where industry is not interested in commercialization, help facilitate startup companies, ideally led by our students. In order to achieve the above it is critical that the IRC develop and document a process for streamlining industry sponsored research that can be used to communicate both inwardly to CCEFP researchers and outwardly to industry sponsors.

A thorough review of our overall sustainability plan will be presented and discussed at the April 2015 NSF Site Visit.

Financial Tables

Table 8 shows the planned functional budget for the current award year 9 (NSF-generated Table 8, Figure 8a, Tables 9, 10 and 11 appear in Appendix I). The research budget shows the following distribution between thrusts and test beds: Efficiency Thrust (32%), Compactness Thrust (23%), Effectiveness Thrust (18%) and Test Beds (26%). The percentage distribution of the functional budget is shown in Figure 8a. The major expense is research, shown at 35% of the budget, with funding for education and outreach activities (including REU and RET) at 7%. Anticipated residual funds remaining (40%) are partially the result of delayed billing and payment of incurred expenses, but mainly the result of our choice to levelize research funding over years 9 and 10. CCEFP funds its research project on a two year cycle. The NSF ERC and the resulting university matching funds will drop by 1/3 from Y9 to Y10. The Center saved a portion of the Y9 funds and will spend them in Y10 to allow our researchers to have consistent financial support across the two year funding cycle.

Table 9 shows no member company income because the Center changed the structure of its agreement with industry. The National Fluid Power Association (NFPA) and CCEFP formalized a new agreement in year 9 whereby the NFPA Foundation (known as the "Pascal Society") collects industry contributions and returns them to the Center at a guaranteed, mutually agreed upon minimum amount through a grant agreement. In year 9, the Pascal Society will contribute $655K to the Center. NFPA also contributed an additional $114,228 toward covering administrative costs of the Center in Year 9. See section 4 and 5.3 for additional information about the Pascal Society contribution structure and annual escalating contribution increase option for previous CCEFP industry members. Through the new grant agreement between CCEFP and the resulting NFPA focus on the recruitment of additional industry contributors, we expect the Year 10 level of funding to be sustained and grow to more than $1M in the years ahead.

The actual number of industry involved contributors grew in year 9 with an energized campaign and with the unprecedented Fluid Power Innovation and Research Conference (FPIRC14) held in Nashville, TN at Vanderbilt University in October, 2014.

It is anticipated that this basic distribution will continue into the future with only minor modifications. It is expected that industry contributions, associated projects from industry and government will continue to grow in year 10. Equipment donations from industry in Year 9 were valued at $34K. Increased donations to CCEFP by member and non-member companies indicate that industry seeks out and recognizes CCEFP as the leader in fluid power. Associated project funding is expected to increase with $2.4M in Y9 up from roughly $2M in reported Y8.

Table 8b (next page) shows the Year 9 budget distribution by university. The largest recipient of direct cash funding is the lead university with 52%. The largest recipient of associated project funding in year 9 is Purdue with 56%. The difference between the lead and core university direct cash funding is largely due to the additional expenses of Center administration.

Table 8b: Proportional Distribution of Current Award Year Budget					
Institution	**Direct Cash (Unrestricted and Restricted)**	**Associated Projects**	**Total Cash and Associated Projects**	**% of Total Direct Cash**	**% of Total Assoc. Projects**
University of Minnesota	$2,172,249	$443,768	$2,616,017	52%	18%
Georgia Tech	$455,828	$151,612	$607,440	11%	6%
Milwaukee School of Engineering	$149,422	$219,100	$368,522	4%	9%
North Carolina A & T	$121,000	$0	$121,000	3%	0%
Purdue University	$554,584	$1,353,242	$1,907,826	13%	56%
UIUC	$339,000	$2,797	$341,797	8%	0%
Vanderbilt University	$253,828	$255,319	$509,147	6%	11%
Science Museum of Minnesota	$50,000	$0	$50,000	1%	N/A
Quality Evaluation Design (QED)	$50,000	$0	N/A	1%	N/A
FolsomTechnologies International	$0	$0	N/A	N/A	N/A
Grand Total	$4,145,911	$2,425,838	$6,521,749		

Table 8c: Current Award Year Education Budget, a part of the overall Center budget, is shown below as funds are distributed by program area.

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	$55,776	$0	**$55,776**	$0	**$55,776**
University Education	$92,610	$0	**$92,610**	$0	**$92,610**
Student Leadership Council	$32,994	$0	**$32,994**	$0	**$32,994**
Young Scholars	$0	$0	**$0**	$0	**$0**
REU	$30,034	$0	**$30,034**	$0	**$30,034**
RET	$28,000	$0	**$28,000**	$0	**$28,000**
Assessment	$50,000	$0	**$50,000**	$0	**$50,000**
Community College activities	$0	$0	**$0**	$0	**$0**
Other	$48,000	$0	**$48,000**	$0	**$48,000**
Education Program Total	**$337,414**	**$0**	**$337,414**	**$0**	**$337,414**

Table 9a (next page) shows the funding history of the Center and includes funding amounts on the base grant for years 1-9, plus supplements since inception. In year 9, CCEFP provided $250K toward two diversity graduate students using NSF CORE research funding.

Table 9a: History of ERC Funding of the Center						
Award Number	**Award Type**	**Award Title**	**Award Duration**	**Amount**	**Status**	**Final Report Approved?**
0540834	Base	Engineering Research Center for Compact and Efficient Fluid Power	8 years	$32,161,000	In progress	N/A
0540834	REU Supplement	Engineering Research Center for Compact and Efficient Fluid Power	1 year	$65,801	Completed	N/A
0540834	NSF/GRS Supplement	Engineering Research Center for Compact and Efficient Fluid Power	1 year	$44,814	Completed	N/A
0540834	NSF/SECO Supplement	Engineering Research Center for Compact and Efficient Fluid Power	2 years	$199,999	In progress	N/A
0540834	NSF/GRS Supplement	Engineering Research Center for Compact and Efficient Fluid Power	1 year	$81,725	Completed	N/A
0540834	NSF/GRS Supplement	Engineering Research Center for Compact and Efficient Fluid Power	1 year	$39,989	Completed	N/A
0540834	NSF/GRS Supplement	Engineering Research Center for Compact and Efficient Fluid Power	1 year	$52,000	Completed	N/A
0540834	NSF/Travel Supplement	Engineering Research Center for Compact and Efficient Fluid Power	1 year	$5,120	Completed	N/A
1263346	REU Site	Engineering Research Center for Compact and Efficient Fluid Power	3 years	$390,000	In progress	N/A

Table 9 (located in Appendix I) shows the sources of support, and Table 9b (next page) includes the cost sharing by institution. In year 8, the Core Partner universities contributed $745,173 in cost-share spending toward the obligated $800,000. Cost share commitment in years 1-8 was based on 23.852% of *funds allocated*. Because funds occasionally are reallocated by the Center, as was the case in year 8 to year 9, cost share contributions were revised in year 9 to require cost share on 23.852% of total *expenditures.* Actual cost-share contributions since year 1 Center-wide are in excess of the commitment.

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)		Cumulative	Cumulative
Institution	**Committed**	**Actual**	**Committed**	**Actual**	**Committed**	**Actual**
U. of Minnesota	$339,537	$602,309	$339,537	$569,662	$2,070,294	$2,627,715
Georgia Tech	$130,232	$61,944	$130,232	$69,552	$1,060,551	$896,234
MSOE	$0	-	$0	-	$10,800	$18,086
Purdue	$152,557	$56,262	$152,557	$119,663	$1,127,526	$1,087,067
UIUC	$92,093	$84,695	$92,093	-$32,346	$899,740	$922,500
Vanderbilt	$85,581	$35,335	$85,581	$18,642	$692,630	$631,092

Table 10 (located in Appendix I) shows the annual expenditures and budgets, with Table 10a below showing unexpended residuals. Referring to the residual amounts in Table 10a, the carry-forward amount of $2,065,994 and $0 residuals, shows that all money was either committed or encumbered, at the start of year 9. The residual balance of $0, after committed/encumbered/obligated funds, demonstrates that all funds have been committed. The unexpended funds are needed to complete Y9 projects. In the close of year 8, all allocated funds that were unspent by May 31, 2014, were returned to the Center for re-allocation. The amendment process between the Lead Institution and sub-contracting institutions caused delays in billing during year 8 and into year 9. Spending was not inhibited during the amendment process. Mid-way through Year 9, spending has been normalized and disciplined.

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	$2,065,994	$2,679,727
Committed, Encumbered, Obligated funds (obligated = planned for)	$2,065,994	$2,679,727
Residual Funds Without Specified Use	$0	$0

Table 11 Details the modes of recent and historical support provided by Industry Members and non-member organizations alike. As mentioned above and in other sections, former “Industrial Practitioners/Members” are now classified under Non-member Organizations: Funders of Sponsored projects, Funders of Associated Projects, and Contributing Organizations” to the Center and are shown as such.

5.4 RESOURCES AND UNIVERSITY COMMITMENT

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.

Since the Center's inception, CCEFP universities hired twelve faculty members, thus fulfilling its commitment to hire twelve new faculty hires for the Center. The new faculty are:

- Douglas Adams, Vanderbilt University
- Randy Ewoldt, University of Illinois at Urbana-Champaign
- Zongliang Jiang, North Carolina A&T State University
- Thomas Kurfess, Georgia Institute of Technology
- Michael Leamy, Georgia Institute of Technology
- Ashlie Martini, Purdue University
- Zongxuan Sun, University of Minnesota
- Jun Ueda, Georgia Institute of Technology
- Andrea Vacca, Purdue University
- Pietro Valdastri, Vanderbilt University
- James Van de Ven, University of Minnesota
- Robert Webster, Vanderbilt University

CCEFP researchers are fully committed to supporting post-docs as part of the research and education mission of the center. In the last year, two post-docs have been supported. As the prominence of our research increases, CCEFP is expected to attract more high-quality researchers to post-doc positions.

CCEFP university administrators have been fully supportive of the Center. The CCEFP Director has a formal meeting semiannually with the Dean or Associate Deans of the Institute of Technology at the University of Minnesota. Less formal meetings occur with much greater frequency. Through the Council of Deans, an administrative structure exists to handle any major issues, but good cooperation between universities at lower levels has meant that this structure has not been needed in the past. However, the emerging challenge of sustainability has required consultation, input and commitment from the Deans. During the Year 6 and Year 7 Site Visits, sustainability workshops were held with the Deans. Administrative agreements between universities have been handled with some delays, but no major difficulties. These include intellectual property agreements, sub-contracts funded by NSF and industry, and billing. CCEFP universities actively promote cross-disciplinary research. Being part of an ERC research team is an asset, not a liability, in tenure and promotion. As we approach sustainability, additional agreements between universities will be needed. The Deans have agreed in principle to reduced indirect charges on pooled industry funding for pre-competitive research, but this process remains to be codified in formal agreements.

CCEFP is committed to providing a safe research environment. The University of Minnesota (Lead Institution) has formally defined and implemented fluid power safety standards into its existing lab training (http://www.me.umn.edu/intranet/safety/fp/index.shtml) as appropriate for CCEFP students. A fluid power lab safety slide presentation was created (http://www.me.umn.edu/~trchase/hydraulics/safetySlides/) as part of the fluid power safety specific training, and was provided to principal and co-principal investigators at all CCEFP Core and Collaborating Institutions. CCEFP institutional partners worked with their lab safety officers to include the slides during fluid power training. PIs and Co-PIs determine who needs to receive safety training and institutional Safety Officers or designated safety staff manage the safety training process. The safety process includes ensuring approvals and forms are completed, implementing and recording safety training, before any work begins in the lab. In many cases, certificates of lab safety are issued to researchers upon completion.

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SUMMARY PROPOSAL BUDGET

YEAR 10

FOR NSF USE ONLY

ORGANIZATION	PROPOSAL NO.	DURATION (MONTHS)
University of Minnesota		Proposed / Granted
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR	AWARD NO.	Funds Granted by NSF
Kim A. Stelson	0540834	

A. SENIOR PERSONNEL: PI/PD, Co-PI´S, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)

0.	First Name	M	Last Name	Title	CAL	ACAD	SUMR	Funds Requested By Proposer	Fringe	Funds Granted by NSF
1.	Kim	A	Stelson	Dr.	0.00	0.00	2.00	$29,816	$10,018	
2.	Perry		Li	Dr.	0.00	0.00	1.00	$25,750	$8,652	
3.	Paul		Imbertson	Dr.	0.00	0.00	2.00	$22,093	$7,423	
4.	Thomas		Chase	Dr.	0.00	0.00	1.00	$13,319	$4,475	
6.	Zongxuan		Sun	Dr.	0.00	0.00	1.00	$7,500	$2,520	
7.	David		Kittelson	Dr.	0.00	0.00	0.50	$9,104	$3,059	
8.	William		Durfee	Dr.	0.00	0.00	1.00	$15,001	$5,040	
(6)	TOTAL SENIOR PERSONNEL (1-6)							122,583	$41,188	

B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)	CAL	ACAD	SUMR	Funds Requested By Proposer	Fringe
1. 0) POST DOCTORAL ASSOCIATES	0.00	0.00	0.00		
2. 1) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	12.00	0.00	0.00	$40,964	$15,075
3. 9) GRADUATE STUDENTS	12.00			$150,150	$108,108
4. 3) UNDERGRADUATE STUDENTS	12.00			$28,672	$0
5. 2) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)	12.00				
6. 3) OTHER	12.00			$64,025	$23,561
TOTAL SALARIES AND WAGES (A+B)				$406,393	$146,744
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				$187,931	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)				$594,324	

D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000)

0
0

TOTAL EQUIPMENT		$0
E. TRAVEL	1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)	$15,000
	2. FOREIGN	$4,000

F. PARTICIPANT SUPPORT COSTS		
1. STIPENDS	$0	
2. TRAVEL	$0	
3. SUBSISTENCE	$0	
4. OTHER	$0	
(25) TOTAL NUMBER OF PARTICIPANTS	$0	$0

G. OTHER DIRECT COSTS			
1. MATERIALS AND SUPPLIES		$10,000	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION		$5,000	
3. CONSULTANT SERVICES	Program Evaluation of E&O (25K); Systems Eng ($5K); Prof. Svcs (30K) Western	$0	
4. COMPUTERS SERVICES		$0	60300
5. SUBAWARDS		$909,768	
6. OTHER		$0	
TOTAL OTHER DIRECT COSTS		$924,768	
H. TOTAL DIRECT COSTS (A THROUGH G)	Rate	$1,538,092	

I. INDIRECT COSTS (SPECIFY RATE AND BASE) 0

	Direct costs	$628,324.49	
Grad fringe and eqpt exempt idc	Less Grad fringe, equipment Ex	$108,108.00	49.50%
	Total DC	$520,216.49	
Equip. exempt idc	Total IDC	$257,507.16	

TOTAL INDIRECT COSTS	$257,507
J. TOTAL DIRECT AND INDIRECT COSTS (H+I)	$1,795,600
K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECTS SEE GPG II.D.7.j.)	$0
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)	$1,795,600
M. COST SHARING: PROPOSED LEVEL — AGREED LEVEL IF DIFFERENT $	$359,120

PI/PD NAME	DATE	FOR NSF USE ONLY		
Kim A. Stelson	3/12/13	INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME	DATE	Date Checked	Date Rate of Sheet	Initials-ORG
InstRepFullName				

*SIGNATURES REQUIRED ONLY FOR REVISED BUDGET (GPG III.B)

Instructions to NSF Submitters: The functions below work on this spreadsheet only.
These functions may not work properly if you add any columns.
These functions will add the necessary labels required for each row.

Notes: If you delete a row created with the b
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YEAR 10

FOR NSF USE ONLY

ORGANIZATION **Science Museum of Minnesota**	PROPOSAL NO.		DURATION (M Proposed / Granted
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR **J. Newlin**	AWARD NO.		

6/1/2015 - 5/30/2016

A. SENIOR PERSONNEL: PI/PD, Co-PI´S, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By Proposer	Funds Granted by NSF
0. First Name M Last Name Title					
1. J. S Newlin Director, Physical Sciences	0.00	0.00	0.00	$1,800	
(1) TOTAL SENIOR PERSONNEL (1-6)				$1,800	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (0) POST DOCTORAL ASSOCIATES	0.00	0.00	0.00	$0	
2. (0) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.00	0.00	0.00	$16,000	
3. (0) GRADUATE STUDENTS				$0	
4. (0) UNDERGRADUATE STUDENTS				$0	
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				$0	
6. (0) OTHER				$0	
TOTAL SALARIES AND WAGES (A+B)				$17,800	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				$7,654	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)				$25,454	
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000)					
equipment item 1 — $0					
Equipment Item — $0					
TOTAL EQUIPMENT				$0	
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				$0	
2. FOREIGN				$0	
F. PARTICIPANT SUPPORT COSTS					
1. STIPENDS — $0					
2. TRAVEL — $0					
3. SUBSISTENCE — $0					
4. OTHER — $0					
(0) TOTAL NUMBER OF PARTICIPANTS				$0	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				$2,799	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				$0	
3. CONSULTANT SERVICES				$0	
4. COMPUTERS SERVICES				$0	
5. SUBAWARDS				$0	
6. OTHER				$0	
TOTAL OTHER DIRECT COSTS				$2,799	
H. TOTAL DIRECT COSTS (A THROUGH G)				$28,253	
I. INDIRECT COSTS (SPECIFY RATE AND BASE)					
Name of indirect cost item: TDC less equipment — Amount: $28,252 — Rate: ###### 12148					
TOTAL INDIRECT COSTS				$12,148	
J. TOTAL DIRECT AND INDIRECT COSTS (H+I)				$40,401	
K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECTS SEE GPG II.D.7.j.)				$0	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				$40,401	
M. COST SHARING: PROPOSED LEVEL — AGREED LEVEL IF DIFFERENT $				$0	

PI/PD NAME J. Shipley Newlin Jr.	DATE 4/9/2012	**FOR NSF USE ONLY** INDIRECT COST RATE VERIFICATION	Initials-ORG
ORG. REP. NAME Paul Martin Jr	DATE 4/9/2012	Date Checked / Date Rate of Sheet	

*SIGNATURES REQUIRED ONLY FOR REVISED BUDGET (GPG III.B)

SUMMARY PROPOSAL BUDGET

6/1/12 - 5/31/13 **YEAR 10**

ORGANIZATION				**FOR NSF USE ONLY**	
Georgia Tech Research Corp			PROPOSAL NO.	DURATION (MONTHS)	
				Proposed	Granted
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR **Wayne Book**			AWARD NO.		

A. SENIOR PERSONNEL: PI/PD, Co.-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-mos. CAL	ACAD	SUMR	**Funds Requested by Proposer**	**Funds Granted By NSF (If Different)**
1. **Wayne Book**				**1,172**	
2. **Jun Ueda**				**643**	
3. **Scott Bair**				**4,850**	
4. **Ken Cunefare**				**1,310**	
5. **Richard Salant**				**1,657**	
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)					
7. (**0**) TOTAL SENIOR PERSONNEL (1-6)				**9,631**	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (**3**) POST DOCTORAL ASSOCIATES				**10,850**	
2. (**0**) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)					
3. (**7**) GRADUATE STUDENTS				**48,894**	
4. (**0**) UNDERGRADUATE STUDENTS					
5. (**0**) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)					
6. (**0**) OTHER					
TOTAL SALARIES AND WAGES (A + B)				**69,375**	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				**6,243**	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)				**75,618**	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TOTAL EQUIPMENT					
E. TRAVEL 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)				**7,376**	
2. FOREIGN					
F. PARTICIPANT SUPPORT COSTS					
1. STIPENDS **$5,445 ($5000 per student+545)**					
2. TRAVEL **$990 ($990 per student)**					
3. SUBSISTENCE **$1,120 ($1120 per student)**					
4. OTHER **$1,650 ($1650 per student)**					
( ) TOTAL PARTICIPANT COSTS				**9,205**	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				**9,985**	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION					
3. CONSULTANT SERVICES [maximum allowable rate @ http://www.nsf.gov/bfa/dias/policy/]					
4. COMPUTER SERVICES					
5. SUBAWARDS	Amount subject to Indirect:		**$0**		
6. OTHER Sum of **all other Direct Costs**, **NOT tuition** =	**Tuition =**			**29,216**	
TOTAL OTHER DIRECT COSTS				**39,202**	
H. TOTAL DIRECT COSTS (A THROUGH G)				**131,400**	
I. INDIRECT COSTS (F&A) (SPECIFY RATE AND BASE) 51.0% Modified Total Direct Costs					
TOTAL INDIRECT COSTS (F&A)	Base Amount:		**$92,979**	**48,780**	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				**180,180**	
K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECTS SEE GPG II.D.7.j.)					
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				**180,180**	
M. COST SHARING: PROPOSED LEVEL $ 130232	AGREED LEVEL IF DIFFERENT $			**42,977**	

PI/PD TYPED NAME & SIGNATURE*	DATE	**FOR NSF USE ONLY** INDIRECT COST RATE VERIFICATION		
ORG. REP. TYPED NAME & SIGNATURE*	DATE	Date Checked	Date of Rate Sheet	Initials-ORG

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YEAR 10

PROPOSAL BUDGET

ORGANIZATION North Carolina A & T State University	FOR NSF USE ONLY			
	PROPOSAL NO.	DURATION (MONTHS)		
		Proposed	Granted	
Dr. Eul Park	AWARD NO. 0540834			

A. SENIOR PERSONNEL: PI/PD, Co-PI'S, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By Proposer	Funds Granted by NSF
0. First Name M Last Name Title					
1. Eul Park	0.00	0.00	0.90	$13,059	
2. Steven Jiang	0.00	0.00	0.90	$10,852	
3.	0.00	0.00	0.00	$0	
4.	0.00	0.00	0.00	$0	
5.	0.00	0.00	0.00		
6.			0.00		
(2) TOTAL SENIOR PERSONNEL (1-6)				$23,911	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. ( ) POST DOCTORAL ASSOCIATES	0.00	9.00	0.00	$0	
2. ( ) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.00	0.00	0.00	$0	
3. 1) GRADUATE STUDENTS				$20,400	
4. 1) UNDERGRADUATE STUDENTS				$3,600	
5. 0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				$0	
6. ( ) OTHER				$0	
TOTAL SALARIES AND WAGES (A+B)				$47,911	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				$7,891	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)				$55,802	
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000)					
TOTAL EQUIPMENT				$0	
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				$4,000	
2. FOREIGN				$0	
F. PARTICIPANT SUPPORT COSTS					
1. STIPENDS $0					
2. TRAVEL $0					
3. SUBSISTENCE $0					
4. OTHER $0					
(0) TOTAL NUMBER OF PARTICIPANTS				$0	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				$1,492	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				$0	
3. CONSULTANT SERVICES				$0	
4. COMPUTERS SERVICES				$0	
5. SUBAWARDS				$0	
6. OTHER (tuition for graduate students)				$12,000	
TOTAL OTHER DIRECT COSTS				$0	
H. TOTAL DIRECT COSTS (A THROUGH G)				$73,294	
I. INDIRECT COSTS (SPECIFY RATE AND BASE) Name of Indirect cost item — Amount $24,518 — Rate 40.00% $0					
TOTAL INDIRECT COSTS				$24,518	
J. TOTAL DIRECT AND INDIRECT COSTS (H+I)				$97,812	
K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECTS SEE GPG II.D.7.J.)				$0	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				$97,812	
M. COST SHARING: PROPOSED LEVEL — AGREED LEVEL IF DIFFERENT $				$0	

PI/PD NAME Eul Park	DATE	FOR NSF USE ONLY INDIRECT COST RATE VERIFICATION

Celestine Ntuen, PhD. 4/10/12

Interim Vice Chancellor for Research and Economic Development

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SUMMARY PROPOSAL BUDGET – YEAR 10

FOR NSF USE ONLY

ORGANIZATION The Board of Trustees of the University of Illinois	PROPOSAL NO.	DURATION (MONTHS) Proposed	Granted
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR Andrew Alleyne	AWARD NO.		

A. SENIOR PERSONNEL: PI/PD, Co-PIs, Faculty and Other Senior Associates List each separately with name and title. (A.7. Show number in brackets)	NSF-Funded Person-months CAL	ACAD	SUMR	Funds Requested By Proposer	Funds Granted by NSF (If Different)
1. Alleyne - PI	0.0	0.0	0.00	0.00	$
2. Hsiao-Wecksler			0.00	0.00	
3. King			0.00	0.00	
4. Ewoldt			0.00	0.00	
5.					
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)	0.0	0.0	0.0		
7. (4) TOTAL SENIOR PERSONNEL (1-6)	0.0	0.0	0.0	0.00	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. ( ) POSTDOCTORAL ASSOCIATES				0	
2. ( ) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)				0	
3. (2) GRADUATE STUDENTS				62,218	
4. () UNDERGRADUATE STUDENTS				0	
5. ( ) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				0	
6. ( ) OTHER				0	
TOTAL SALARIES AND WAGES (A + B)				62,218	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				3,889	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				66,107	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TOTAL EQUIPMENT				0	
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				0	
2. FOREIGN					
F. PARTICIPANT SUPPORT 1. STIPENDS $ 0 2. TRAVEL 0 3. SUBSISTENCE 0 4. OTHER 0					
TOTAL NUMBER OF PARTICIPANTS () TOTAL PARTICIPANT COSTS				0	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				2,123	
2. PUBLICATION/DOCUMENTATION/DISSEMINATION				0	
3. CONSULTANT SERVICES				0	
4. COMPUTER SERVICES				0	
5. SUBAWARDS				0	
6. OTHER Tuition Remission line B.3. x 37.0%				23,021	
TOTAL OTHER DIRECT COSTS				25,144	
H. TOTAL DIRECT COSTS (A THROUGH G)				91,251	
I. INDIRECT COSTS (F&A) (SPECIFY RATE AND BASE) 53% of MTDC					
TOTAL INDIRECT COSTS (F&A)				36,162	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				127,413	
K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECT SEE GPG II.D.7.j.)				0	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				127,413	$

M. COST SHARING: PROPOSED LEVEL $36,302	AGREED LEVEL IF DIFFERENT: $			
PI/PD TYPED NAME AND SIGNATURE* Andrew Alleyne	DATE 3/14/12	FOR NSF USE ONLY INDIRECT COST RATE VERIFICATION		
ORG. REP. TYPED NAME & SIGNATURE*	DATE	Date Checked	Date of Rate Sheet	Initials-ORG

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*SIGNATURES REQUIRED ONLY FOR REVISED BUDGET (GPG III.C)

SUMMARY PROPOSAL BUDGET

ORGANIZATION Vanderbilt University Year 10 Budget	FOR NSF USE ONLY PROPOSAL NO.	DURATION (MONTHS)			
		Proposed	Granted		
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR Michael Goldfarb	AWARD NO.				

A. SENIOR PERSONNEL: PI/PD, Co-PIs, Faculty and Other Senior Associates List each separately with name and title. (A.7. Show number in brackets)	NSF-Funded Person-months CAL	ACAD	SUMR	Funds Requested By Proposer	Funds Granted by NSF (If Different)
1. Eric J. Barth, Associate Professor			1.0	$	$6,132
2. Robert J. Webster, III, Assistant Professor			1.0		3,427
3.					
4.					
5.					
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)					
7. (2) TOTAL SENIOR PERSONNEL (1-6)					9,559
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. ( ) POSTDOCTORAL ASSOCIATES					
2. ( ) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)					
3. (1) GRADUATE STUDENTS					26,400
4. ( ) UNDERGRADUATE STUDENTS					
5. ( ) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)					
6. ( ) OTHER					
TOTAL SALARIES AND WAGES (A + B)					35,959
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)					1,969
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)					37,928
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TOTAL EQUIPMENT					
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)					5,000
2. FOREIGN					
F. PARTICIPANT SUPPORT (2 CCEFP REU's and 2 Teachers/RET's) 1. STIPENDS $ 20,000 ($4000 per student, $6,000 per teacher) 2. TRAVEL 5,000 ($1500 per student, $1,000 per teacher) 3. SUBSISTENCE 2,000 ($1,000 per student) 4. OTHER 7,000 ($2,000 per student housing costs @ $30/day, $1,500 supplies & equip & Other costs per year)					
TOTAL NUMBER OF PARTICIPANTS (2 students, 2 teachers) TOTAL PARTICIPANT COSTS					34,000
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES					7,801
2. PUBLICATION/DOCUMENTATION/DISSEMINATION					1,000
3. CONSULTANT SERVICES					
4. COMPUTER SERVICES					
5. SUBAWARDS					
6. OTHER					
TOTAL OTHER DIRECT COSTS					8,801
H. TOTAL DIRECT COSTS (A THROUGH G)					85,729
I. INDIRECT COSTS (F&A) (SPECIFY RATE AND BASE) 25% Indirect Cost on REU/RET costs ($20,000 Stipends Base) 53.5% Indirect Cost on CCEFP Project costs ($51,729 MTDC Base)					
TOTAL INDIRECT COSTS (F&A)					32,675
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)					118,404
K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECT SEE GPG II.D.7.j.)					
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				$	$118,404

M. COST SHARING: PROPOSED LEVEL $	AGREED LEVEL IF DIFFERENT: $28,242			
PI/PD TYPED NAME AND SIGNATURE*	DATE	FOR NSF USE ONLY INDIRECT COST RATE VERIFICATION		
ORG. REP. TYPED NAME & SIGNATURE*	DATE	Date Checked	Date of Rate Sheet	Initials-ORG

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*SIGNATURES REQUIRED ONLY FOR REVISED BUDGET (GPG III.C)

2015-2016 Year 10 PROPOSAL BUDGET

ORGANIZATION MSOE			PROPOSAL NO	DURATION (MONTHS) Proposed
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR NSF Funds			AWARD NO.	
A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with name and title. (A.7. Show numbers in brackets)	Funded Person-months			
	CAL	ACAD	SUMR	
1. Professional Staff	0.00	0.00	0.00	7,306
2.				0
3.				0
4.				0
5.				0
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)	-	-	-	0
7. ( ) TOTAL SENIOR PERSONNEL (1-6)	-	-	-	7,306
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)				
1. ( ) POST DOCTORAL ASSOCIATES				0
2. ( ) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)				0
3. ( ) GRADUATE STUDENTS				12,000
4. ( ) UNDERGRADUATE STUDENTS				7,500
5. ( ) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				0
6. ( ) OTHER				0
TOTAL SALARIES AND WAGES (A+B)				26,806
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				4,727
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)				31,533
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.) xx $0				
TOTAL EQUIPMENT				0
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				5,000
2. FOREIGN				0
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ 10,000 2. TRAVEL 2,000 3. SUBSISTENCE 7,800 4. OTHER 9,600				
TOTAL NUMBER OF PARTICIPANTS 0 TOTAL PARTICIPANT COSTS				29,400
G. OTHER DIRECT COSTS				
1. MATERIALS AND SUPPLIES				18,999
2. PUBLICATION/DOCUMENTATION/DISSEMINATION				0
3. CONSULTANT SERVICES				0
4. COMPUTER SERVICES				0
5. SUBAWARDS				0
6. OTHER				12,000
TOTAL OTHER DIRECT COSTS				30,999
H. TOTAL DIRECT COSTS (A THROUGH G)				96,932
I. INDIRECT COSTS (F&A) (SPECIFY RATE AND BASE) 40% on salaries & fringe base $31,533 25% on REU stipends base = $10,000				
TOTAL INDIRECT COSTS (F&A)				15,113
J. TOTAL DIRECT AND INDIRECT COSTS (H+I)				112,045
K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECTS SEE GPG II.D.7.j.)				0
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				112,045
M. COST SHARING: PROPOSED LEVEL $ 0	AGREED LEVEL IF DIFFERENT $			
PI/PD TYPED NAME & SIGNATURE* Vito Gervasi	DATE 2/26/13	INDIRECT COST RATE VERIFICATION		
ORG. REP. TYPED NAME & SIGNATURE* Tom Bray	DATE 2/26/2013	Date Checked	Date of Rate Sheet	

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SUMMARY PROPOSAL BUDGET

ORGANIZATION Purdue University (YEAR 10)	FOR NSF USE ONLY PROPOSAL NO.	DURATION (MONTHS)		
		Proposed	Granted	
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR Monika Ivantysynova	AWARD NO.			

A. SENIOR PERSONNEL: PI/PD, Co-PIs, Faculty and Other Senior Associates List each separately with name and title. (A.7. Show number in brackets)	NSF-Funded Person-months CAL	ACAD	SUMR	Funds Requested By Proposer	Funds Granted by NSF (If Different)
1. Monika Ivantysynova, Professor			1.5	26,628	$
2. John Lumkes, Associate Professor			1.0	11,546	
3. Andrea Vacca, Assistant Professor			1.0	10,622	
4.					
5.					
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)					
7. ( ) TOTAL SENIOR PERSONNEL (1-6)					
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. () POSTDOCTORAL ASSOCIATES					
2. ( ) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)					
3. (1) GRADUATE STUDENTS				26,736	
4. ( ) UNDERGRADUATE STUDENTS					
5. ( ) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)					
6. ( ) OTHER					
TOTAL SALARIES AND WAGES (A + B)					
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				15,762	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				91,294	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TOTAL EQUIPMENT					
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				0	
2. FOREIGN				0	
F. PARTICIPANT SUPPORT 1. STIPENDS $ 2. TRAVEL 3. SUBSISTENCE 4. OTHER					
TOTAL NUMBER OF PARTICIPANTS ( ) TOTAL PARTICIPANT COSTS				0	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				39,309	
2. PUBLICATION/DOCUMENTATION/DISSEMINATION					
3. CONSULTANT SERVICES					
4. COMPUTER SERVICES					
5. SUBAWARDS					
6. OTHER Grad Fee Remission				11,899	
TOTAL OTHER DIRECT COSTS					
H. TOTAL DIRECT COSTS (A THROUGH G)				142,502	
I. INDIRECT COSTS (F&A) (SPECIFY RATE AND BASE) 52.5% of MDTC (Base used $130,603)				68,566	
TOTAL INDIRECT COSTS (F&A)				68,566	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				211,068	
K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECT SEE GPG II.D.7.j.)					
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				$	$

M. COST SHARING: PROPOSED LEVEL $50,342	AGREED LEVEL IF DIFFERENT: $			
PI/PD TYPED NAME AND SIGNATURE*	DATE	FOR NSF USE ONLY INDIRECT COST RATE VERIFICATION		
ORG. REP. TYPED NAME & SIGNATURE* Amy J. Wright-Signature on Cumulative Budget	DATE 4/6/12	Date Checked	Date of Rate Sheet	Initials-ORG

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*SIGNATURES REQUIRED ONLY FOR REVISED BUDGET (GPG III.C)

CCEFP/QED Year 10	CCEFP Budget: June-May, 2015-2016		
	CAL person months		
A. Senior Personnel			
Gary Lichtenstein	0.10	$10,000.00	
Maggie Miller	0.02	$1,500.00	
Others			
7. TOTAL SENIOR PERSONNEL		$11,500.00	
B. Other Personnel			
Post Doc			
Other Professionals (e.g. computer programmer)			
Clerical (if charged directly)			
Other			
TOTAL SALARIES & WAGES		$11,500.00	
Fringe Benefit (if charged as direct cost)		$0.00	
TOTAL SALARIES & WAGES + Fringe (A+B+C)		$11,500.00	
D. Total Equipment		$0.00	
a.			
b.			
c.			
E. Travel			
E. Travel-- Domestic (incl. Canada, Mex, U.S. Possessions)		$1,500.00	
E. Travel--Foreign			
F. Participant Support (Grad Students, those being trained)		$0.00	
Travel	0		
Stipends			
Subsistence			
Other			
G. Other Direct Costs		$9,445.00	
1. MATERIALS AND SUPPLIES	500		
2. PUBLICATION/DOCUMENTATION/DISSEMINATION			
3. CONSULTANT SERVICES	8945		
4. COMPUTER SERVICES			
5. SUBAWARDS			
6. OTHER			
H. TOTAL DIRECT COSTS (A-G)		$22,445.00	
I. Indirect Coss		$0.00	
RATE:			
J. Total Direct & Indirect (sum H+I)		$22,445.00	
K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECT SEE GPG II.D.7.j.)		$0.00	
L. AMOUNT OF THIS REQUEST (J MINUS K)		**$22,445.00**	

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APPENDIX I

Data Tables and Figures

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Table 1: Quantifiable Outputs							
Outputs	Early Cumulative Total [1]	Feb-01-2010 - Jan-31-2011	Feb-01-2011 - Jan-31-2012	Feb-01-2012 - Jan-31-2013	Feb-01-2013 - Jan-31-2014	Feb-01-2014 - Jan-31-2015	All Years
Publications Resulting From Core Funding							
In Peer-Reviewed Technical Journals	39	22	12	22	24	17	136
In Peer-Reviewed Conference Proceedings	127	59	52	32	23	37	330
In Trade Journals	26	0	2	0	3	1	32
With Multiple Authors:	183	76	51	54	50	55	469
Co-authored With ERC Students	134	50	51	40	35	35	345
Co-authored With Industry	6	3	2	2	0	4	17
With Authors From Multiple Engineering Disciplines	16	3	6	7	4	9	45
With Authors From Both Engineering and Non-Engineering Fields	18	2	6	2	7	5	40
With Authors From Multiple Institutions	18	10	9	0	8	8	53
Publications Resulting From Associated Projects in the Strategic Plan							
In Peer-Reviewed Technical Journals	30	6	5	7	8	14	70
In Peer-Reviewed Conference Proceedings	60	7	10	13	17	22	129
Publications Resulting From Sponsored Projects							
In Peer Reviewed Technical Journals	6	0	0	0	2	0	8
In Peer-Reviewed Conference Proceedings	24	0	0	0	3	1	28
Participating Organizations							
Industrial Practitioner Members	226	54	48	41	46	0	415
Innovation Partners	0	0	1	1	1	0	3
Funders of Sponsored Projects	0	0	0	0	1	1	2
Funders of Associated Projects	19	15	8	8	10	10	70
Contributing Organizations	2	5	9	6	4	12	38
ERC Technology Transfer							
Inventions Disclosed (by researchers or tech transfer office)	24	7	12	3	6	4	56
Total Patent Applications Filed	16	4	4	6	6	5	41
Provisional Patent Applications Filed [1]	N/A	N/A	N/A	3	5	4	12
Full Patent Applications Filed [1]	N/A	N/A	N/A	3	1	1	5
Patent Awarded	1	1	2	1	1	1	7
Licenses Issued	0	2	0	2	1	0	5
Spin-off Companies Started	1	0	0	1	1	1	4
Estimated Number of Spin-off Company Employees	0	0	0	1	1	2	4
Building Codes Impacts	0	0	0	0	0	0	0
Technology Standards Impacts	4	4	1	1	1	0	11
New Surgical and Other Medical Procedures Adopted	0	0	0	0	0	0	0
Degrees to ERC Students							
Bachelor's Degrees Granted	76	18	10	10	7	12	133
Master's Degrees Granted	56	14	10	10	7	12	109
Doctoral Degrees Granted	13	9	6	12	11	12	63
Job Sector of ERC Graduates							
Undergraduates Hired by:							
Industry:	N/A	N/A	4	0	1	2	7
ERC Member Firms	N/A	N/A	0	0	1	0	1
Other U.S. Firms	N/A	N/A	4	0	0	2	6
Other Foreign Firms	N/A	N/A	0	0	0	0	0
Government	N/A	N/A	0	0	0	1	1
Academic Institutions	N/A	N/A	4	3	0	0	7
Other	N/A	N/A	0	1	0	0	1
Undecided/Still Looking/Unknown	N/A	N/A	2	6	6	9	23
Undergraduate ERC Graduates Total	0	0	10	10	7	12	39
Master's Graduates Hired by:							
Industry:	N/A	N/A	8	1	0	1	10
ERC Member Firms	N/A	N/A	2	1	0	0	3
Other U.S. Firms	N/A	N/A	6	0	0	1	7
Other Foreign Firms	N/A	N/A	0	0	0	0	0
Government	N/A	N/A	0	0	0	2	2
Academic Institutions	N/A	N/A	2	0	0	0	2
Other	N/A	N/A	0	2	2	1	5
Undecided/Still Looking/Unknown	N/A	N/A	0	7	5	8	20
Master's ERC Graduates Total	0	0	10	10	7	12	39
Ph.D.s Hired by:							
Industry:	N/A	N/A	2	0	1	10	13
ERC Member Firms	N/A	N/A	1	0	1	0	2
Other U.S. Firms	N/A	N/A	1	0	0	10	11
Other Foreign Firms	N/A	N/A	0	0	0	0	0
Government	N/A	N/A	0	0	1	0	1
Academic Institutions	N/A	N/A	3	0	0	0	3
Other	N/A	N/A	0	4	1	0	5
Undecided/Still Looking/Unknown	N/A	N/A	1	8	8	2	19
Ph.D. ERC Graduates Total	0	0	6	12	11	12	41
ERC Influence on Curriculum							
New Courses Based on ERC Research That Have Been Approved by the Curriculum Committee and Are Currently Offered [2]	6	8	2	0	4	2	22
Currently Offered, ongoing Courses With ERC Content	27	12	19	28	29	31	N/A
New Textbooks Based on ERC Research	3	1	0	0	0	0	4
New Textbook Chapter Based on ERC Research	1	0	0	0	0	1	2
Free-Standing Course Modules or Instructional CDs	0	0	3	5	2	7	17
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	0	1710	1700	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]	40	9	83	85	62	22	301
Number of Participants That Attended Events	86	135	2322	5189	500	1000	9232
Innovation-focused Workshops, Short courses, Webinars, and Seminars	N/A	5	39	14	1	0	59
Number of Participants That Attended Events	N/A	25	1172	1120	25	0	2342

Table 1: Quantifiable Outputs							
Outputs	Early Cumulative Total [1]	Feb-01-2010 - Jan-31-2011	Feb-01-2011 - Jan-31-2012	Feb-01-2012 - Jan-31-2013	Feb-01-2013 - Jan-31-2014	Feb-01-2014 - Jan-31-2015	All Years
Seminars, Colloquia, Invited Talks, Etc.	92	35	18	7	10	89	251
ERC Sponsored Educational Outreach Events for K-12 Students	14	28	15	19	25	12	113
Number of Students That Attended Events	4365	3251	10926	11000	40513	34023	104078
Number of Teachers That Attended Events	26	30	100	500	5141	4317	10114
ERC Sponsored Educational Outreach Events for Community Colleges	8	9	9	4	1	0	31
Number of Community College Students That Attended Events	244	125	5000	250	10	0	5629
Number of Community College Faculty That Attended Events	24	9	50	4	0	0	87
ERC Sponsored Educational Outreach Events for Non-ERC Undergraduate Students	0	N/A	N/A	N/A	15	0	15
Number of Non-ERC Undergraduate Students That Attended Events	0	N/A	N/A	N/A	25	0	25
Number of Undergraduate Faculty That Attended Events	0	N/A	N/A	N/A	0	0	0
Personnel Exchanges							
Student Internships in Industry	27	14	12	9	5	9	76
Faculty Working at Member Firm	1	1	1	0	0	0	3
Member Firm Personnel Working at ERC	10	0	0	0	1	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: 2014 Average Metrics Benchmarked Against All Active ERCs and the Center's Tech Sector					
Metric	Average All Active ERCs FY 2014	Average Advanced Manufacturing Sector FY 2014	Average Class of 2006 FY 2014	Minnesota Twin Cities-CCEFP Total	Minnesota Twin Cities-CCEFP Total
	(17 ERCs)	(5 ERCs)	(5 ERCs)	FY 2014	FY 2015
Organizations Within Non-Industry Sectors	**23**	**14**	**26**	**4**	**6**
Organizations Within Industry Sectors	**25**	**33**	**37**	**58**	**17**
Small	44%	46%	54%	45%	59%
Medium	8%	5%	6%	7%	0%
Large	48%	48%	41%	48%	41%
Industrial/Practitioner Member Firms	**24**	**31**	**36**	**46**	**0**
Innovation Partners	**9**	**5**	**10**	**1**	**0**
Funders of Sponsored Projects	**1**	**1**	**0**	**1**	**1**
Funders of Associated Projects	**13**	**10**	**16**	**10**	**10**
Contributing Organizations	**2**	**1**	**1**	**4**	**12**
Total Number of Organizations	**48**	**48**	**63**	**62**	**23**
Total Membership Fees Received	**$319,207**	**$531,743**	**$434,315**	**$730,717**	**$0**
Direct Sources of Support [1]	**$5,782,442**	**$5,930,069**	**$5,917,849**	**$6,298,153**	**$4,304,616**
NSF	72%	72%	72%	70%	62%
Other Federal	0%	0%	0%	0%	0%
State Government	1%	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)	8%	13%	11%	17%	3%
University (U.S. and Foreign)	16%	14%	14%	13%	12%
Other	3%	1%	2%	0%	22%
Associated Project Support	**$4,221,807**	**$4,686,861**	**$5,816,965**	**$2,016,854**	**$2,425,839**
ERC Personnel and Educational Participants	**6,875**	**10,291**	**11,130**	**45,945**	**38,576**
Leadership Team [2]	15	14	13	11	9
Faculty [3]	44	35	43	32	37
Graduate Students	95	93	91	89	92
Undergraduate Students	59	78	75	112	50
REU Students	17	20	29	23	25
Community College RET	0	0	0	0	2
K-12 Teachers (RET and non-RET)	14	26	12	14	21
K-12 Students (Young Scholars)	18	27	33	0	0
Faculty/Teachers That Attended ERC Sponsored Educational Outreach Events for K-12 Students [4]	443	1,078	1,117	5,141	4,317
Students That Attended ERC Sponsored Educational Outreach Events for K-12 Students [4]	5,967	8,844	9,576	40,513	34,023
Faculty That Attended ERC Sponsored Educational Outreach Events for Community Colleges [4]	15	26	3	0	0
Students That Attended ERC Sponsored Educational Outreach Events for Community Colleges [4]	187	52	139	10	0
% Women [5]	30%	32%	32%	22%	20%
% Underrepresented Racial Minorities [6]	12%	9%	11%	24%	9%
% Hispanic [6]	10%	11%	12%	2%	4%
Publications	**Average**	**Average**	**Average**	**Total**	**Total**
In Peer-Reviewed Technical Journals	37	39	50	24	17
In Peer-Reviewed Conference Proceedings	25	24	37	23	37
Multiple Authors: Co-Authored With ERC Students	44	42	56	35	35
Multiple Authors: Co-Authored With Industry	6	2	5	0	4
Intellectual Property	**Average**	**Average**	**Average**	**Total**	**Total**
Invention Disclosures	7	5	5	6	4
Patent Applications (Provisional and Full)	7	8	7	6	5
Patents Awarded	1	0	0	1	1
Licenses (patents, software)	1	2	0	1	0
Education and Outreach Outputs	**Average**	**Average**	**Average**	**Total**	**Total**
New Courses Developed	3	2	3	4	2
Currently Offered, Ongoing Courses With ERC Content	19	18	28	29	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.

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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	$577,117	$0	$1,849,340	$2,426,457	$2,426,725
2: Compactness	$422,106	$0	$0	$422,106	$422,106
3: Effectiveness	$333,730	$0	$286,540	$620,270	$620,002
Test Beds	$480,000	$0	$289,959	$769,959	$480,000

Table 2: Estimated Budgets by Research Thrust [1]

Thrust	Project Name	Organizational Sponsor	Project Leader	Investigators	Current Year Budget	Estimated Next Year Budget
	1A.2: Control and Prognostics for Hybrid Displacement Control Systems (Center Controlled Project)	NSF ERC Program	Monika M. Ivantysynova (Purdue University)		$6,250	
	1B.1: Next Steps towards Virtual Prototyping of Pumps and Motors (Center Controlled Project)	NSF ERC Program	Monika M. Ivantysynova (Purdue University)		$75,000	
	1E.1: Helical Ring On/Off Valve Based 4-quadrant Virtually Variable Displacement Pump/Motor (Center Controlled Project)	NSF ERC Program	Perry Y. Li (University of Minnesota)	Thomas R. Chase (University of Minnesota)	$7,177	
	1E.3: Actively Controlled Digital Pump Motor (Center Controlled Project)	NSF ERC Program	John H. Lumkes (Purdue University)	Monika M. Ivantysynova (Purdue University)	$63,365	
	1E.4: Piston-by-piston control of pumps and motors using mechanical methods (Center Controlled Project)	NSF ERC Program	Perry Y. Li (University of Minnesota)	Thomas R. Chase (University of Minnesota)	$25,000	
	1E.5: System Configuration & Control Using Hydraulic Transformers (Center Controlled Project)	NSF ERC Program	Perry Y. Li (University of Minnesota)		$37,500	
	1E.6: High Performance Valves Enabled by Kinetic Energy (Center Controlled Project)	NSF ERC Program	John H. Lumkes (Purdue University)		$63,365	
	1F.1: Variable Displacement External Gear Machine (Center Controlled Project)	NSF ERC Program	Andrea Vacca (Purdue University)		$63,365	
	1G.1: Energy Efficient Fluids (Center Controlled Project)	NSF ERC Program	Paul W. Michael (Milwaukee School of Engineering-Fluid Power Institute)		$63,365	
	1G.3: Rheological Design for Efficient Fluid Power (Center Controlled Project)	NSF ERC Program	Randy H. Ewoldt (University of Illinois at Urbana-Champaign-Department of Mechanical Science and Engineering)	James T. Allison (University of Illinois at Urbana-Champaign-Industrial and Enterprise Systems Engineering)	$63,365	
	1J.1: Hydraulic Transmissions for Wind Power (Center Controlled Project)	NSF ERC Program	Kim A. Stelson (University of Minnesota-Mechanical Engineering)	Brad Bohlmann (University of Minnesota-Mechanical Engineering)	$46,000	
	1J.2: A Novel Pressure-Controlled Hydro-Mechanical Transmission (Center Controlled Project)	NSF ERC Program	Kim A. Stelson (University of Minnesota-Mechanical Engineering)		$63,365	
	A Characterization of the Pressure-Viscosity and Compressibility Response of Five Oils for a Wide Range of Temperatures (Associated Project)	Deere and Company	Scott S. Bair (Georgia Institute of Technology-School of Mechanical Engineering)		$15,500	
	Adjustable Linkage Pump (Associated Project)	Cat Pumps	James D. Van de Ven (University of Minnesota-Mechanical Engineering)	Shawn Wilhelm (University of Minnesota-Mechanical Engineering)	$116,923	
	Advanced Hydraulic Systems for Next Generation of Skid Steer Loaders (Associated Project)	Confidential Organization (optional use for associated or sponsored projects only)	Monika M. Ivantysynova (Purdue University)		$356,547	
	Development of a Gasoline Engine Driven Ultra High Pressure Hydraulic Pump (Associated Project)	Dae Jin Hydraulics - TECPOS	Andrea Vacca (Purdue University)		$50,000	

Table 2: Estimated Budgets by Research Thrust [1]						
Thrust	**Project Name**	**Organizational Sponsor**	**Project Leader**	**Investigators**	**Current Year Budget**	**Estimated Next Year Budget**
	EFRI-RESTOR: Novel Compressed Air Approach for Off-shore Wind Energy Storage (Associated Project - NSF)		Perry Y. Li (University of Minnesota)	Terrence W. Simon (University of Minnesota) James D. Van de Ven (University of Minnesota-Mechanical Engineering)	$85,149	
	Energy Efficient Fluids (Associated Project)	Confidential Organization (optional use for associated or sponsored projects only)	Paul W. Michael (Milwaukee School of Engineering Fluid Power Institute)		$196,600	
	Energy Saving Hydraulic System Architecture Utilizing Displacement Control (Associated Project)	Confidential Organization (optional use for associated or sponsored projects only)	Monika M. Ivantysynova (Purdue University)		$82,685	
	Evaluation And Design Improvements For A Hydraulic Pump (Associated Project)	Confidential Organization (optional use for associated or sponsored projects only)	Monika M. Ivantysynova (Purdue University)		$96,428	
	Evaluation and Design Study of the Piston/Cylinder Interface of a Swash Plate Type Hydraulic Motor (Associated Project)	Confidential Organization (optional use for associated or sponsored projects only)	Monika M. Ivantysynova (Purdue University)		$135,863	
	Investigation of Alternative Cylinder Block Materials using Fluid Structure Interaction Modeling (FSTI). (Associated Project)	Confidential Organization (optional use for associated or sponsored projects only)	Monika M. Ivantysynova (Purdue University)		$217,957	
	Modeling and analysis of swash plate type piston motor (Associated Project)	Confidential Organization (optional use for associated or sponsored projects only)	Monika M. Ivantysynova (Purdue University)		$64,053	
	Modeling of lubricating features of external gear machines and development of quieter solutions (Associated Project)	Casappa S.p.A.	Andrea Vacca (Purdue University)		$13,834	
	Modelling and analysis of swash plate axial piston pump (Associated Project)	Confidential Organization (optional use for associated or sponsored projects only)	Monika M. Ivantysynova (Purdue University)		$81,636	
	MRI: Development of a Controlled-Trajectory Rapid Compression and Expansion Machine (Associated Project - NSF)		Zongxuan Sun (University of Minnesota)	David B. Kittelson (University of Minnesota-Mechanical Engineering) Kim A. Stelson (University of Minnesota-Mechanical Engineering)	$209,585	
	New Geometries for External Gear Machines towards the reduction of Noise Emissions (Associated Project)	Casappa S.p.A.	Andrea Vacca (Purdue University)		$96,670	
	Numerical Modeling of GEROTORs unit (Associated Project)	Thomas Magnete GmbH	Andrea Vacca (Purdue University)		$29,910	
				Translational Research Projects Within Thrust	**$0**	
				Subtotal (all projects) for Thrust	**$2,426,457**	**$2,426,725**
				Total Number of Undergraduate Students in Thrust	**2**	
				Total Number of Graduate Students (M.S. and Ph.D.) in Thrust	**33**	
				Total Number of Postdocs in Thrust	**2**	
				Total Number of Personnel in Thrust	**52**	
2: Compactness Thrust Leader: Andrew G. Alleyne (University of Illinois at Urbana-Champaign)	2B.2: Miniature HCCI Free Piston Engine Compressor (Center Controlled Project)	NSF ERC Program	William Durfee (University of Minnesota-Mechanical Engineering)	David B. Kittelson (University of Minnesota-Mechanical Engineering)	$25,000	$422,106
	2B.3: Free Piston Engine Hydraulic Pump (Center Controlled Project)	NSF ERC Program	Zongxuan Sun (University of Minnesota)		$63,365	
	2B.4: Controlled Stirling Thermocompressors (Center Controlled Project)	NSF ERC Program	Eric J. Barth (Vanderbilt University)		$63,365	
	2C.3: Flywheel Accumulator for Compact Energy Storage (Center Controlled Project)	NSF ERC Program	James D. Van de Ven (University of Minnesota-Mechanical Engineering)		$43,646	
	2F.1: Soft Pneumatic Actuator for Arm Orthosis (Center Controlled Project)	NSF ERC Program	Elizabeth T. Hsiao-Wecksler (University of Illinois at Urbana-Champaign-Department of Mechanical Science & Engineering)	Placid Ferreira (University of Illinois at Urbana-Champaign) Girish Krishnan (University of Illinois at Urbana-Champaign) Brooke Slavens (University of Wisconsin – Milwaukee)	$63,365	

Table 2: Estimated Budgets by Research Thrust [1]

Thrust	Project Name	Organizational Sponsor	Project Leader	Investigators	Current Year Budget	Estimated Next Year Budget
				Sameh Tawfick (University of Illinois at Urbana-Champaign-Mechanical Science and Engineering)		
	2F: MEMS Proportional Pneumatic Valve (Center Controlled Project)	NSF ERC Program	Thomas R. Chase (University of Minnesota)		$63,365	
	2G: Fluid Powered Surgery and Rehabilitation via Compact, Integrated Systems (Center Controlled Project)	NSF ERC Program	Robert J. Webster (Vanderbilt University)	Eric J. Barth (Vanderbilt University) Vito R. Gervasi (Milwaukee School of Engineering) Jun Ueda (Georgia Institute of Technology)	$100,000	
Translational Research Projects Within Thrust					$0	
Subtotal (all projects) for Thrust					$422,106	$422,106
Total Number of Undergraduate Students in Thrust					2	
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					34	
3: Effectiveness Thrust Leader: Wayne J. Book (Georgia Institute of Technology)	3A.1: Operator Interface Design Principles for Hydraulics (Center Controlled Project)	NSF ERC Program	Wayne J. Book (Georgia Institute of Technology)	James D. Huggins (Georgia Institute of Technology-Mechanical Engineering) Steven X. Jiang (North Carolina Agriculture and Technical State University-Industrial and Systems Engineering) Eui H. Park (North Carolina Agriculture and Technical State University)	$63,365	$620,002
	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)	Zongliang Jiang (North Carolina Agriculture and Technical State University) Eui H. Park (North Carolina Agriculture and Technical State University)	$100,000	
	3B.3: Active Vibration Damping of Mobile Hydraulic Machines (Center Controlled Project)	NSF ERC Program	Andrea Vacca (Purdue University)		$25,000	
	3D.1: Leakage/Seal Friction Reduction in Fluid Power Systems (Center Controlled Project)	NSF ERC Program	Richard F. Salant (Georgia Institute of Technology)		$32,000	
	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)		$63,365	
	3E.1: Pressure Ripple Energy Harvester (Center Controlled Project)	NSF ERC Program	Kenneth A. Cunefare (Georgia Institute of Technology)		$50,000	
	High Pressure Compliant Material Development (Associated Project)	Danfoss	Kenneth A. Cunefare (Georgia Institute of Technology)		$84,830	
	Model Predictive Control of Pneumatic Actuators (Associated Project)	National Defense Science and Engineering Fellowship Grant (NDSEG)	Wayne J. Book (Georgia Institute of Technology)		$15,429	
	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)	Monika M. Ivantysynova (Purdue University)	Andrea Vacca (Purdue University)	$127,660	
	Rheology Modeling for Mechanical Face Seals (Associated Project)	John Crane	Scott S. Bair (Georgia Institute of Technology-School of Mechanical Engineering)		$4,960	
	Self-powered leak detection system for pipeline monitoring (Associated Project)	Veraphotonics, Mistras	Kenneth A. Cunefare (Georgia Institute of Technology)		$31,161	
	Static Dissipating Hydraulic Filters (Associated Project)	Confidential Organization (optional use for associated or sponsored projects only)	Paul W. Michael (Milwaukee School of Engineering Fluid Power Institute)		$22,500	
Translational Research Projects Within Thrust					$0	
Subtotal (all projects) for Thrust					$620,270	$620,002
Total Number of Undergraduate Students in Thrust					7	
Total Number of Graduate Students (M.S. and Ph.D.) in Thrust					14	
Total Number of Postdocs in Thrust					0	
Total Number of Personnel in Thrust					32	

Table 2: Estimated Budgets by Research Thrust [1]

Thrust	Project Name	Organizational Sponsor	Project Leader	Investigators	Current Year Budget	Estimated Next Year Budget
Test Beds Thrust Leader: Kim A. Stelson (University of Minnesota-Mechanical Engineering)	Test bed 1: Heavy Mobile Equipment - High Efficiency Excavator (Center Controlled Project)	NSF ERC Program	Monika M. Ivantysynova (Purdue University)		$120,000	$480,000
	Test bed 3: Highway Vehicles - Hyrdraulic Hybrid Passenger Vehicle (Center Controlled Project)	NSF ERC Program	Perry Y. Li (University of Minnesota)		$120,000	
	Test Bed 4: Patient Transfer Device (Center Controlled Project)	NSF ERC Program	Wayne J. Book (Georgia Institute of Technology)		$120,000	
	Test bed 6: Human Assist Devices -- Fluid Power Ankle-Foot Orthosis (Center Controlled Project)	NSF ERC Program	Elizabeth T. Hsiao-Wecksler (University of Illinois at Urbana-Champaign-Department of Mechanical Science & Engineering)	William Durfee (University of Minnesota-Mechanical Engineering) Geza F. Kogler (Georgia Institute of Technology)	$120,000	
	Controllable Hydraulic Ankle Prosthesis (Associated Project)	Minneapolis Veterans Administration Medical Center	William Durfee (University of Minnesota-Mechanical Engineering)		$3,600	
	CPS: Synergy: Integrated Modeling, Analysis and Synthesis of Miniature Medical Devices (Associated Project - NSF)		Pietro Valdastri (Vanderbilt University-Mechanical Engineering)	Robert J. Webster (Vanderbilt University)	$255,319	
	Modulation of Anticipatory Postural Adjustments in Parkinson's disease Using a Portable Powered Ankle-Foot Orthosis (Associated Project - NSF)		Elizabeth T. Hsiao-Wecksler (University of Illinois at Urbana-Champaign-Department of Mechanical Science & Engineering)		$2,789	
	Wearable eMbots to Induce Recovery of Function (Associated Project)		William Durfee (University of Minnesota-Mechanical Engineering)		$28,251	
				Translational Research Projects Within Thrust	**$0**	
				Subtotal (all projects) for Thrust	**$769,959**	**$480,000**
				Total Number of Undergraduate Students in Thrust	**5**	
				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	**28**	

[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

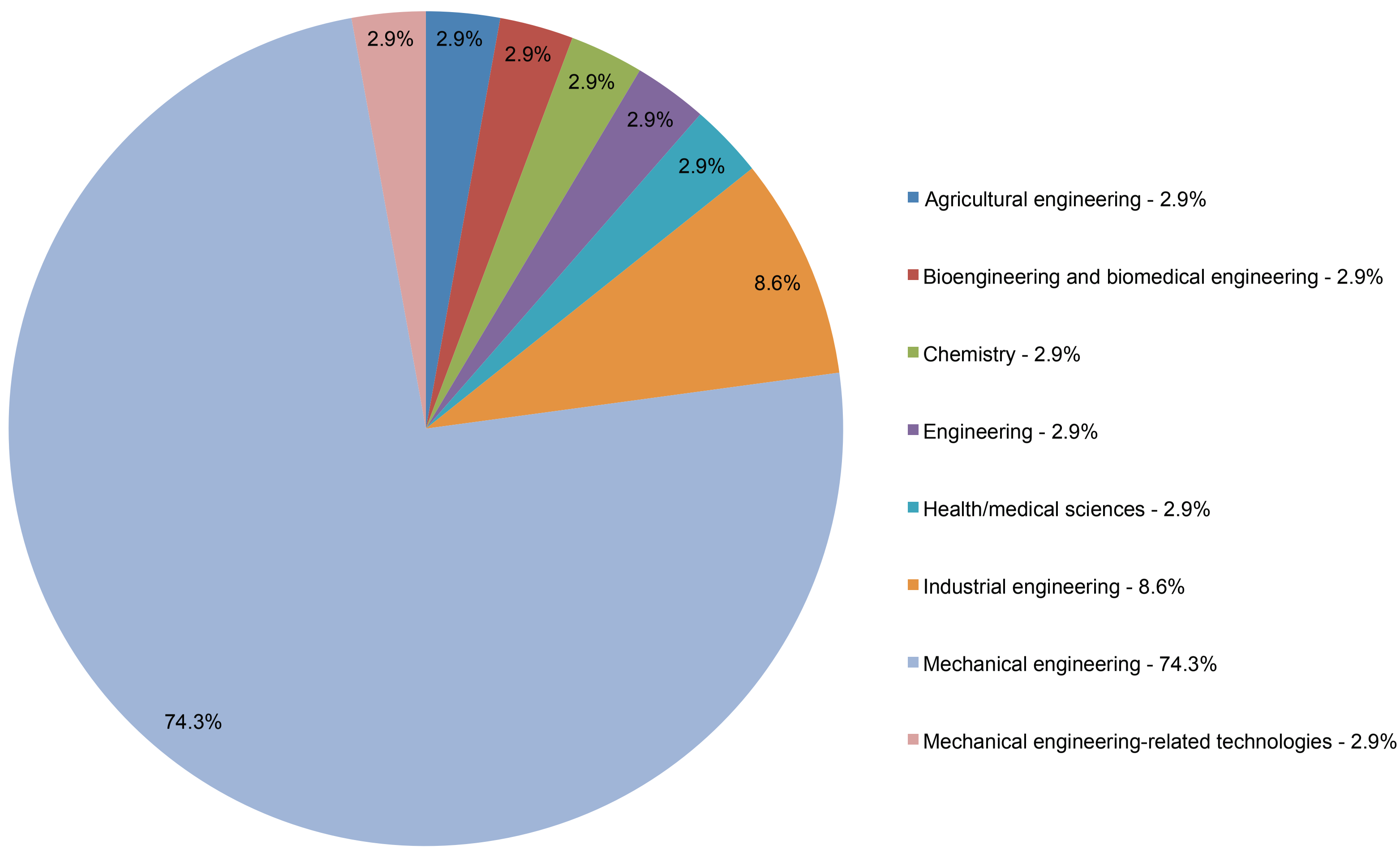
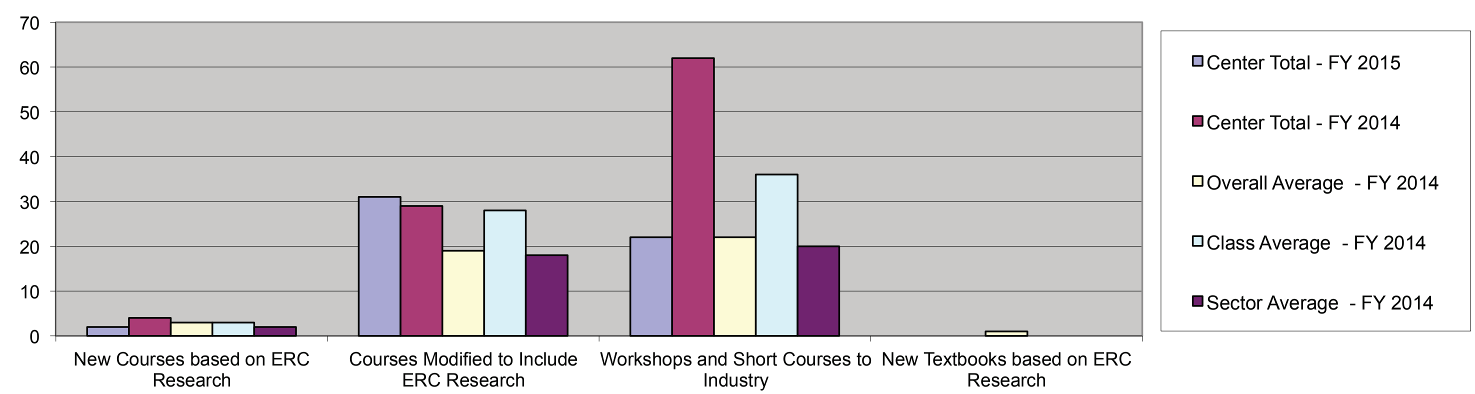


Table 3a: Educational Impact

	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, 2014- Jan 31, 2015	Percent	Feb 01, 2014- Jan 31, 2015	Percent	Feb 01, 2014- Jan 31, 2015	Percent	Feb 01, 2014- Jan 31, 2015	Percent	Feb 01, 2014- Jan 31, 2015	Percent	Feb 01, 2014- Jan 31, 2015	Percent	
New Courses Currently Offered [1]	2	2	100%	0	0%	0	0%	0	0%	0	0%	0	0%	22
Currently Offered Ongoing Courses With ERC Content [2]	31	31	100%	0	0%	0	0%	13	42%	4	13%	6	19%	N/A
Workshops, Short Courses, and Webinars	22	22	100%	0	0%	0	0%	22	100%	22	100%	22	100%	301
New textbooks based on ERC research	0	0	0%	0	0%	N/A	N/A	0	0%	0	0%	0	0%	4

Table 3a: Educational Impact - Comparison of Center, ERC Program Overall, Center Class, and Center Sector



[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 2014	59	95	1.6	17	172	18	189
Average Advanced Manufacturing Sector FY 2014	78	93	1.2	20	190	27	217
Average for Class of 2006 FY 2014	75	91	1.2	29	195	33	228
Minnesota Twin Cities-CCEFP FY 2014	112	89	0.8	23	224	0	224
Minnesota Twin Cities-CCEFP FY 2015	**50**	**92**	**1.8**	**25**	**167**	**0**	**167**

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
1 - Funder of Sponsored Projects
10 - 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: 1 Funder 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

Section 4: 10 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	2
Cat Pumps	Industry	Fluid power components and systems	Associated Project Support	Participates in science/engineering research projects	Domestic	Small (<500 employees)	Yes	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	10
Dae Jin Hydraulics - TECPOS	Industry	Power Solutions	Associated Project Support	Participates in science/engineering research projects	Foreign	Small (<500 employees)	No	1
Deere and Company	Industry	Vehicle OEM	Associated Project Support	Participates in science/engineering research projects Participation in education/outreach activities Participation in translational research Involvement in Technology Transfer	Domestic	Large (>1000 employees)	No	1
John Crane	Industry	Engineering services	Associated Project Support	Participates in science/engineering research projects	Domestic	Small (<500 employees)	No	1
Minneapolis Veterans Administration Medical Center	U.S. Government (Not NSF)	N/A	Associated Project Support	Participates in science/engineering research projects	Domestic	N/A	Yes	1
National Defense Science and Engineering Fellowship Grant (NDSEG)	U.S. Government (Not NSF)	N/A	Associated Project Support	Participates in science/engineering research projects	Domestic	N/A	No	1
Thomas Magnete GmbH	Industry	Automotive	Associated Project Support	Participates in science/engineering research projects	Foreign	Small (<500 employees)	Yes	1
Veraphotonics, Mistras	Industry	Engineering services	Associated Project Support	Participates in science/engineering research projects Participation in translational research	Domestic	Small (<500 employees)	No	1

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.							
Danfoss	Industry	Fluid power components and systems	Associated Project Support In-Kind Donations	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	Participates in science/engineering research projects Involvement in Technology Transfer	Domestic	Large (>1000 employees)	No
Eaton Corporation	Industry	Fluid power components and systems	Unrestricted 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
International Fluid Power Society	Industrial Association	N/A	Restricted Cash Donations	Participation in education/outreach activities	Domestic	N/A	No
Lee Company	Industry	Fluid power components and systems	In-Kind Donations	Participates in science/engineering research projects	Domestic	Small (<500 employees)	Yes
Moog, Inc.	Industry	Fluid power components and systems	In-Kind Donations	Participates in science/engineering research projects	Domestic	Large (>1000 employees)	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
NFPA Education and Technology Foundation	Private Foundation	N/A	Unrestricted Cash Donations Restricted Cash Donations	Member of Center's Industrial Advisory Board Participates in science/engineering research projects Participation in education/outreach activities	Domestic	N/A	Yes
Parker Hannifin Corporation	Industry	Fluid power components and systems	In-Kind Donations	Member of Center's Industrial Advisory Board Participates in science/engineering research projects	Domestic	Large (>1000 employees)	No
Takako Industries	Industry	Fluid power components and systems	In-Kind Donations	Participates in science/engineering research projects	Foreign	Small (<500 employees)	No
Contributing Organizations That Will Provide Support by the End of the Current Award Year.							

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)**
Igus, Inc.	Industry	small business	In-Kind Donations	Participates in science/engineering research projects	Domestic	Small (<500 employees)	Yes
WIKA	Industry	small business	In-Kind Donations		Domestic	Small (<500 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
No organizations with involvement in innovation and entrepreneurship activities have been entered.					

Table 5: Innovation Ecosystem Partners and Support, by Year

	Jun 01, 2011 - May 31, 2012	Jun 01, 2012 - May 31, 2013	Jun 01, 2013 - May 31, 2014	Jun 01, 2014 - May 31, 2015 [1]
Industrial/Practitioner Members	48	41	46	0
Innovation Partners	1	1	1	0
Funders of Sponsored Projects	0	0	1	1
Funders of Associated Projects	8	8	10	10
Contributing Organizations	9	6	4	12
Total Participating Organizations	**66**	**56**	**62**	**23**
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	$707,817	$583,100	$454,717	$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	$95,295	$78,336	$115,269	$0
Member In-Kind Total Dollar Amount [3]	$92,150	$12,257	$0	$0
Total Dollar Amount, Industrial/Practitioner Member Support to Center	**$895,262**	**$673,693**	**$569,986**	**$0**

[1] Partial Award Year data only.

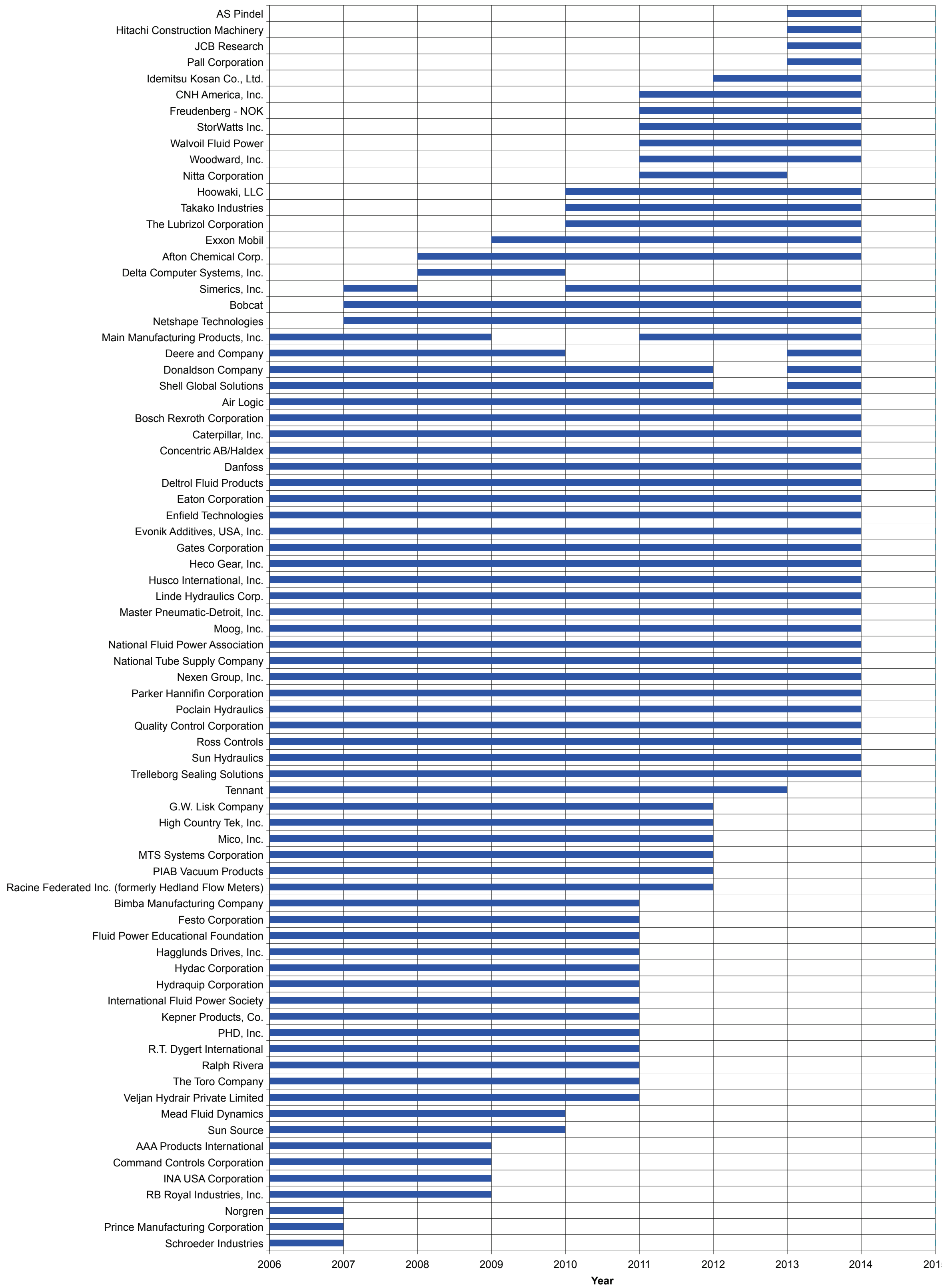
[2] Only applies for organizatons that were already Industrial/Practitioner Members in a prior year.

[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
Casappa S.p.A.									
Cat Pumps									
Confidential Organization (optional use for associated or sponsored projects only)									
Dae Jin Hydraulics - TECPOS									
Danfoss		✔			✔				
Deere and Company			✔			✔			
Donaldson Company		✔	✔						
Eaton Corporation	✔	✔			✔	✔	✔		
Igus, Inc.									
John Crane									
Lee Company									
Minneapolis Veterans Administration Medical Center									
Moog, Inc.									
National Defense Science and Engineering Fellowship Grant (NDSEG)									
National Fluid Power Association									
NFPA Education and Technology Foundation									
Parker Hannifin Corporation									
Takako Industries									
Thomas Magnete GmbH									
Veraphotonics, Mistras									
WIKA									

Figure 5b: Lifetime Industrial/Practitioner Membership History



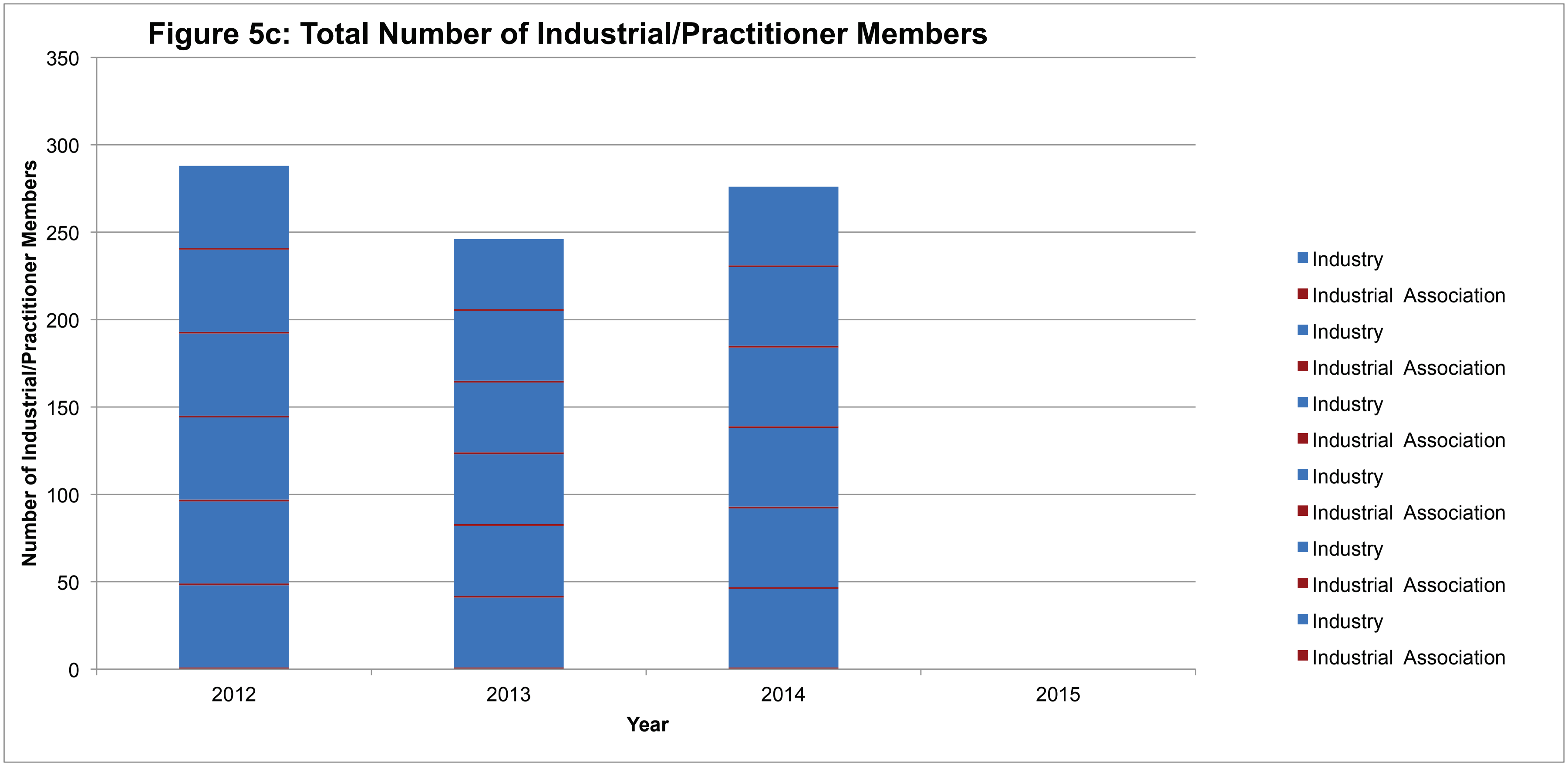
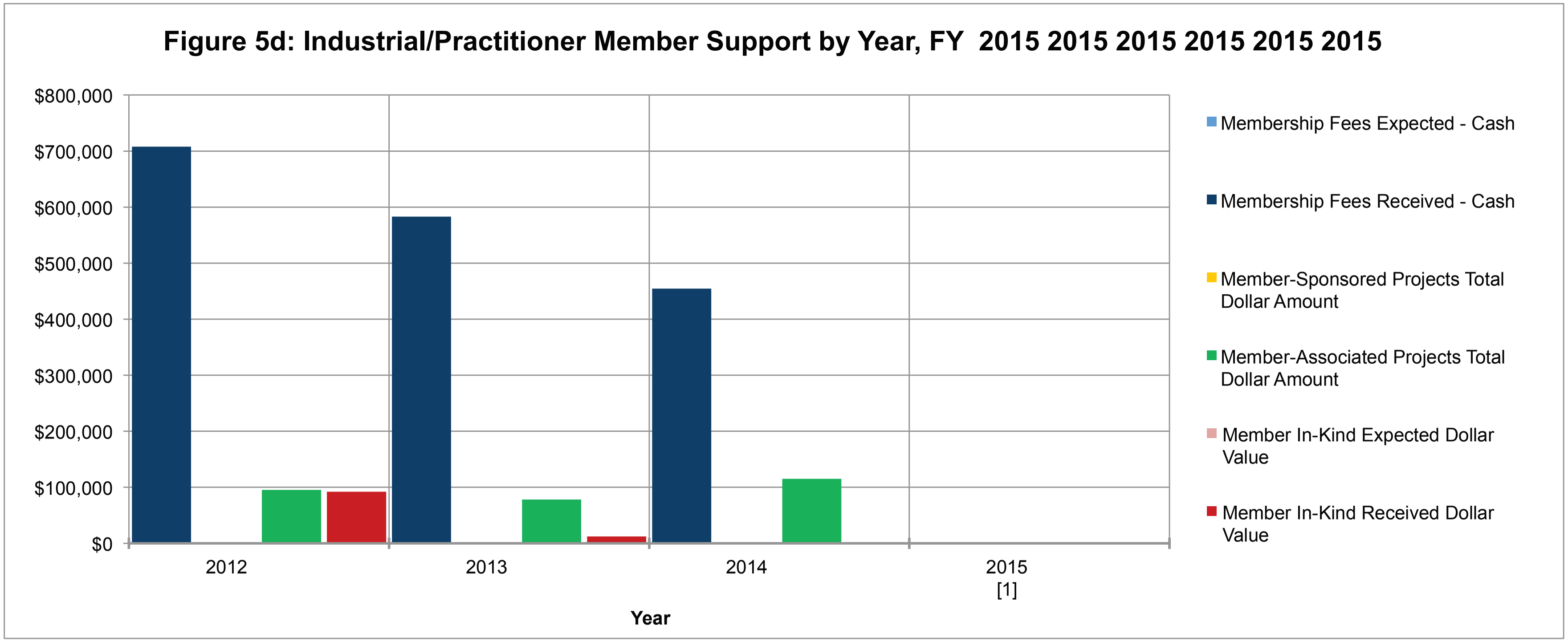


Figure 5c: Total Number of Industrial/Practitioner Members
Number of Industrial/Practitioner Members
350
300
250
200
150
100
50
0
2012
2013
2014
2015
Year
Industry
Industrial Association
Industry
Industrial Association
Industry
Industrial Association
Industry
Industrial Association
Industry
Industrial Association
Industry
Industrial Association



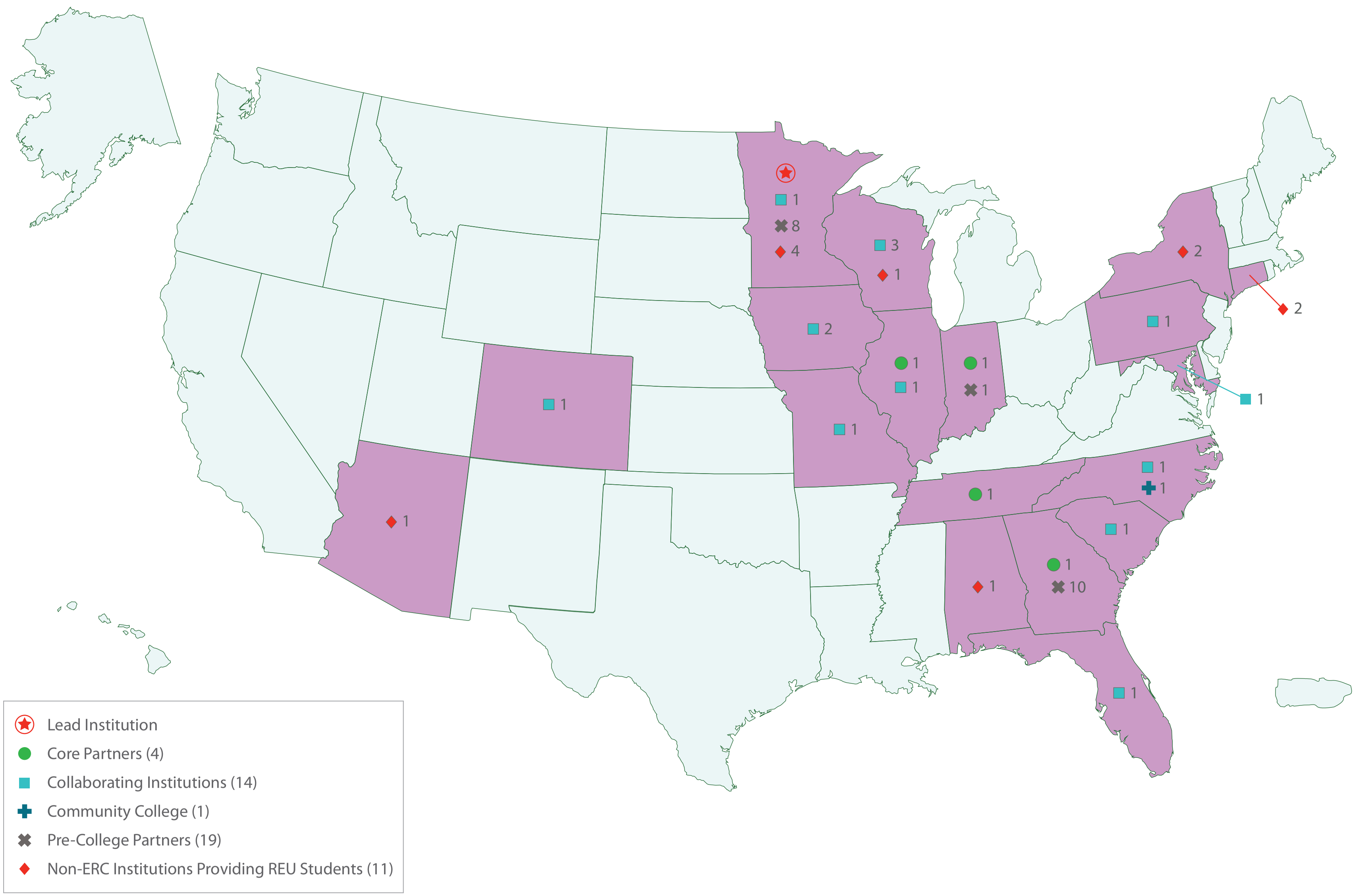
[1] - Member support provided through end of current reporting year (includes only partial data)

Table 6: Institutions Executing the ERC's Research, Technology Transfer, and Education Programs

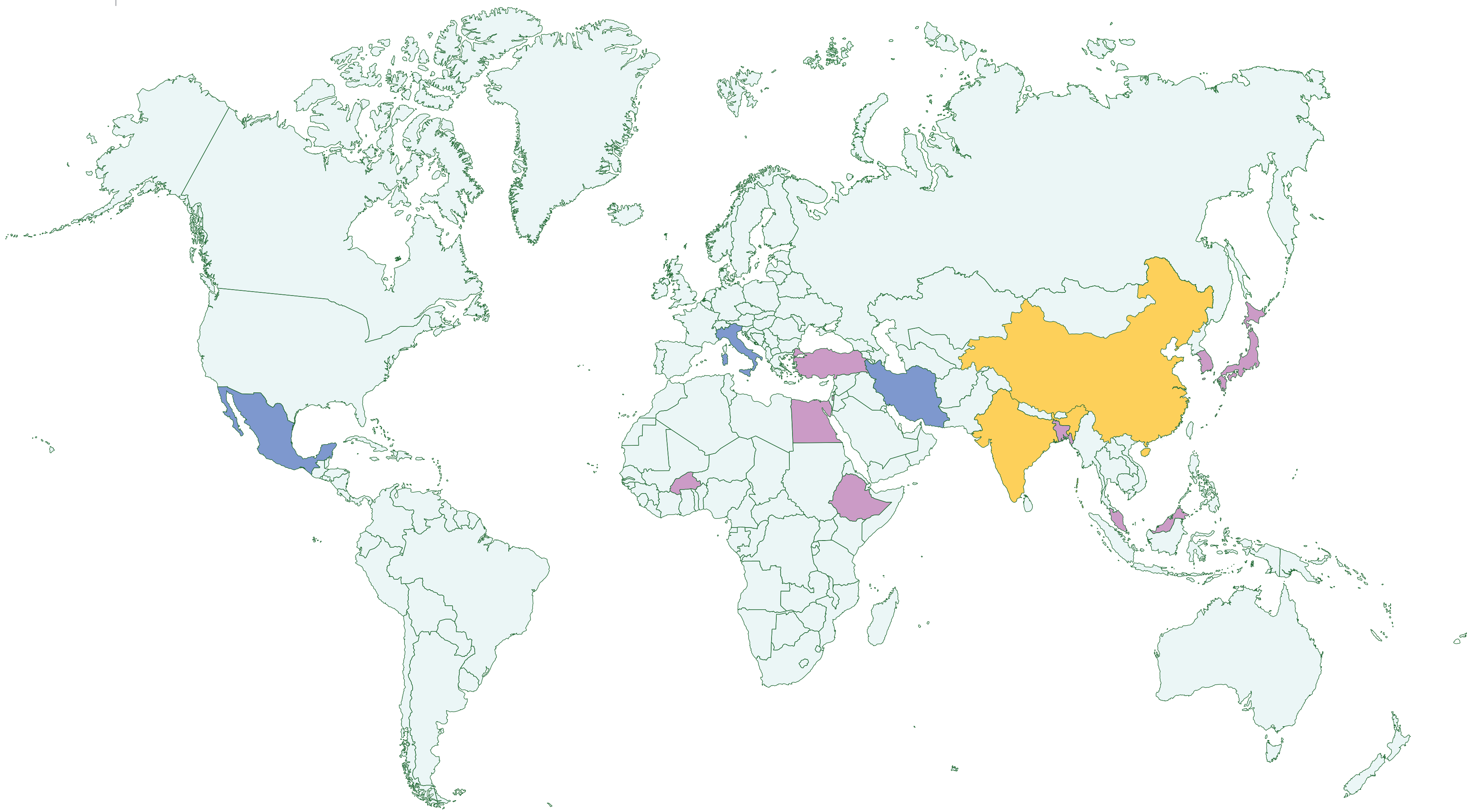
Institutions							Personnel in ERC Activities [1]									
Name and Type	Total	Female Serving	Minority Serving	HBCU	Hispanic Serving	Large Number of URM Students in Engineering	Faculty	Community College RET	Teachers (K-12)		Postdocs	Students				Young Scholars
									RET	Non-RET		Graduate		UG Non-REU	REU	
												Doctoral	Masters			
I. Lead	**1**	**0**	**0**	**0**	**0**	**0**	**10**	**N/A**	**N/A**	**N/A**	**2**	**20**	**9**	**11**	**3**	**N/A**
University of Minnesota, Minneapolis, MN							10	N/A	N/A	N/A	2	20	9	11	3	N/A
II. Core Partners	**4**	**0**	**0**	**0**	**0**	**0**	**22**	**N/A**	**N/A**	**N/A**	**0**	**35**	**20**	**31**	**8**	**N/A**
Georgia Institute of Technology, Atlanta, GA							7	N/A	N/A	N/A	0	7	5	11	3	N/A
Purdue University, West Lafayette, IN							4	N/A	N/A	N/A	0	20	8	6	1	N/A
University of Illinois at Urbana-Champaign, Urbana, IL							7	N/A	N/A	N/A	0	5	4	11	3	N/A
Vanderbilt University, Nashville, TN							4	N/A	N/A	N/A	0	3	3	3	1	N/A
III. Collaborating Institutions	**14**	**0**	**0**	**2**	**0**	**0**	**7**	**N/A**	**N/A**	**N/A**	**0**	**2**	**6**	**11**	**5**	**N/A**
Bradley University, Peoria, IL							0	N/A	N/A	N/A	0	0	1	3	0	N/A
Clemson University, Clemson, SC							0	N/A	N/A	N/A	0	0	0	0	0	N/A
Iowa State University, Ames, IA							0	N/A	N/A	N/A	0	0	0	0	0	N/A
Kirkwood Community College, Cedar Rapids, IA							0	N/A	N/A	N/A	0	0	0	0	0	N/A
Milwaukee School of Engineering, Milwaukee, WI							1	N/A	N/A	N/A	0	0	4	3	0	N/A
Missouri University, Columbia, MO							0	N/A	N/A	N/A	0	0	0	0	0	N/A
Morgan State University, Baltimore, MD				✔			0	N/A	N/A	N/A	0	0	0	1	1	N/A
National Fluid Power Association, Milwaukee, WI							0	N/A	N/A	N/A	0	0	0	0	0	N/A
North Carolina Agriculture and Technical State University, Greensboro, NC				✔			5	N/A	N/A	N/A	0	2	1	4	4	N/A
Philadelphia Universtiy, Philadelphia, PA							0	N/A	N/A	N/A	0	0	0	0	0	N/A
Quality Evaluation Designs, Denver, CO							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	0	0	0	N/A
University of Florida, Gainesville, FL							0	N/A	N/A	N/A	0	0	0	0	0	N/A
University of Wisconsin – Milwaukee, Milwaukee, WI							1	N/A	N/A	N/A	0	0	0	0	0	N/A
IV. Non-ERC Institutions Providing REU Students	**11**	**0**	**0**	**0**	**0**	**0**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**12**	**N/A**
Arizona State Universtiy, Temple, AZ							N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	1	N/A
Auburn University, Auburn, AL							N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	1	N/A
Columbia University, New York, NY							N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	1	N/A
Macalester College, St. Paul, MN							N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	1	N/A
Mankato State Universtiy, Mankato, MN							N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	1	N/A
Minneapolis Community and Technical College, Minneapolis, MN							N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	1	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
University of Hartford, West Hartford, CT							N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	1	N/A
University of Rochester, Rochester, NY							N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	1	N/A
University of Wisconsin- Madison, Madison, WI							N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	2	N/A
Yale University, New Haven, CT							N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	1	N/A
V. NSF Diversity Program Awardees	**2**	**0**	**2**	**0**	**1**	**2**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**1**	**0**	**1**	**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)	**1**	**0**	**1**	**0**	**1**	**1**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**0**	**0**	**1**	**0**	**N/A**
North Star STEM Alliance			✔		✔	✔	N/A	N/A	N/A	N/A	N/A	0	0	1	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**	**0**	**1**	**0**	**N/A**	**N/A**	**N/A**	**0**	**1**	**0**	**0**	**0**	**N/A**
National GEM Consortium			✔			✔	0	N/A	N/A	N/A	0	1	0	0	0	N/A
VI. Precollege Partners	**19**	**0**	**0**	**0**	**0**	**0**	**N/A**	**N/A**	**2**	**19**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**0**
Ashby Public School, Ashby, MN							N/A	N/A	0	1	N/A	N/A	N/A	N/A	N/A	0
Brainerd Public Schools, Brainerd, MN							N/A	N/A	0	1	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	2	N/A	N/A	N/A	N/A	N/A	0
Cooper Middle School, Austell, GA							N/A	N/A	0	1	N/A	N/A	N/A	N/A	N/A	0
Gainesville Middle School, Gainesville, GA							N/A	N/A	0	1	N/A	N/A	N/A	N/A	N/A	0
Georgia Cyber Academy, Lawrenceville, GA							N/A	N/A	0	1	N/A	N/A	N/A	N/A	N/A	0
John Metcalf Jr. High School, Burnsville, MN							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	2	0	N/A	N/A	N/A	N/A	N/A	0
Leadership Preparatory Academy, Lithonia, GA							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
North Gwinnett Middle School, Sugar Hill, GA							N/A	N/A	0	1	N/A	N/A	N/A	N/A	N/A	0
North Junior High, Saint Cloud, MN							N/A	N/A	0	1	N/A	N/A	N/A	N/A	N/A	0
Osakis Public School, Osakis, MN							N/A	N/A	0	1	N/A	N/A	N/A	N/A	N/A	0
Reden Middle School, Lithonia, GA							N/A	N/A	0	1	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, Doraville, GA							N/A	N/A	0	1	N/A	N/A	N/A	N/A	N/A	0
Steampunk Robotics Homeschool Technology Club, Jonesboro, GA							N/A	N/A	0	1	N/A	N/A	N/A	N/A	N/A	0
Trickum Middle School, Lilburn, GA							N/A	N/A	0	1	N/A	N/A	N/A	N/A	N/A	0
Twin Rivers Middle School, Buford, GA							N/A	N/A	0	1	N/A	N/A	N/A	N/A	N/A	0
VII. Community Colleges	**1**	**0**	**0**	**0**	**0**	**0**	**2**	**2**	**N/A**	**N/A**	**0**	**0**	**0**	**0**	**0**	**N/A**
Guilford Technical Community College, Jamestown, NC							2	2	N/A	N/A	0	0	0	0	0	N/A
Total	**52**	**0**	**2**	**2**	**1**	**2**	**41**	**2**	**2**	**19**	**2**	**58**	**35**	**54**	**28**	**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



Legend:
- ♙ = Number of ERC personnel from this country
- 1 person
- 2–10 people
- 11+ people

1 person ♙		
Bangladesh	Ethiopia	Palestine
Burkina Faso	Japan	South Korea
Egypt	Malaysia	Turkey

2–10 people	♙
Iran	2
Italy	2
Mexico	2

11+ people	♙
China	13
India	11

	♙
Country Not Reported	1*

* Number of ERC personnel who are foreign and did not provide a country name

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																		
Total [2]	237	164	48	25	1	0	12	110	5	1	2	33	41	32	7	2	0	3
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	2	1	1	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0
Staff	9	5	3	1	0	0	1	5	0	0	0	2	0	1	0	0	0	0
Subtotal	**18**	**12**	**5**	**1**	**0**	**0**	**1**	**12**	**1**	**1**	**0**	**2**	**0**	**1**	**0**	**0**	**0**	**0**
Research Under Strategic Research Plan																		
Senior Faculty	18	16	1	1	0	0	0	9	3	1	0	1	1	3	0	0	0	0
Junior Faculty	13	11	1	1	0	0	0	7	1	0	0	1	2	2	2	0	0	0
Research Staff	4	4	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0
Total Postdocs	2	1	0	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0
Total Doctoral Students	55	40	10	5	0	0	3	18	0	0	0	3	24	7	1	1	0	1
Total Master's Students	33	21	6	6	0	0	0	14	0	0	1	2	7	9	0	1	0	0
Total Undergraduate Students	36	23	8	5	0	0	5	21	0	0	1	2	4	3	2	0	0	0
Subtotal	**161**	**116**	**26**	**19**	**0**	**0**	**8**	**73**	**4**	**1**	**2**	**9**	**39**	**25**	**5**	**2**	**0**	**1**
Curriculum Development and Outreach																		
Senior Faculty	8	7	1	0	0	0	0	4	2	1	0	1	0	0	0	0	0	0
Junior Faculty	9	7	2	0	0	0	2	5	1	0	0	1	0	0	1	0	0	0
Research Staff	9	6	3	0	1	0	1	6	0	0	0	1	0	0	0	0	0	2
Visiting Faculty	2	0	2	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0
Industry Researchers	4	2	2	0	0	0	0	3	0	0	0	1	0	0	0	0	0	0
Total Doctoral Students	14	10	3	1	0	0	1	7	0	0	0	2	3	1	1	1	0	1
Total Master's Students	7	5	1	1	0	0	0	5	0	0	0	0	1	1	0	0	0	0
Total Undergraduate Students	38	25	9	4	0	0	5	22	1	0	1	4	3	2	4	0	0	0
Other Visiting College Students	9	4	0	5	0	0	0	0	0	0	0	3	0	6	0	0	0	0
Subtotal	**98**	**66**	**21**	**11**	**1**	**0**	**9**	**52**	**4**	**1**	**1**	**13**	**7**	**10**	**6**	**1**	**0**	**3**
ERC REU Students																		
NSF REU Site Award Students	20	11	6	3	0	0	4	11	1	0	1	1	0	2	2	0	0	0
ERC's Own REU Students	5	5	0	0	0	0	1	3	0	0	0	0	1	0	0	0	0	0
Subtotal	**25**	**16**	**6**	**3**	**0**	**0**	**5**	**14**	**1**	**0**	**1**	**1**	**1**	**2**	**2**	**0**	**0**	**0**
Community College																		
Participant in RET Program	2	0	2	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0
Subtotal	**2**	**0**	**2**	**0**	**0**	**0**	**2**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Precollege (K-12)																		
Teachers (non-RET)	19	11	8	0	0	0	0	4	0	0	0	15	0	0	0	0	0	0
Teachers (RET)	2	2	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0
Subtotal	**21**	**13**	**8**	**0**	**0**	**0**	**0**	**5**	**0**	**0**	**0**	**16**	**0**	**0**	**0**	**0**	**0**	**0**
University of Minnesota - Lead Institution																		
Total [2]	61	46	11	4	1	0	1	34	2	0	1	2	14	6	2	0	0	1
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	2	1	1	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0
Staff	7	3	3	1	0	0	1	4	0	0	0	1	0	1	0	0	0	0
Subtotal	**12**	**7**	**4**	**1**	**0**	**0**	**1**	**8**	**1**	**0**	**0**	**1**	**0**	**1**	**0**	**0**	**0**	**0**
Research Under Strategic Research Plan																		
Senior Faculty	6	6	0	0	0	0	0	5	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 Postdocs	2	1	0	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0
Total Doctoral Students	19	16	2	1	0	0	0	6	0	0	0	0	12	1	0	0	0	0
Total Master's Students	9	8	0	1	0	0	0	6	0	0	0	0	0	3	0	0	0	0
Total Undergraduate Students	6	3	3	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0
Subtotal	**44**	**36**	**5**	**3**	**0**	**0**	**0**	**24**	**2**	**0**	**0**	**0**	**13**	**5**	**0**	**0**	**0**	**0**
Curriculum Development and Outreach																		
Senior Faculty	3	3	0	0	0	0	0	2	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	4	1	3	0	1	0	0	2	0	0	0	1	0	0	0	0	0	1
Total Doctoral Students	2	2	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0
Total Undergraduate Students	9	7	2	0	0	0	0	6	0	0	1	1	1	0	2	0	0	0
Subtotal	**20**	**15**	**5**	**0**	**1**	**0**	**0**	**13**	**2**	**0**	**1**	**2**	**1**	**0**	**2**	**0**	**0**	**1**
ERC REU Students																		
NSF REU Site Award Students	1	1	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0
ERC's Own REU Students	2	2	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0
Subtotal	**3**	**3**	**0**	**0**	**0**	**0**	**0**	**3**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**
Georgia Institute of Technology - Core Partner																		
Total [2]	32	24	4	4	0	0	0	21	1	0	0	1	4	5	1	0	0	0
Leadership/Administration																		
Thrust Leaders	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Staff	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Subtotal	**2**	**2**	**0**	**0**	**0**	**0**	**0**	**2**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Research Under Strategic Research Plan																		
Senior Faculty	5	5	0	0	0	0	0	3	0	0	0	0	1	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
Research Staff	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Total Doctoral Students	7	5	2	0	0	0	0	4	0	0	0	1	2	0	1	0	0	0
Total Master's Students	5	3	1	1	0	0	0	3	0	0	0	0	1	1	0	0	0	0
Total Undergraduate Students	9	6	1	2	0	0	0	7	0	0	0	0	0	2	0	0	0	0
Subtotal	**28**	**20**	**4**	**4**	**0**	**0**	**0**	**18**	**0**	**0**	**0**	**1**	**4**	**5**	**1**	**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 Doctoral Students	3	2	1	0	0	0	0	2	0	0	0	0	1	0	0	0	0	0
Total Undergraduate Students	5	3	1	1	0	0	0	3	1	0	0	0	0	1	0	0	0	0
Subtotal	**9**	**6**	**2**	**1**	**0**	**0**	**0**	**6**	**1**	**0**	**0**	**0**	**1**	**1**	**0**	**0**	**0**	**0**
ERC REU Students																		
NSF REU Site Award Students	2	1	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0
ERC's Own REU Students	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Subtotal	**3**	**2**	**0**	**1**	**0**	**0**	**0**	**1**	**1**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**
Purdue University - Core Partner																		
Total [2]	39	28	6	5	0	0	1	15	0	0	0	5	13	5	2	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																		
Junior Faculty	3	3	0	0	0	0	0	2	0	0	0	1	0	0	1	0	0	0
Total Doctoral Students	20	15	3	2	0	0	0	7	0	0	0	2	8	3	0	1	0	0
Total Master's Students	8	4	2	2	0	0	0	3	0	0	0	0	3	2	0	1	0	0
Total Undergraduate Students	6	5	0	1	0	0	1	2	0	0	0	1	2	0	1	0	0	0
Subtotal	**37**	**27**	**5**	**5**	**0**	**0**	**1**	**14**	**0**	**0**	**0**	**4**	**13**	**5**	**2**	**2**	**0**	**0**
Curriculum Development and Outreach																		

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																		
Junior Faculty	3	3	0	0	0	0	0	2	0	0	0	1	0	0	1	0	0	0
Total Doctoral Students	4	4	0	0	0	0	0	1	0	0	0	1	2	0	0	1	0	0
Total Master's Students	3	1	1	1	0	0	0	2	0	0	0	0	0	1	0	0	0	0
Total Undergraduate Students	3	2	0	1	0	0	1	1	0	0	0	1	0	0	1	0	0	0
Other Visiting College Students	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Subtotal	**14**	**11**	**1**	**2**	**0**	**0**	**1**	**6**	**0**	**0**	**0**	**4**	**2**	**1**	**2**	**1**	**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**
University of Illinois at Urbana-Champaign - Core Partner																		
Total [2]	28	17	7	4	0	0	0	11	1	1	2	0	7	6	1	0	0	1
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	3	2	1	0	0	0	0	0	1	1	0	0	0	1	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 Doctoral Students	4	3	0	1	0	0	0	1	0	0	0	0	2	1	0	0	0	1
Total Master's Students	4	2	1	1	0	0	0	0	0	0	1	0	2	1	0	0	0	0
Total Undergraduate Students	4	2	1	1	0	0	0	1	0	0	1	0	1	1	0	0	0	0
Subtotal	**19**	**13**	**3**	**3**	**0**	**0**	**0**	**4**	**1**	**1**	**2**	**0**	**6**	**5**	**0**	**0**	**0**	**1**
Curriculum Development and Outreach																		
Senior Faculty	2	1	1	0	0	0	0	0	1	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	2	1	1	0	0	0	0	2	0	0	0	0	0	0	0	0	0	1
Total Master's Students	1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Total Undergraduate Students	10	5	4	1	0	0	0	7	0	0	1	0	1	1	1	0	0	0
Other Visiting College Students	1	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Subtotal	**17**	**9**	**6**	**2**	**0**	**0**	**0**	**10**	**1**	**1**	**1**	**0**	**2**	**2**	**1**	**0**	**0**	**1**
ERC REU Students																		
NSF REU Site Award Students	3	1	2	0	0	0	0	2	0	0	1	0	0	0	0	0	0	0
Subtotal	**3**	**1**	**2**	**0**	**0**	**0**	**0**	**2**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Vanderbilt University - Core Partner																		
Total [2]	13	9	2	2	0	0	1	6	0	0	0	2	1	3	0	0	0	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	2	1	0	1	0	0	0	1	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	3	1	1	1	0	0	1	0	0	0	0	0	0	2	0	0	0	0
Total Master's Students	3	3	0	0	0	0	0	1	0	0	0	2	0	0	0	0	0	0
Total Undergraduate Students	3	2	1	0	0	0	0	2	0	0	0	0	1	0	0	0	0	0
Subtotal	**12**	**8**	**2**	**2**	**0**	**0**	**1**	**5**	**0**	**0**	**0**	**2**	**1**	**3**	**0**	**0**	**0**	**0**
Curriculum Development and Outreach																		
Junior Faculty	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Total Doctoral Students	2	0	1	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0
Total Master's Students	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	2	0	0	0	0	1	0	0	0	0	0
Subtotal	**7**	**4**	**2**	**1**	**0**	**0**	**1**	**4**	**0**	**0**	**0**	**0**	**1**	**1**	**0**	**0**	**0**	**0**
ERC REU Students																		
ERC's Own REU Students	1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**
Bradley University - Collaborating Institution																		
Total [2]	4	3	1	0	0	0	0	3	0	0	0	1	0	0	0	0	0	0
Curriculum Development and Outreach																		
Total Master's Students	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	2	0	0	0	1	0	0	0	0	0	0
Subtotal	**4**	**3**	**1**	**0**	**0**	**0**	**0**	**3**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**
Clemson University - Collaborating Institution																		
Total [2]	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Curriculum Development and Outreach																		
Other Visiting College Students	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**
Iowa State University - Collaborating Institution																		
Total [2]	1	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Curriculum Development and Outreach																		
Other Visiting College Students	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**
Kirkwood Community College - Collaborating Institution																		
Total [2]	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Curriculum Development and Outreach																		
Other Visiting College Students	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**
Milwaukee School of Engineering - Collaborating Institution																		
Total [2]	13	7	3	3	0	0	0	8	0	0	0	1	1	3	0	0	0	0
Research Under Strategic Research Plan																		
Research Staff	3	3	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0
Total Master's Students	3	0	2	1	0	0	0	0	0	0	0	0	1	2	0	0	0	0
Total Undergraduate Students	3	1	1	1	0	0	0	2	0	0	0	1	0	0	0	0	0	0
Subtotal	**9**	**4**	**3**	**2**	**0**	**0**	**0**	**5**	**0**	**0**	**0**	**1**	**1**	**2**	**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
Research Staff	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Total Master's Students	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Total Undergraduate Students	3	1	1	1	0	0	0	2	0	0	0	1	0	0	0	0	0	0
Other Visiting College Students	1	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Subtotal	**7**	**4**	**1**	**2**	**0**	**0**	**0**	**5**	**0**	**0**	**0**	**1**	**0**	**1**	**0**	**0**	**0**	**0**
Missouri University - Collaborating Institution																		
Total [2]	1	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Curriculum Development and Outreach																		
Other Visiting College Students	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**
Morgan State University - Collaborating Institution																		
Total [2]	1	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Curriculum Development and Outreach																		
Total Undergraduate Students	1	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Subtotal	**1**	**0**	**0**	**1**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**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																		
ERC REU Students																		
NSF REU Site Award Students	1	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Subtotal	**1**	**0**	**0**	**1**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
National Fluid Power Association - Collaborating Institution																		
Total [2]	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Leadership/Administration																		
Staff	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**
North Carolina Agriculture and Technical State University - Collaborating Institution																		
Total [2]	12	7	5	0	0	0	8	1	1	0	0	1	1	0	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	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Total Undergraduate Students	4	3	1	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0
Subtotal	**10**	**7**	**3**	**0**	**0**	**0**	**6**	**1**	**1**	**0**	**0**	**1**	**1**	**0**	**0**	**0**	**0**	**0**
Curriculum Development and Outreach																		
Senior Faculty	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Visiting Faculty	2	0	2	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0
Total Undergraduate Students	4	3	1	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0
Subtotal	**7**	**4**	**3**	**0**	**0**	**0**	**6**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**
ERC REU Students																		
NSF REU Site Award Students	3	2	1	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0
ERC's Own REU Students	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Subtotal	**4**	**3**	**1**	**0**	**0**	**0**	**4**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Philadelphia Universtiy - 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																		
Other Visiting College 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**
Quality Evaluation Designs - Collaborating Institution																		
Total [2]	4	2	2	0	0	0	0	3	0	0	0	1	0	0	0	0	0	0
Curriculum Development and Outreach																		
Industry Researchers	4	2	2	0	0	0	0	3	0	0	0	1	0	0	0	0	0	0
Subtotal	**4**	**2**	**2**	**0**	**0**	**0**	**0**	**3**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**
Science Museum of Minnesota - Collaborating Institution																		
Total [2]	3	3	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	1
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**
University of Florida - Collaborating Institution																		
Total [2]	1	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Curriculum Development and Outreach																		
Other Visiting College Students	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**
University of Wisconsin – Milwaukee - Collaborating Institution																		
Total [2]	1	0	1	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0
Research Under Strategic Research Plan																		
Junior Faculty	1	0	1	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0
Subtotal	**1**	**0**	**1**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**
Arizona State Universtiy - Non-ERC Institution Providing REU Students																		
Total [2]	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
ERC REU Students																		
NSF REU Site Award Students	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Auburn 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**
Columbia University - Non-ERC Institution Providing REU Students																		
Total [2]	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
ERC REU Students																		
NSF REU Site Award Students	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**
Macalester College - Non-ERC Institution Providing REU Students																		
Total [2]	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
ERC REU Students																		
NSF REU Site Award Students	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**
Mankato State Universtiy - 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**
Minneapolis Community and Technical College - Non-ERC Institution Providing REU Students																		
Total [2]	1	1	0	0	0	0	0	1	0	0	0	0	0	0	1	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	1	0	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**
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**
University of Hartford - Non-ERC Institution Providing REU Students																		
Total [2]	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
ERC REU Students																		
NSF REU Site Award Students	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**
University of Rochester - Non-ERC Institution Providing REU Students																		

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																		
Total [2]	1	1	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0
ERC REU Students																		
NSF REU Site Award Students	1	1	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**1**	**0**	**0**	**0**
University of Wisconsin- Madison - Non-ERC Institution Providing REU Students																		
Total [2]	2	2	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0
ERC REU Students																		
NSF REU Site Award Students	2	2	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0
Subtotal	**2**	**2**	**0**	**0**	**0**	**0**	**0**	**2**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Yale University - Non-ERC Institution Providing REU Students																		
Total [2]	1	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0
ERC REU Students																		
NSF REU Site Award Students	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**
Guilford Technical Community College - Community College																		
Total [2]	2	0	2	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0
Curriculum Development and Outreach																		
Junior Faculty	2	0	2	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0
Subtotal	**2**	**0**	**2**	**0**	**0**	**0**	**2**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Community College																		
Participant in RET Program	2	0	2	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0
Subtotal	**2**	**0**	**2**	**0**	**0**	**0**	**2**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Ashby Public School - Pre-college Partner																		
Total [2]	1	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Precollege (K-12)																		
Teachers (non-RET)	1	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Subtotal	**1**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**
Brainerd 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**
Capitol Hill Gifted and Talented Magnet - Pre-college Partner																		
Total [2]	2	2	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0
Precollege (K-12)																		
Teachers (non-RET)	2	2	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0
Subtotal	**2**	**2**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**
Cooper Middle School - Pre-college Partner																		
Total [2]	1	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Precollege (K-12)																		
Teachers (non-RET)	1	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Subtotal	**1**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**
Gainesville Middle School - Pre-college Partner																		
Total [2]	1	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Precollege (K-12)																		
Teachers (non-RET)	1	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Subtotal	**1**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**
Georgia Cyber Academy - 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**
John Metcalf Jr. High 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**
Lafayette Jefferson High School - Pre-college Partner																		
Total [2]	2	2	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0
Precollege (K-12)																		
Teachers (RET)	2	2	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0
Subtotal	**2**	**2**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**
Leadership Preparatory Academy - Pre-college Partner																		
Total [2]	1	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Precollege (K-12)																		
Teachers (non-RET)	1	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Subtotal	**1**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**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**
North Gwinnett 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**
North Junior High - Pre-college Partner																		
Total [2]	1	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Precollege (K-12)																		
Teachers (non-RET)	1	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Subtotal	**1**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**
Osakis Public 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**
Reden Middle School - Pre-college Partner																		
Total [2]	1	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Precollege (K-12)																		
Teachers (non-RET)	1	0	1	0	0	0	0	0	0	0	0	1	0	0	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																		
Subtotal	**1**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**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	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Precollege (K-12)																		
Teachers (non-RET)	1	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Subtotal	**1**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**
Steampunk Robotics Homeschool Technology Club - Pre-college Partner																		
Total [2]	1	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Precollege (K-12)																		
Teachers (non-RET)	1	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Subtotal	**1**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**
Trickum 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**
Twin Rivers 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**
North Star STEM Alliance - LSAMP																		
Total [2]	1	1	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0
Research Under Strategic Research Plan																		
Total Undergraduate 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**
National GEM Consortium - Alliance with NSF Diversity Awardees																		
Total [2]	2	2	0	0	0	0	1	0	0	0	0	1	0	0	1	0	0	0
Research Under Strategic Research Plan																		
Total Doctoral Students	1	1	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**1**	**0**	**0**	**0**
Curriculum Development and Outreach																		
Research Staff	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Total Doctoral Students	1	1	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0
Subtotal	**2**	**2**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**1**	**0**	**0**	**0**

[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

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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**	**29**	**0**	**26**	**19**	**41**	**22**	**0**	**3**	**1**	**24**	**7**	**6**	**0**	**5**	**1**	**7**	**9**	**3**
Women																			
Category Total	2	4	0	9	1	10	6	0	0	0	1	4	1	0	0	0	1	1	0
Center Percent	22.2%	13.8%	0	34.6%	5.3%	24.4%	27.3%	0	0.0%	0.0%	4.2%	57.1%	16.7%	0	0.0%	0.0%	14.3%	11.1%	0.0%
National Percent [1][2]	N/A	14.5%	N/A	24.0%	21.4%	19.6%	N/A	N/A	N/A	N/A	23.2%	26.9%	19.2%	N/A	N/A	N/A	N/A	N/A	N/A
Underrepresented Racial Minorities																			
Category Total	1	3	0	3	0	5	5	0	0	0	1	0	1	0	0	0	0	0	0
Center Percent	11.1%	10.3%	0	11.5%	0.0%	12.2%	22.7%	0	0.0%	0.0%	4.2%	0.0%	16.7%	0	0.0%	0.0%	0.0%	0.0%	0.0%
National Percent [1][2]	N/A	2.9%	N/A	4.7%	5.8%	6.0%	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
Hispanic or Latino																			
Category Total	0	2	0	1	0	4	2	0	0	0	1	1	0	0	0	0	0	0	0
Center Percent	0.0%	6.9%	0	3.8%	0.0%	9.8%	9.1%	0	0.0%	0.0%	4.2%	14.3%	0.0%	0	0.0%	0.0%	0.0%	0.0%	0.0%
National Percent [1][2]	N/A	3.6%	N/A	6.3%	9.6%	12.3%	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	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Center Percent	0.0%	0.0%	0	3.8%	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 - 2013, Underrepresented Racial Minorities - 2013, Hispanic or Latino - 2013, 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).

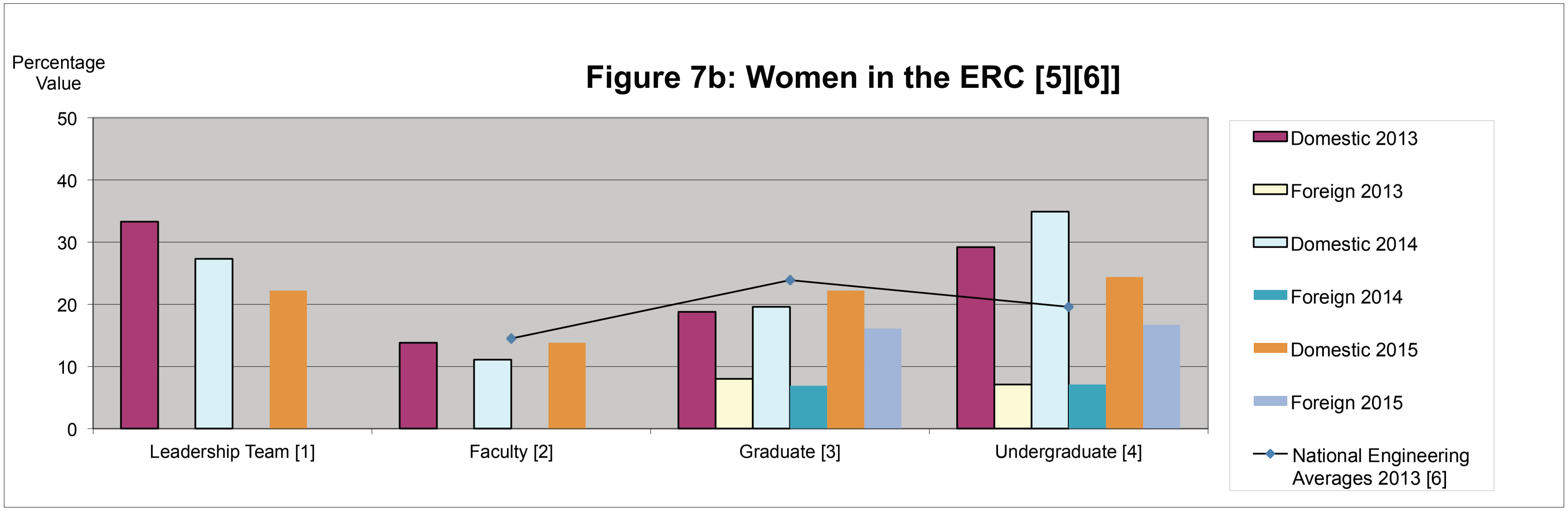
[4]Leadership Team includes Directors, Thrust Leaders, Education Program Leaders, Industrial Liason Officer, Administrative Director, and Research Thrust Management and Strategic Planning.

[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
		RET	Non-RET		Graduate		UG Non-REU	REU			
					Doctoral	Masters					
37	2	2	19	2	57	35	50	25	0	36	237

[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 2013 [6]	N/A	14.5%	23.9%	19.6%
All ERC's 2014 (Domestic)	31%	26.4%	27.6%	37.4%
All ERC's 2014 (Foreign)	16.7%	18.7%	26.4%	34.6%
Domestic Percentage for Engineering Research Center for Compact and Efficient Fluid Power at the University of Minnesota – Twin Cities 2015	22.2%	13.8%	22.2%	24.4%
Foreign Percentage for Engineering Research Center for Compact and Efficient Fluid Power at the University of Minnesota – Twin Cities 2015	0%	0%	16.1%	16.7%

[1] The Leadership Team includes Directors, Thrust Leaders, Industrial Liaison Officer, Education Program Leaders, Administrative Directors, and Research Thrust Management and Strategic Planning.

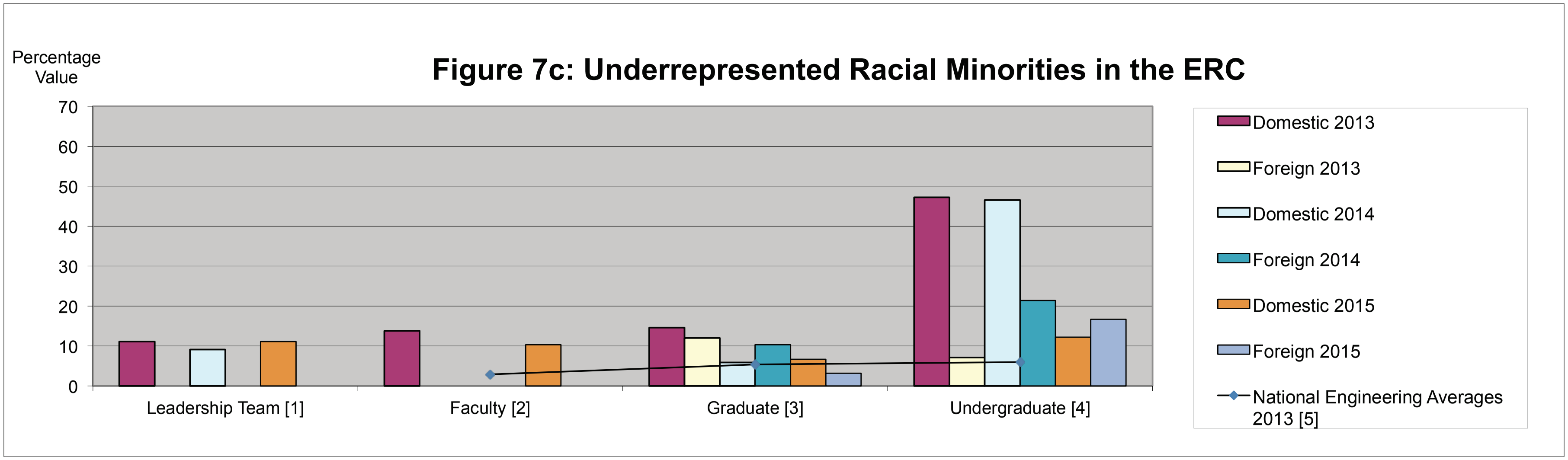
[2] Faculty includes Research - Senior Faculty, Research - Junior Faculty, Research - Visiting Faculty, Curriculum Development and Outreach - Senior Faculty, Curriculum Development and Outreach - Junior Faculty, and Curriculum Development and Outreach - Visiting Faculty.

[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 2013 [5]	N/A	2.9%	5.4%	6%
All ERC's 2014 (Domestic)	9.9%	7.6%	9.6%	18.9%
All ERC's 2014 (Foreign)	0%	2.2%	3.6%	6.4%
Domestic Percentage for Engineering Research Center for Compact and Efficient Fluid Power at the University of Minnesota – Twin Cities 2015	11.1%	10.3%	6.7%	12.2%
Foreign Percentage for Engineering Research Center for Compact and Efficient Fluid Power at the University of Minnesota – Twin Cities 2015	0%	0%	3.2%	16.7%

[1] The Leadership Team includes Directors, Thrust Leaders, Industrial Liaison Officer, Education Program Leaders, Administrative Directors, and Research Thrust Management and Strategic Planning.

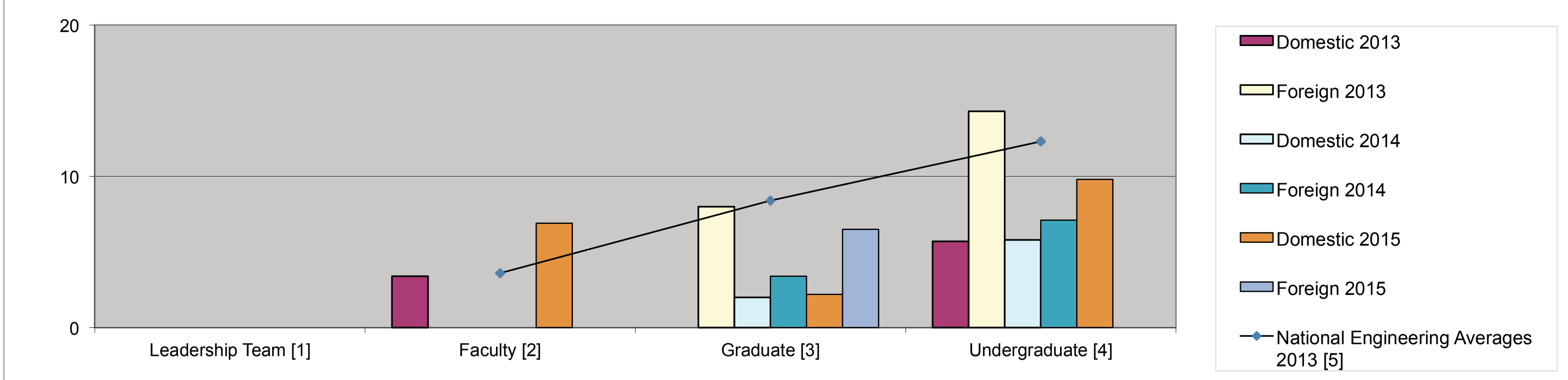
[2] Faculty includes Research - Senior Faculty, Research - Junior Faculty, Research - Visiting Faculty, Curriculum Development and Outreach - Senior Faculty, Curriculum Development and Outreach - Junior Faculty, and Curriculum Development and Outreach - Visiting Faculty.

[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 2013 [5]	N/A	3.6%	8.4%	12.3%
All ERC's 2014 (Domestic)	6.2%	4.8%	9.9%	17.5%
All ERC's 2014 (Foreign)	8.3%	4.4%	3.3%	10.3%
Domestic Percentage for Engineering Research Center for Compact and Efficient Fluid Power at the University of Minnesota – Twin Cities 2015	0%	6.9%	2.2%	9.8%
Foreign Percentage for Engineering Research Center for Compact and Efficient Fluid Power at the University of Minnesota – Twin Cities 2015	0%	0%	6.5%	0%

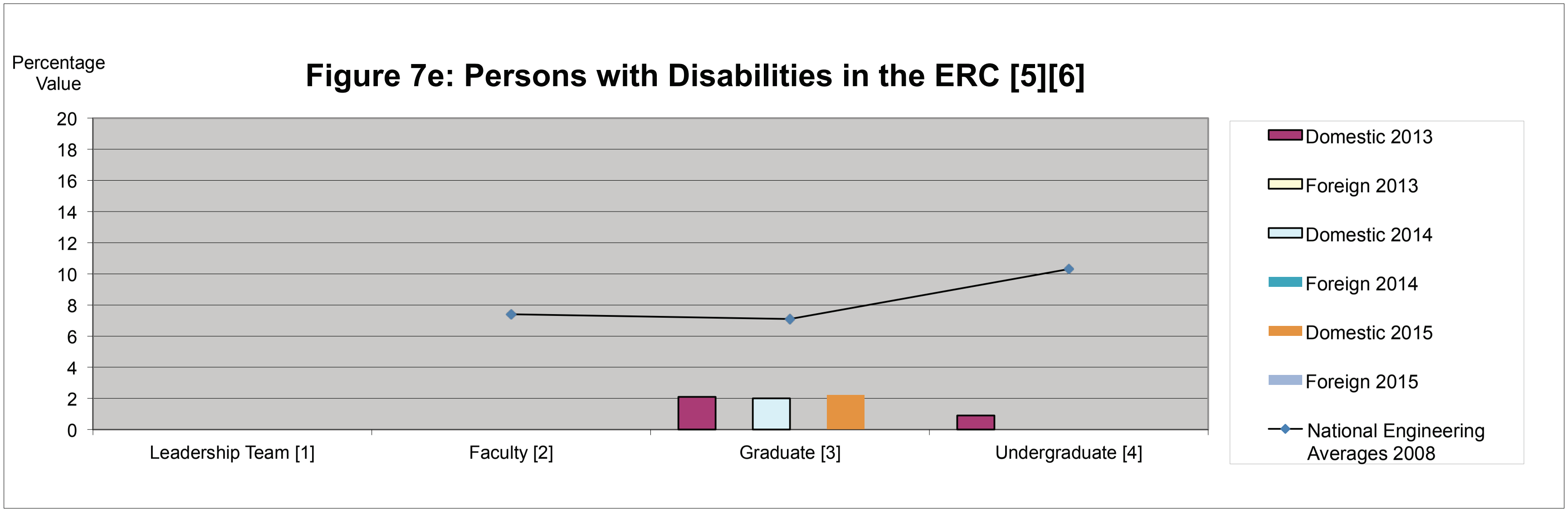
[1] The Leadership Team includes Directors, Thrust Leaders, Industrial Liaison Officer, Education Program Leaders, Administrative Directors, and Research Thrust Management and Strategic Planning.

[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] 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 2014 (Domestic)	3.3%	2%	0.9%	2.3%
All ERC's 2014 (Domestic)	0%	0%	0.1%	0%
Domestic Percentage for Engineering Research Center for Compact and Efficient Fluid Power at the University of Minnesota – Twin Cities 2015	0%	0%	2.2%	0%
Foreign Percentage for Engineering Research Center for Compact and Efficient Fluid Power at the University of Minnesota – Twin Cities 2015	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	10	24%	2	5%	2	5%
Core Partners						
Georgia Institute of Technology	3	13%	0	0%	1	4%
Purdue University	4	19%	1	5%	2	10%
University of Illinois at Urbana-Champaign	5	33%	1	7%	1	7%
Vanderbilt University	2	22%	1	11%	0	0%
Collaborating Institutions						
Bradley University	1	25%	0	0%	0	0%
Clemson University	0	0%	0	0%	0	0%
Iowa State University	0	0%	0	0%	0	0%
Kirkwood Community College	0	0%	0	0%	0	0%
Milwaukee School of Engineering	1	11%	0	0%	0	0%
Missouri University	0	0%	0	0%	0	0%
Morgan State University	0	0%	1	100%	0	0%
National Fluid Power Association	0	0%	0	0%	0	0%
North Carolina Agriculture and Technical State University	5	45%	8	73%	0	0%
Philadelphia Universtiy	0	0%	0	0%	0	0%
Quality Evaluation Designs	2	50%	0	0%	0	0%
Science Museum of Minnesota	0	0%	0	0%	0	0%
University of Florida	0	0%	0	0%	0	0%
University of Wisconsin – Milwaukee	1	100%	0	0%	1	100%
Non-ERC Institutions Providing REU Students						
Arizona State Universtiy	0	0%	0	0%	0	0%
Auburn University	0	0%	0	0%	0	0%
Columbia University	1	100%	0	0%	0	0%
Macalester College	1	100%	0	0%	0	0%
Mankato State Universtiy	0	0%	0	0%	0	0%
Minneapolis Community and Technical College	0	0%	0	0%	1	100%
St. John's University	0	0%	0	0%	0	0%
University of Hartford	1	100%	0	0%	0	0%
University of Rochester	0	0%	0	0%	1	100%
University of Wisconsin- Madison	0	0%	0	0%	0	0%
Yale University	0	0%	0	0%	0	0%
Precollege Partners						
Ashby Public School	1	100%	0	0%	0	0%
Brainerd Public Schools	0	0%	0	0%	0	0%
Capitol Hill Gifted and Talented Magnet	0	0%	0	0%	0	0%
Cooper Middle School	1	100%	0	0%	0	0%
Gainesville Middle School	1	100%	0	0%	0	0%
Georgia Cyber Academy	0	0%	0	0%	0	0%
John Metcalf Jr. High School	0	0%	0	0%	0	0%
Lafayette Jefferson High School	0	0%	0	0%	0	0%
Leadership Preparatory Academy	1	100%	0	0%	0	0%
North Branch Area Public Schools	0	0%	0	0%	0	0%
North Gwinnett Middle School	0	0%	0	0%	0	0%
North Junior High	1	100%	0	0%	0	0%
Osakis Public School	0	0%	0	0%	0	0%
Reden Middle School	1	100%	0	0%	0	0%
Royalton Middle School	0	0%	0	0%	0	0%
Sequoyah Middle School	1	100%	0	0%	0	0%
Steampunk Robotics Homeschool Technology Club	1	100%	0	0%	0	0%
Trickum Middle School	0	0%	0	0%	0	0%
Twin Rivers Middle School	0	0%	0	0%	0	0%
Community Colleges						
Guilford Technical Community College	2	100%	2	100%	0	0%
Louis Stokes Alliances for Minority Participation (LSAMP)						
North Star STEM Alliance	0	0%	0	0%	1	100%
NSF Diversity Program Collaborations (NSF Diversity Program Collaborations)						
National GEM Consortium	0	0%	1	50%	1	50%

[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	$577,117	$0	$577,117	$1,849,340	$2,426,457
2: Compactness	$422,106	$0	$422,106	$0	$422,106
3: Effectiveness	$333,730	$0	$333,730	$286,540	$620,270
Test Beds	$480,000	$0	$480,000	$289,959	$769,959
Research Total	**$1,812,953**	**$0**	**$1,812,953**	**$2,425,839**	**$4,238,792**
Educational Program Total	$337,414	$0	$337,414	$0	$337,414
General Shared Equipment	$0	$0	$0	$0	$0
New Facilities/New Construction	$0	$0	$0	$0	$0
Leadership/Administration/Management	$642,917	$0	$642,917	$0	$642,917
Industrial Collaboration/Innovation Program	$287,000	$0	$287,000	$0	$287,000
Center Related Travel	$67,000	$0	$67,000	$0	$67,000
Indirect Cost	$998,628	$0	$998,628	N/A	$998,628
Functional and Educational Budget Total	**$5,113,244**	**$0**	**$5,113,244**	**$0**	**$5,113,244**
Support Reserved for Future Years	N/A	N/A	$0	N/A	$0
Residual Funds Remaining	$2,780,285	$0	$2,780,285	N/A	$2,780,285
Total	**$6,926,197**	**$0**	**$6,926,197**	**$2,425,839**	**$9,352,036**

Figure 8a: Functional Budget as a percentage of Direct Support

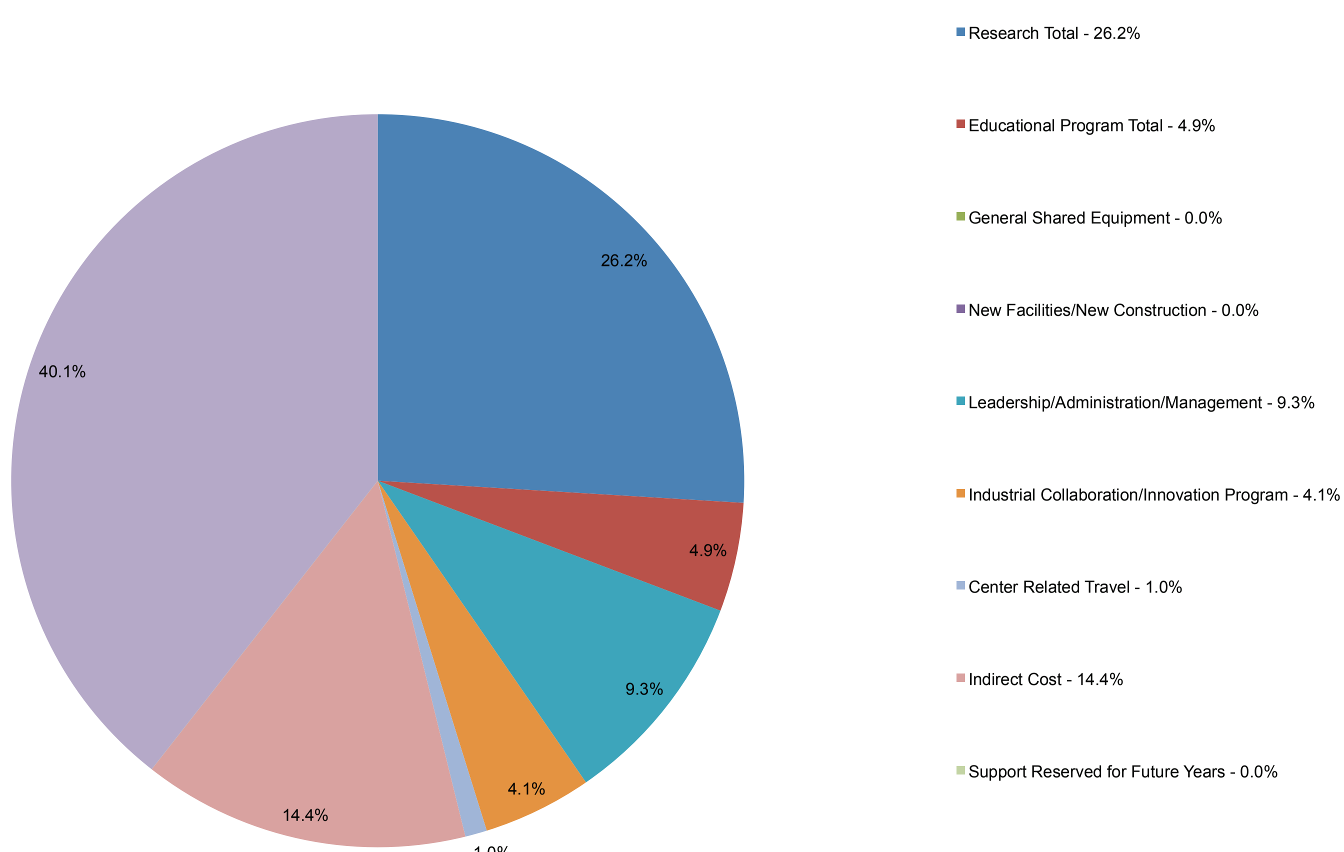


Figure 8b: Functional Budget as a percentage of Associated Project Support

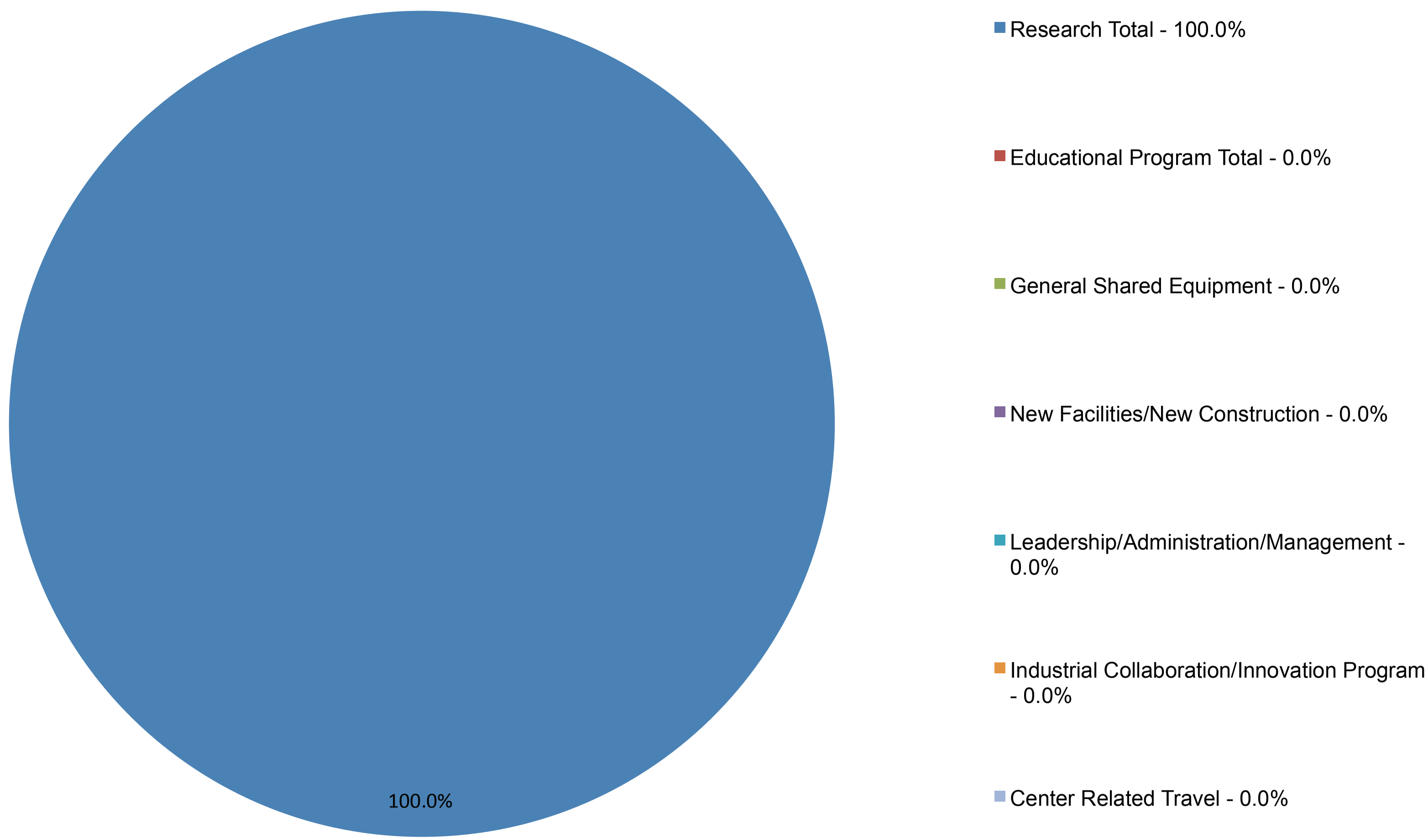


Table 8c: Current Award Year Education Functional Budget

Education Programs	Direct Support		Direct Support Total	Associated Projects	Total Budget
	Unrestricted Cash OR Core Projects	Restricted Cash OR Sponsored Projects			
Precollege Education Activities	$55,776	$0	**$55,776**	$0	**$55,776**
University Education	$92,610	$0	**$92,610**	$0	**$92,610**
Student Leadership Council	$32,994	$0	**$32,994**	$0	**$32,994**
Young Scholars	$0	$0	**$0**	$0	**$0**
REU	$30,034	$0	**$30,034**	$0	**$30,034**
RET	$28,000	$0	**$28,000**	$0	**$28,000**
Assessment	$50,000	$0	**$50,000**	$0	**$50,000**
Community College activities	$0	$0	**$0**	$0	**$0**
Other	$48,000	$0	**$48,000**	$0	**$48,000**
Education Program Total	**$337,414**	**$0**	**$337,414**	**$0**	**$337,414**

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Table 9: Sources of Support

Sources of Support	Early Cumulative Total	Jun 1, 2010 - May 31, 2011	Jun 1, 2011 - May 31, 2012	Jun 1, 2012 - May 31, 2013	Jun 1, 2013 - May 31, 2014	Jun 1, 2014 - May 31, 2015			Cumulative Total [1]
						Received	Promised	Total	
Unrestricted Cash									
Government									
NSF Funding									
NSF ERC Base Award	$12,446,020	$4,010,000	$4,000,000	$4,000,000	$4,000,000	$2,681,000	$0	$2,681,000	$31,137,020
Other NSF (Not ERC Program)	$0	$0	$0	$0	$390,000	$0	$0	$0	$390,000
TOTAL NSF FUNDING	**$12,446,020**	**$4,010,000**	**$4,000,000**	**$4,000,000**	**$4,390,000**	**$2,681,000**	**$0**	**$2,681,000**	**$31,527,020**
Other U.S. Government (Not NSF)	$0	$0	$0	$3,500	$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	**$12,446,020**	**$4,010,000**	**$4,000,000**	**$4,003,500**	**$4,390,000**	**$2,681,000**	**$0**	**$2,681,000**	**$31,530,520**
Industry									
U.S. Industry	$1,854,708	$517,250	$583,817	$443,100	$568,767	$500	$0	$500	$3,968,142
Foreign Industry	$369,000	$119,000	$112,000	$102,000	$122,750	$0	$0	$0	$824,750
Industrial Association	$0	$51,000	$41,000	$41,000	$105,549	$114,228	$0	$114,228	$352,777
TOTAL INDUSTRY FUNDING	**$2,223,708**	**$687,250**	**$736,817**	**$586,100**	**$797,066**	**$114,728**	**$0**	**$114,728**	**$5,145,669**
University									
U.S. University	$2,709,294	$800,000	$800,000	$840,543	$800,000	$536,000	$0	$536,000	$6,485,837
Foreign University	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL UNIVERSITY FUNDING	**$2,709,294**	**$800,000**	**$800,000**	**$840,543**	**$800,000**	**$536,000**	**$0**	**$536,000**	**$6,485,837**
Other									
Private Foundation	$0	$1,000	$0	$0	$0	$491,250	$163,750	$655,000	$656,000
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**	**$1,000**	**$0**	**$0**	**$0**	**$491,250**	**$163,750**	**$655,000**	**$656,000**
Total Unrestricted Cash	**$17,379,022**	**$5,498,250**	**$5,536,817**	**$5,430,143**	**$5,987,066**	**$3,822,978**	**$163,750**	**$3,986,728**	**$43,818,026**
Restricted Cash									
NSF Funding									
NSF ERC Program Special Purpose Awards and Supplements	$169,748	$281,724	$39,989	$52,000	$5,120	$0	$0	$0	$548,581
Other NSF (Not ERC Program)	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL NSF FUNDING	**$169,748**	**$281,724**	**$39,989**	**$52,000**	**$5,120**	**$0**	**$0**	**$0**	**$548,581**
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	$0	$500	$1,000	$0	$1,000	$1,500
Foreign Industry	$0	$0	$0	$0	$0	$0	$0	$0	$0
Industrial Association	$0	$0	$0	$0	$0	$500	$0	$500	$500
TOTAL INDUSTRY FUNDING	**$0**	**$0**	**$0**	**$0**	**$500**	**$1,500**	**$0**	**$1,500**	**$2,000**
University									
U.S. University	$0	$0	$0	$0	$500	$1,500	$0	$1,500	$2,000
Foreign University	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL UNIVERSITY FUNDING	**$0**	**$0**	**$0**	**$0**	**$500**	**$1,500**	**$0**	**$1,500**	**$2,000**
Other									
Private Foundation	$0	$0	$0	$0	$0	$10,000	$0	$10,000	$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**	**$0**	**$10,000**	**$0**	**$10,000**	**$10,000**
Total Restricted Cash - Non Translational	**$0**	**$0**	**$0**	**$0**	**$1,000**	**$13,000**	**$0**	**$13,000**	**$14,000**
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	$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

Sources of Support	Early Cumulative Total	Jun 1, 2010 - May 31, 2011	Jun 1, 2011 - May 31, 2012	Jun 1, 2012 - May 31, 2013	Jun 1, 2013 - May 31, 2014	Jun 1, 2014 - May 31, 2015			Cumulative Total [1]
						Received	Promised	Total	
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**	**$0**	**$0**	**$0**	**$0**
Total Restricted Cash	**$169,748**	**$281,724**	**$39,989**	**$52,000**	**$6,120**	**$13,000**	**$0**	**$13,000**	**$562,581**
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	$2,316,244	$316,643	$589,405	$1,975,463	$2,179,981	$2,065,994	N/A	$2,065,994	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	**$2,365,900**	**$316,643**	**$589,405**	**$1,975,463**	**$2,179,981**	**$2,065,994**	**N/A**	**$2,065,994**	**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	**$2,365,900**	**$316,643**	**$589,405**	**$1,975,463**	**$2,179,981**	**$2,065,994**	**N/A**	**$2,065,994**	**N/A**
Industry									
U.S. Industry	$1,969,313	$297,485	$464,648	$455,211	$621,271	$860,475	N/A	$860,475	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	**$1,969,313**	**$297,485**	**$464,648**	**$455,211**	**$621,271**	**$860,475**	**N/A**	**$860,475**	**N/A**
University									
U.S. University	$940,033	$232,757	$184,201	$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	**$940,033**	**$232,757**	**$184,201**	**$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]	**$5,275,246**	**$846,885**	**$1,238,254**	**$2,430,674**	**$2,801,252**	**$2,926,469**	**N/A**	**$2,926,469**	**N/A**
Associated Projects [3]									
NSF Funding									
NSF ERC Program	$0	$640,109	$0	$0	$0	$0	$0	$0	$640,109
Other NSF (Not ERC Program)	$340,543	$640,749	$591,183	$508,500	$635,485	$374,587	$178,255	$552,842	$3,269,302
TOTAL NSF FUNDING	**$340,543**	**$1,280,858**	**$591,183**	**$508,500**	**$635,485**	**$374,587**	**$178,255**	**$552,842**	**$3,909,411**
Associated Projects - Non Translational [3]									
Government									
Other U.S. Government (Not NSF)	$2,064,782	$181,654	$13,320	$69,707	$10,629	$15,429	$0	$15,429	$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
Quasi-government research organization	$0	$57,276	$0	$0	$0	$0	$0	$0	$57,276
TOTAL GOVERNMENT FUNDING	**$2,064,782**	**$238,930**	**$13,320**	**$69,707**	**$10,629**	**$15,429**	**$0**	**$15,429**	**$2,412,797**
Industry									
U.S. Industry	$2,840,547	$350,123	$0	$1,974	$93,366	$7,962	$0	$7,962	$3,293,972
Foreign Industry	$0	$52,865	$78,000	$70,417	$167,562	$120,700	$69,714	$190,414	$559,258
Industrial Association	$0	$71,067	$0	$0	$0	$0	$0	$0	$71,067
TOTAL INDUSTRY FUNDING	**$2,840,547**	**$474,055**	**$78,000**	**$72,391**	**$260,928**	**$128,662**	**$69,714**	**$198,376**	**$3,924,297**
University									
U.S. University	$0	$0	$128,550	$5,826	$500	$5,650	$22,600	$28,250	$163,126

Sources of Support	Early Cumulative Total	Jun 1, 2010 - May 31, 2011	Jun 1, 2011 - May 31, 2012	Jun 1, 2012 - May 31, 2013	Jun 1, 2013 - May 31, 2014	Jun 1, 2014 - May 31, 2015			Cumulative Total [1]
						Received	Promised	Total	
Foreign University	$0	$32,000	$13,714	$3,077	$0	$0	$0	$0	$48,791
TOTAL UNIVERSITY FUNDING	**$0**	**$32,000**	**$142,264**	**$8,903**	**$500**	**$5,650**	**$22,600**	**$28,250**	**$211,917**
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	$166,620	$527,388	$1,099,920	$1,549,850	$0	$0	$0	$0	$3,343,778
TOTAL OTHER FUNDING	**$166,620**	**$527,388**	**$1,099,920**	**$1,549,850**	**$0**	**$0**	**$0**	**$0**	**$3,343,778**
Total Associated Projects - Non Translational	**$5,071,949**	**$1,272,373**	**$1,333,504**	**$1,700,851**	**$272,057**	**$149,741**	**$92,314**	**$242,055**	**$9,892,789**
Associated Projects - Translational [3]									
Government									
Other U.S. Government (Not NSF)	$0	$0	$187,208	$60,667	$0	$2,000	$1,600	$3,600	$251,475
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**	**$187,208**	**$60,667**	**$0**	**$2,000**	**$1,600**	**$3,600**	**$251,475**
Industry									
U.S. Industry	$0	$0	$115,701	$76,362	$183,430	$168,776	$76,638	$245,414	$620,907
Foreign Industry	$0	$5,000	$83,974	$37,583	$0	$0	$0	$0	$126,557
Industrial Association	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL INDUSTRY FUNDING	**$0**	**$5,000**	**$199,675**	**$113,945**	**$183,430**	**$168,776**	**$76,638**	**$245,414**	**$747,464**
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	$44,750	$925,882	$1,009,398	$372,530	$1,381,928	$2,352,560
TOTAL OTHER FUNDING	**$0**	**$0**	**$0**	**$44,750**	**$925,882**	**$1,009,398**	**$372,530**	**$1,381,928**	**$2,352,560**
Total Associated Projects - Translational	**$0**	**$5,000**	**$386,883**	**$219,362**	**$1,109,312**	**$1,180,174**	**$450,768**	**$1,630,942**	**$3,351,499**
Total Associated Projects	**$5,412,492**	**$2,558,231**	**$2,311,570**	**$2,428,713**	**$2,016,854**	**$1,704,502**	**$721,337**	**$2,425,839**	**$17,153,699**
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									
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	$0	$39,253	$11,957	$275,816	$27,888	$500	$28,388	$939,816
Foreign Industry	$0	$0	$500	$2,300	$13,600	$6,000	$0	$6,000	$22,400
Industrial Association	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL INDUSTRY FUNDING	**$584,402**	**$0**	**$39,753**	**$14,257**	**$289,416**	**$33,888**	**$500**	**$34,388**	**$962,216**

Sources of Support	Early Cumulative Total	Jun 1, 2010 - May 31, 2011	Jun 1, 2011 - May 31, 2012	Jun 1, 2012 - May 31, 2013	Jun 1, 2013 - May 31, 2014	Jun 1, 2014 - May 31, 2015			Cumulative Total [1]
						Received	Promised	Total	
University									
U.S. University	$0	$0	$0	$0	$15,550	$500	$0	$500	$16,050
Foreign University	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL UNIVERSITY FUNDING	**$0**	**$0**	**$0**	**$0**	**$15,550**	**$500**	**$0**	**$500**	**$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**	**$0**	**$39,753**	**$14,257**	**$304,966**	**$34,388**	**$500**	**$34,888**	**$978,266**
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	$0	$1	$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**	**$0**	**$1**	**$0**	**$0**	**$0**	**$22,501**
University									
U.S. University	$16,200	$0	$8,000	$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**	**$0**	**$8,000**	**$0**	**$0**	**$0**	**$0**	**$0**	**$83,700**
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	$270,000	$0	$270,000	$270,000
TOTAL OTHER FUNDING	**$0**	**$0**	**$0**	**$0**	**$0**	**$270,000**	**$0**	**$270,000**	**$270,000**
Total Value of Visting Personnel	**$98,200**	**$0**	**$8,000**	**$0**	**$1**	**$270,000**	**$0**	**$270,000**	**$376,201**
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	$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									

Sources of Support	Early Cumulative Total	Jun 1, 2010 - May 31, 2011	Jun 1, 2011 - May 31, 2012	Jun 1, 2012 - May 31, 2013	Jun 1, 2013 - May 31, 2014	Jun 1, 2014 - May 31, 2015			Cumulative Total [1]
						Received	Promised	Total	
U.S. Industry	$0	$219,621	$106,408	$0	$0	$0	$0	$0	$326,029
Foreign Industry	$0	$9,000	$62,308	$0	$0	$0	$0	$0	$71,308
Industrial Association	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL INDUSTRY FUNDING	**$0**	**$228,621**	**$168,716**	**$0**	**$0**	**$0**	**$0**	**$0**	**$397,337**
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	**$169,032**	**$228,621**	**$168,716**	**$0**	**$0**	**$0**	**$0**	**$0**	**$566,369**
Total In-Kind Support, All Sources	**$1,477,225**	**$228,621**	**$216,469**	**$14,257**	**$304,967**	**$304,388**	**$500**	**$304,888**	**$2,546,427**
Total Cash Support, All Sources [2]	**$22,824,016**	**$6,626,859**	**$6,815,060**	**$7,912,817**	**$8,794,438**	**$6,762,447**	**$163,750**	**$6,926,197**	**$44,380,607**
Percent Non-ERC Program Cash	**35%**	**30%**	**32%**	**24%**	**30%**	**30%**	**100%**	**31%**	**29%**
Total Cash + In-Kind	**$24,301,241**	**$6,855,480**	**$7,031,529**	**$7,927,074**	**$9,099,405**	**$7,066,835**	**$164,250**	**$7,231,085**	**$46,927,034**
Grand Total (Cash + In-Kind + Associated Projects)	**$29,713,733**	**$9,413,711**	**$9,343,099**	**$10,355,787**	**$11,116,259**	**$8,771,337**	**$885,587**	**$9,656,924**	**$64,080,733**

[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.

Explanation of Residual Funds entry in Direct Sources of Support - Cash

Table 10: Annual Expenditures and Budgets

Total Direct Center Cash Support	Early Cumulative Total [1]	Jun-01-2010 - May 31-2011	Jun-01-2011 - May 31-2012	Jun-01-2012 - May 31-2013	Jun-01-2013 - May 31-2014	Jun-01-2014 - May 31-2015	Proposed Budget - Next Award Year
Direct Cash Support (All Sources)	**$17,548,770**	**$5,779,974**	**$5,576,806**	**$5,482,143**	**$5,993,186**	**$3,999,728**	**N/A**
Multi-year Support brought forward from Prior Year (All Sources)	**N/A**	**N/A**	**N/A**	**$0**	**$0**	**$0**	**N/A**
Residual Funds brought forward from Prior Year (All Sources)	**$5,275,246**	**$846,885**	**$1,238,254**	**$2,430,674**	**$2,801,252**	**$2,934,837**	**N/A**
Total Direct Center Cash Support	**$22,824,016**	**$6,626,859**	**$6,815,060**	**$7,912,817**	**$8,794,438**	**$6,934,565**	**N/A**

Expenses	Early Cumulative Total [1]	Jun-01-2010 - May 31-2011	Jun-01-2011 - May 31-2012	Jun-01-2012 - May 31-2013	Jun-01-2013 - May 31-2014	Jun-01-2014 - May 31-2015	Proposed Budget - Next Award Year
Salaries & Benefits							
A. Senior Personnel: PI/PD, Co-PIs, Faculty and Other Senior Associates	$1,538,706	$505,207	$741,340	$354,294	$559,711	$431,749	$360,635
B. Other Personnel	$6,318,796	$1,853,739	$1,133,600	$1,569,030	$1,667,187	$1,286,032	$1,074,206
Postdoctoral associates	$485,443	$19,180	$0	$46,368	$48,240	$37,211	$31,082
Other professionals (technician, programmer, etc.)	$620,314	$113,991	$112,105	$0	$59,841	$46,160	$38,557
Graduate Students	$2,799,495	$1,117,358	$799,764	$816,483	$937,392	$723,084	$603,983
Undergraduate students	$494,030	$59,537	$43,105	$80,342	$64,823	$50,003	$41,767
Secretarial - clerical	N/A	$188,104	$143,463	$104,769	$129,866	$100,176	$83,675
Other	$1,919,514	$355,569	$35,163	$521,068	$427,025	$329,398	$275,142
C. Fringe Benefits	$1,851,048	$587,333	$562,251	$440,533	$544,014	$419,641	$350,521
Total Salaries & Benefits (A+B+C)	**$9,708,550**	**$2,946,279**	**$2,437,191**	**$2,363,857**	**$2,770,912**	**$2,137,422**	**$1,785,362**

Other Expenses							
D. Equipment	$832,713	$147,311	$83,508	$91,183	$100,238	$77,322	$64,586
E. Travel	N/A	$253,621	$175,231	$250,789	$237,142	$182,926	$152,796
F. Participant Support	N/A	$161,046	$111,808	$160,576	$120,031	$92,589	$77,339
G. Other Direct Costs	$2,957,455	$629,139	$396,298	$830,931	$802,684	$619,174	$517,188
H. Direct Costs Total (A through G)	**$13,498,718**	**$4,137,396**	**$3,204,036**	**$3,697,336**	**$4,031,007**	**$3,109,433**	**$2,597,271**
I. Indirect Costs	**$4,154,038**	**$1,251,209**	**$993,916**	**$1,324,508**	**$1,341,857**	**$1,036,478**	**$864,589**
TOTAL Expenditures and Budgets (A through I)	**$17,652,756**	**$5,388,605**	**$4,197,952**	**$5,021,844**	**$5,372,864**	**$4,145,911**	**$3,461,860**

Totals and Residuals	Early Cumulative Total [1]	Jun-01-2010 - May 31-2011	Jun-01-2011 - May 31-2012	Jun-01-2012 - May 31-2013	Jun-01-2013 - May 31-2014	Jun-01-2014 - May 31-2015	Proposed Budget - Next Award Year
Total Direct Center Cash Support	**$22,824,016**	**$6,626,859**	**$6,815,060**	**$7,912,817**	**$8,794,438**	**$6,934,565**	**N/A**
J. TOTAL Expenditures and Budgets (A through I)	$17,652,756	$5,388,605	$4,197,952	$5,021,844	$5,372,864	$4,145,911	$3,461,860
K. Support Reserved for Future Years	N/A	N/A	N/A	$0	$0	$0	N/A
L. Residual Funds Remaining	$4,278,673	$1,238,254	$262,725	$2,890,973	$3,421,574	$2,788,654	$0
Balance (Subtract J+K+L from Current Year Support)	**$892,587**	**$0**	**$2,354,383**	**$0**	**$0**	**$0**	**N/A**

[1] - For Centers in operation for more than five years.

Explanation for Remaining Residual Funds

Residuals are higher than estimated due to a budget reallocation process at the end of year 8 (May 31, 2014) and into Year 9 (June 1, 2014 - May 31, 2015). Sub-contract invoices in large part are not paid in the year the expense occurs due to late billing/payment of invoices. This process is being improved under new federal guidelines and university processes.

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Table 11: Modes of Support, by Industry and Other Practitioner Organizations

Organization	Jun 1, 2013 - May 31, 2014						Jun 1, 2014 - May 31, 2015						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													
Afton Chemical Corp.	$10,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Air Logic	$1,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
AS Pindel	$667	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Bobcat	$15,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Bosch Rexroth Corporation	$50,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Caterpillar, Inc.	$50,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
CNH America, Inc.	$40,000	$0	$0	$0	$101,807	$0	$0	$0	$0	$0	$0	$0	$0
Concentric AB/Haldex	$6,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Deltrol Fluid Products	$5,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Enfield Technologies	$5,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Evonik Additives, USA, Inc.	$10,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Exxon Mobil	$40,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Freudenberg - NOK	$6,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Gates Corporation	$40,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Heco Gear, Inc.	$2,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Hitachi Construction Machinery	$13,750	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Hoowaki, LLC	$1,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Husco International, Inc.	$40,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Idemitsu Kosan Co., Ltd.	$2,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
JCB Research	$6,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Main Manufacturing Products, Inc.	$1,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Master Pneumatic-Detroit, Inc.	$1,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
National Tube Supply Company	$1,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Netshape Technologies	$15,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Nexen Group, Inc.	$1,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Pall Corporation	$21,300	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Poclain Hydraulics	$15,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Quality Control Corporation	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Ross Controls	$5,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Shell Global Solutions	$12,000	$0	$0	$13,462	$0	$0	$0	$0	$0	$0	$0	$0	$0
Simerics, Inc.	$1,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
StorWatts Inc.	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Sun Hydraulics	$6,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
The Lubrizol Corporation	$5,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Trelleborg Sealing Solutions	$6,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Walvoil Fluid Power	$6,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Woodward, Inc.	$15,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Total Members	**$454,717**	**$0**	**$0**	**$13,462**	**$101,807**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
Non-Member Organizations: Funders of Sponsored Projects, Funders of Associated Projects, and Contributing Organizations													
Casappa S.p.A.	$0	$0	$0	$104,100	$0	$0	$0	$0	$0	$73,677	$0	$0	$36,827
Cat Pumps	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$77,949	$0	$38,974
Confidential Organization (optional use for associated or sponsored projects only)	$0	$0	$0	$0	$925,882	$0	$0	$0	$0	$0	$1,009,398	$0	$372,530
Cummins Engines	$0	$0	$0	$39,000	$0	$0	$0	$0	$0	$0	$0	$0	$0
Dae Jin Hydraulics - TECPOS	$0	$0	$0	$50,000	$0	$0	$0	$0	$0	$27,083	$0	$0	$22,917
Danfoss	$50,000	$0	$0	$0	$6,662	$22,000	$0	$0	$0	$0	$54,553	$4,400	$27,277
Deere and Company	$15,000	$0	$0	$0	$37,200	$0	$0	$0	$0	$0	$15,500	$0	$0
Donaldson Company	$0	$0	$0	$0	$1	$1	$0	$0	$0	$0	$0	$1	$0
DuPont	$0	$0	$0	$0	$5,182	$0	$0	$0	$0	$0	$0	$0	$0
Eaton Corporation	$50,000	$0	$0	$0	$0	$333	$500	$0	$0	$0	$0	$1,100	$0
FORCE America	$0	$500	$0	$0	$0	$0	$0	$1,000	$0	$0	$0	$0	$0
Hydac Corporation	$0	$0	$0	$0	$0	$2,500	$0	$0	$0	$0	$0	$0	$0
Igus, Inc.	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$200
International Fluid Power Society	$0	$0	$0	$0	$0	$0	$0	$500	$0	$0	$0	$0	$0
John Crane	$0	$0	$0	$14,616	$0	$0	$0	$0	$0	$7,962	$0	$0	$0

Organization	Jun 1, 2013 - May 31, 2014						Jun 1, 2014 - May 31, 2015						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		
Non-Member Organizations: Funders of Sponsored Projects, Funders of Associated Projects, and Contributing Organizations													
Keller America, Inc.	$0	$0	$0	$0	$0	$245,650	$0	$0	$0	$0	$0	$0	$0
Lee Company	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$3,600	$0
Linde Hydraulics Corp.	$5,000	$0	$0	$0	$0	$3,600	$0	$0	$0	$0	$0	$0	$0
Mico, Inc.	$500	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Midwest Precision	$0	$0	$0	$18,750	$0	$0	$0	$0	$0	$0	$0	$0	$0
Minneapolis Veterans Administration Medical Center	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$2,000	$0	$1,600
Moog, Inc.	$15,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$17,000	$0
National Defense Science and Engineering Fellowship Grant (NDSEG)	$0	$0	$0	$10,629	$0	$0	$0	$0	$0	$15,429	$0	$0	$0
National Fluid Power Association	$105,549	$0	$0	$0	$0	$0	$114,228	$0	$0	$0	$0	$0	$0
NFPA Education and Technology Foundation	$0	$0	$0	$0	$0	$0	$491,250	$10,000	$0	$0	$0	$0	$163,750
Parker Hannifin Corporation	$100,300	$0	$0	$0	$0	$2,633	$0	$0	$0	$0	$0	$1,787	$0
Stanadyne Corporation	$0	$0	$0	$0	$0	$2,700	$0	$0	$0	$0	$0	$0	$0
Takako Industries	$1,000	$0	$0	$0	$0	$10,000	$0	$0	$0	$0	$0	$6,000	$0
Thomas Magnete GmbH	$0	$0	$0	$0	$0	$0	$0	$0	$0	$19,940	$0	$0	$9,970
Triumph Aerospace Systems	$0	$0	$0	$21,000	$0	$0	$0	$0	$0	$0	$0	$0	$0
Veraphotonics, Mistras	$0	$0	$0	$0	$32,578	$0	$0	$0	$0	$0	$20,774	$0	$10,387
WIKA	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$300
Total Non-Members	**$342,349**	**$500**	**$0**	**$258,095**	**$1,007,505**	**$289,417**	**$605,978**	**$11,500**	**$0**	**$144,091**	**$1,180,174**	**$33,888**	**$684,732**
Total	**$797,066**	**$500**	**$0**	**$271,557**	**$1,109,312**	**$289,417**	**$605,978**	**$11,500**	**$0**	**$144,091**	**$1,180,174**	**$33,888**	**$684,732**

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
1A.2: Control and Prognostics for Hybrid Displacement Control Systems	No	No			Enrique		Busquets		Purdue University	Graduate Researcher	Mechanical Engineering	Research - Doctoral Student Curriculum - Doctoral Student
1A.2: Control and Prognostics for Hybrid Displacement Control Systems	Yes	Yes			Monika	M	Ivantysynova		Purdue University			Leadership/Administration - Thrust Leader
1B.1: Next Steps towards Virtual Prototyping of Pumps and Motors	Yes	Yes			Monika	M	Ivantysynova		Purdue University			Leadership/Administration - Thrust Leader
1B.1: Next Steps towards Virtual Prototyping of Pumps and Motors	No	No		Mr.	Andrew	T	Schenk		Purdue University			Research - Doctoral Student Curriculum - Doctoral Student
1B.1: Next Steps towards Virtual Prototyping of Pumps and Motors	No	No		Ms.	Natalie		Spencer		Purdue University	Graduate Research Assistant	Mechanical Engineering	Research - Master's Student Curriculum - Master's Student
1B.1: Next Steps towards Virtual Prototyping of Pumps and Motors	No	No			Ashley		Wondergem		Purdue University			Research - Doctoral Student
1B.1: Next Steps towards Virtual Prototyping of Pumps and Motors	No	No			Daniel		Mizell		Purdue University			Research - Doctoral Student
1E.1: Helical Ring On/Off Valve Based 4-quadrant Virtually Variable Displacement Pump/Motor	Yes	Yes		Dr.	Perry	Y	Li		University of Minnesota			Curriculum - Senior Faculty Research - Senior Faculty
1E.1: Helical Ring On/Off Valve Based 4-quadrant Virtually Variable Displacement Pump/Motor	No	No		Mr.	John		Dekarski		University of Minnesota			Research - Master's Student
1E.1: Helical Ring On/Off Valve Based 4-quadrant Virtually Variable Displacement Pump/Motor	No	Yes			Thomas	R	Chase		University of Minnesota			Research - Senior Faculty
1E.3: Actively Controlled Digital Pump Motor	No	No		Mr.	Tyler		Helmus		Purdue University		ABE	Research - Doctoral Student Curriculum - Doctoral Student
1E.3: Actively Controlled Digital Pump Motor	No	No		Mr.	Farid		Breidi		Purdue University	Graduate Student	Agricultural and Biological Engineering	Research - Doctoral Student Curriculum - Doctoral Student
1E.3: Actively Controlled Digital Pump Motor	Yes	Yes			John	H	Lumkes	Jr.	Purdue University	Assistant Professor		Research - Junior Faculty Curriculum - Junior Faculty
1E.3: Actively Controlled Digital Pump Motor	No	Yes			Monika	M	Ivantysynova		Purdue University			Leadership/Administration - Thrust Leader
1E.4: Piston-by-piston control of pumps and motors using mechanical methods	No	No			Mike	B	Rannow		University of Minnesota			Research - Doctoral Student
1E.4: Piston-by-piston control of pumps and motors using mechanical methods	Yes	Yes		Dr.	Perry	Y	Li		University of Minnesota			Curriculum - Senior Faculty Research - Senior Faculty
1E.4: Piston-by-piston control of pumps and motors using mechanical methods	No	No		Mr.	John		Dekarski		University of Minnesota			Research - Master's Student
1E.4: Piston-by-piston control of pumps and motors using mechanical methods	No	No		Mr.	Chad		Larish		University of Minnesota			Research - Master's Student
1E.4: Piston-by-piston control of pumps and motors using mechanical methods	No	Yes			Thomas	R	Chase		University of Minnesota			Research - Senior Faculty
1E.5: System Configuration & Control Using Hydraulic Transformers	No	No		Mr.	Pieter		Gagnon		University of Minnesota			Research - Master's Student
1E.5: System Configuration & Control Using Hydraulic Transformers	No	No		Mr.	Sangyoon		Lee		University of Minnesota		Mechanical Engineering	Research - Doctoral Student
1E.5: System Configuration & Control Using Hydraulic Transformers	Yes	Yes		Dr.	Perry	Y	Li		University of Minnesota			Curriculum - Senior Faculty Research - Senior Faculty
1E.6: High Performance Valves Enabled by Kinetic Energy	No	No		Dr.	Perry	Y	Li		University of Minnesota			Curriculum - Senior Faculty Research - Senior Faculty
1E.6: High Performance Valves Enabled by Kinetic Energy	Yes	Yes			John	H	Lumkes	Jr.	Purdue University	Assistant Professor		Research - Junior Faculty Curriculum - Junior Faculty
1E.6: High Performance Valves Enabled by Kinetic Energy	No	No			Jordan		Garrity		Purdue University			Research - Master's Student Curriculum - Master's Student
1E.6: High Performance Valves Enabled by Kinetic Energy	No	No			Shaoping		Xiong		Purdue University		ABE	Research - Doctoral Student
1F.1: Variable Displacement External Gear Machine	Yes	Yes		Dr.	Andrea		Vacca	PhD	Purdue University			Research - Junior Faculty Curriculum - Junior Faculty
1F.1: Variable Displacement External Gear Machine	No	No		Mr.	Sidhant		Gulati	MS	Purdue University			Research - Master's Student
1F.1: Variable Displacement External Gear Machine	No	No		Mr.	Ram Sudarsan		Devendran		Purdue University			Research - Doctoral Student
1G.1: Energy Efficient Fluids	Yes	Yes		Mr.	Paul	W	Michael		Milwaukee School of Engineering	Research Chemist	Fluid Power Institute	Research - Research Staff
1G.1: Energy Efficient Fluids	No	No		Ms.	Shreya		Mettakadapa		Milwaukee School of Engineering	Research Assistant	Mechanical Engineering	Research - Master's Student
1G.1: Energy Efficient Fluids	No	No		Ms.	Shima	s	Shahahmadi		Milwaukee School of Engineering	Graduate Research Assistant	Fluid Power Institute	Research - Master's Student
1G.1: Energy Efficient Fluids	No	No			Sophia	L	Dolan		Columbia University			REU Student - NSF REU Site Award
1G.1: Energy Efficient Fluids	No	No			Thomas	R	Chase		University of Minnesota			Research - Senior Faculty
1G.1: Energy Efficient Fluids	No	No		Dr.	Scott	S	Bair		Georgia Institute of Technology	Regents' Researcher	School of Mechanical Engineering	Research - Senior Faculty
1G.1: Energy Efficient Fluids	No	No			Sophia	L	Dolan		Milwaukee School of Engineering			Curriculum - Undergraduate Student Research - Undergraduate Student
1G.3: Rheological Design for Efficient Fluid Power	No	Yes		Dr.	James	T	Allison	Ph.D.	University of Illinois at Urbana-Champaign	Assistant Professor	Industrial and Enterprise Systems Engineering	Research - Junior Faculty
1G.3: Rheological Design for Efficient Fluid Power	No	No			Nikita		Dutta		Yale University			REU Student - NSF REU Site Award

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
1G.3: Rheological Design for Efficient Fluid Power	No	No			Jonathon		Schuh		University of Illinois at Urbana-Champaign			Research - Master's Student
1G.3: Rheological Design for Efficient Fluid Power	No	No			Nikita		Dutta		University of Illinois at Urbana-Champaign			Curriculum - Undergraduate Student Research - Undergraduate Student
1G.3: Rheological Design for Efficient Fluid Power	Yes	Yes		Dr.	Randy	H	Ewoldt		University of Illinois at Urbana-Champaign	Assistant Professor	Department of Mechanical Science and Engineering	Research - Junior Faculty Curriculum - Junior Faculty
1G.3: Rheological Design for Efficient Fluid Power	No	No			Lakshmi	G	Rao		University of Illinois at Urbana-Champaign			Research - Master's Student
1J.1: Hydraulic Transmissions for Wind Power	No	No		Mr.	Biswaranjan		Mohanty		University of Minnesota			Research - Doctoral Student
1J.1: Hydraulic Transmissions for Wind Power	No	Yes			Brad		Bohlmann		University of Minnesota	Sustainability Director	Mechanical Engineering	Curriculum - Staff Leadership/Administration - Staff
1J.1: Hydraulic Transmissions for Wind Power	Yes	Yes			Kim	A	Stelson		University of Minnesota	Professor	Mechanical Engineering	Leadership/Administration - Director Curriculum - Senior Faculty Research - Senior Faculty
1J.1: Hydraulic Transmissions for Wind Power	No	No		Dr.	Feng		Wang		University of Minnesota	Postdoctoral associate	Mechanical Engineering	Research - Postdoc
1J.2: A Novel Pressure-Controlled Hydro-Mechanical Transmission	Yes	Yes			Kim	A	Stelson		University of Minnesota	Professor	Mechanical Engineering	Leadership/Administration - Director Curriculum - Senior Faculty Research - Senior Faculty
1J.2: A Novel Pressure-Controlled Hydro-Mechanical Transmission	No	No		Mr.	Biswaranjan		Mohanty		University of Minnesota			Research - Doctoral Student
2B.2: Miniature HCCI Free Piston Engine Compressor	No	No		Mr.	Dustin		Johnson		University of Minnesota	student	Mechanical Engineering	Research - Master's Student
2B.2: Miniature HCCI Free Piston Engine Compressor	Yes	Yes			William		Durfee		University of Minnesota	Professor	Mechanical Engineering	Curriculum - Senior Faculty
2B.2: Miniature HCCI Free Piston Engine Compressor	No	Yes		Dr.	David	B	Kittelson		University of Minnesota	Professor	Mechanical Engineering	Research - Senior Faculty
2B.3: Free Piston Engine Hydraulic Pump	No	No			Ke		Li		University of Minnesota			Research - Doctoral Student
2B.3: Free Piston Engine Hydraulic Pump	Yes	Yes		Dr.	Zongxuan		Sun		University of Minnesota			Research - Junior Faculty Curriculum - Junior Faculty Leadership/Administration - Research Thrust Management and Strategic Planning
2B.3: Free Piston Engine Hydraulic Pump	No	No		Mr.	Chen		Zhang	PhD	University of Minnesota	PhD candidate	Mechanical engineering	Research - Doctoral Student
2B.4: Controlled Stirling Thermocompressors	No	No			Anna		Winkelmann		Vanderbilt University			Research - Doctoral Student Curriculum - Doctoral Student
2B.4: Controlled Stirling Thermocompressors	No	No			Nithin		Kumar		Vanderbilt University			REU Student - ERC's Own REU Curriculum - Undergraduate Student Research - Undergraduate Student
2B.4: Controlled Stirling Thermocompressors	Yes	Yes		Dr.	Eric	J	Barth		Vanderbilt University			Leadership/Administration - Research Thrust Management and Strategic Planning Research - Senior Faculty
2C.3: Flywheel Accumulator for Compact Energy Storage	No	No			Paul		Cronk		University of Minnesota			Research - Doctoral Student
2C.3: Flywheel Accumulator for Compact Energy Storage	No	No		Mr.	Kyle	G	Strohmaier		University of Minnesota			Research - Master's Student
2C.3: Flywheel Accumulator for Compact Energy Storage	Yes	Yes		Dr.	James	D	Van de Ven		University of Minnesota	Assistant Professor	Mechanical Engineering	Research - Junior Faculty Curriculum - Junior Faculty Leadership/Administration - Education Program Leader
2F.1: Soft Pneumatic Actuator for Arm Orthosis	No	Yes	co-PI	Dr.	Brooke		Slavens		University of Wisconsin – Milwaukee			Research - Junior Faculty
2F.1: Soft Pneumatic Actuator for Arm Orthosis	Yes	Yes	Leader	Dr.	Elizabeth	T	Hsiao-Wecksler	PhD	University of Illinois at Urbana-Champaign	Associate Professor	Department of Mechanical Science & Engineering	Curriculum - Senior Faculty Research - Senior Faculty
2F.1: Soft Pneumatic Actuator for Arm Orthosis	No	Yes		Dr.	Girish		Krishnan	PhD	University of Illinois at Urbana-Champaign			Research - Junior Faculty
2F.1: Soft Pneumatic Actuator for Arm Orthosis	No	Yes			Placid		Ferreira		University of Illinois at Urbana-Champaign			Research - Senior Faculty
2F.1: Soft Pneumatic Actuator for Arm Orthosis	No	No		Mr.	Gaurav		Singh		University of Illinois at Urbana-Champaign			Research - Doctoral Student
2F.1: Soft Pneumatic Actuator for Arm Orthosis	No	Yes	co-PI	Dr.	Sameh		Tawfick	PhD	University of Illinois at Urbana-Champaign	Assistant Professor	Mechanical Science and Engineering	Research - Junior Faculty
2F.1: Soft Pneumatic Actuator for Arm Orthosis	No	No			Deen		Farooq		University of Illinois at Urbana-Champaign			Research - Master's Student
2F: MEMS Proportional Pneumatic Valve	No	No		Mr.	Nebiyu		Fikru		University of Minnesota	Graduate Research Assistant	Mechanical Engineering	Research - Doctoral Student
2F: MEMS Proportional Pneumatic Valve	Yes	Yes			Thomas	R	Chase		University of Minnesota			Research - Senior Faculty
2F: MEMS Proportional Pneumatic Valve	No	No		Mr.	Erik		Hemstad		University of Minnesota			Research - Master's Student
2G: Fluid Powered Surgery and Rehabilitation via Compact Integrated Systems	No	No			Charles		Williams		Milwaukee School of Engineering			Research - Master's Student
2G: Fluid Powered Surgery and Rehabilitation via Compact Integrated Systems	No	No		Mr.	Jonathon	E	Slightam		Milwaukee School of Engineering	Graduate Research Assistant	Rapid Prototyping Research	Curriculum - Master's Student
2G: Fluid Powered Surgery and Rehabilitation via Compact Integrated Systems	No	No			Lauren		Lacey		Georgia Institute of Technology			Research - Master's Student
2G: Fluid Powered Surgery and Rehabilitation via Compact Integrated Systems	No	No			Ilya		Kovalenko		Georgia Institute of Technology			Research - Undergraduate Student

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
2G: Fluid Powered Surgery and Rehabilitation via Compact Integrated Systems	No	No		Ms.	Euisun		Kim		Georgia Institute of Technology			Research - Master's Student
2G: Fluid Powered Surgery and Rehabilitation via Compact Integrated Systems	No	No		Mr.	Melih		Turkseven		Georgia Institute of Technology			Research - Doctoral Student Curriculum - Doctoral Student
2G: Fluid Powered Surgery and Rehabilitation via Compact Integrated Systems	No	Yes	co-PI	Mr.	Vito	R	Gervasi		Milwaukee School of Engineering			Research - Research Staff
2G: Fluid Powered Surgery and Rehabilitation via Compact Integrated Systems	No	Yes	co-PI	Dr.	Eric	J	Barth		Vanderbilt University			Leadership/Administration - Research Thrust Management and Strategic Planning Research - Senior Faculty
2G: Fluid Powered Surgery and Rehabilitation via Compact Integrated Systems	No	No			Collin	H	Grimes		Vanderbilt University			Research - Master's Student
2G: Fluid Powered Surgery and Rehabilitation via Compact Integrated Systems	No	No		Mr.	David		Comber		Vanderbilt University	Graduate Research Assistant	Mechanical Engineering	Research - Master's Student Curriculum - Master's Student
2G: Fluid Powered Surgery and Rehabilitation via Compact Integrated Systems	Yes	Yes	Project lead	Dr.	Robert	J	Webster	III	Vanderbilt University			Research - Junior Faculty
2G: Fluid Powered Surgery and Rehabilitation via Compact Integrated Systems	No	Yes	co-PI	Dr.	Jun		Ueda		Georgia Institute of Technology	Associate Professor		Research - Senior Faculty
3A.1: Operator Interface Design Principles for Hydraulics	No	Yes	co-PI	Dr.	Steven	X	Jiang		North Carolina Agriculture and Technical State University	Associate Professor	Industrial and Systems Engineering	Curriculum - Senior Faculty Research - Senior Faculty
3A.1: Operator Interface Design Principles for Hydraulics	No	No		Mr.	Reginald	L	White	Student	North Carolina Agriculture and Technical State University			REU Student - ERC's Own REU Curriculum - Undergraduate Student Research - Undergraduate Student
3A.1: Operator Interface Design Principles for Hydraulics	No	No		Mr.	Sam		Seifert		Georgia Institute of Technology		Mechanical Engineering	Research - Master's Student
3A.1: Operator Interface Design Principles for Hydraulics	Yes	Yes	Lead	Dr.	Wayne	J	Book		Georgia Institute of Technology			Curriculum - Senior Faculty Leadership/Administration - Thrust Leader
3A.1: Operator Interface Design Principles for Hydraulics	No	No			Heather	C	Humphreys		Georgia Institute of Technology		Mechanical Engineering	Research - Doctoral Student Curriculum - Doctoral Student
3A.1: Operator Interface Design Principles for Hydraulics	No	Yes	co-PI		James	D	Huggins		Georgia Institute of Technology	Research Engineer II	Mechanical Engineering	Leadership/Administration - Staff
3A.1: Operator Interface Design Principles for Hydraulics	No	Yes	co-Pi	Dr.	Eui	H	Park		North Carolina Agriculture and Technical State University			Research - Senior Faculty
3A.3: Human Performance Modeling and User Centered Design	No	Yes		Dr.	Eui	H	Park		North Carolina Agriculture and Technical State University			Research - Senior Faculty
3A.3: Human Performance Modeling and User Centered Design	No	No		Mr.	Davorin		Stajsic		North Carolina Agriculture and Technical State University		Industrial and Systems Engineering	Research - Master's Student
3A.3: Human Performance Modeling and User Centered Design	No	No		Ms.	Dorian		Davis		North Carolina Agriculture and Technical State University			Research - Doctoral Student
3A.3: Human Performance Modeling and User Centered Design	No	No			Brittney	H	Jimerson		North Carolina Agriculture and Technical State University			Research - Doctoral Student
3A.3: Human Performance Modeling and User Centered Design	Yes	Yes		Dr.	Steven	X	Jiang		North Carolina Agriculture and Technical State University	Associate Professor	Industrial and Systems Engineering	Curriculum - Senior Faculty Research - Senior Faculty
3A.3: Human Performance Modeling and User Centered Design	No	Yes		Dr.	Zongliang		Jiang		North Carolina Agriculture and Technical State University			Research - Junior Faculty
3B.3: Active Vibration Damping of Mobile Hydraulic Machines	Yes	Yes		Dr.	Andrea		Vacca	PhD	Purdue University			Research - Junior Faculty Curriculum - Junior Faculty
3B.3: Active Vibration Damping of Mobile Hydraulic Machines	No	No		Mr.	Guido Francesco		Ritelli		Purdue University			Research - Doctoral Student
3B.3: Active Vibration Damping of Mobile Hydraulic Machines	No	No			Addison		Alexander		Purdue University		Mechanical Engineering	Research - Doctoral Student
3D.1: Leakage/Seal Friction Reduction in Fluid Power Systems	No	No		Mr.	Yuli		Huang		Georgia Institute of Technology	Graduate Research Assistant	Mechanical Engineering	Research - Doctoral Student
3D.1: Leakage/Seal Friction Reduction in Fluid Power Systems	Yes	Yes			Richard	F	Salant		Georgia Institute of Technology			Research - Senior Faculty
3D.2: New Directions in Elastohydrodynamic Lubrication to Solve Fluid Power Problems	Yes	Yes		Dr.	Scott	S	Bair		Georgia Institute of Technology	Regents' Researcher	School of Mechanical Engineering	Research - Senior Faculty
3E.1: Pressure Ripple Energy Harvester	Yes	Yes		Dr.	Kenneth	A	Cunefare	Ph.D.	Georgia Institute of Technology			Research - Senior Faculty
3E.1: Pressure Ripple Energy Harvester	No	No		Mr.	John	D	Cavanaugh II		Georgia Institute of Technology			Curriculum - Undergraduate Student Research - Undergraduate Student
3E.1: Pressure Ripple Energy Harvester	No	No			Ellen		Skow		Georgia Institute of Technology			Research - Doctoral Student
3E.1: Pressure Ripple Energy Harvester	No	No			Karthika		Venkatasubramanian		Georgia Institute of Technology			Research - Undergraduate Student
3E.1: Pressure Ripple Energy Harvester	No	No			Brian		Hults		Georgia Institute of Technology			Research - Undergraduate Student
3E.1: Pressure Ripple Energy Harvester	No	No			Zack		Koontz		Georgia Institute of Technology			Research - Undergraduate Student
3E.1: Pressure Ripple Energy Harvester	No	No			Tri		Nguyen		Georgia Institute of Technology			REU Student - NSF REU Site Award Curriculum - Undergraduate Student Research - Undergraduate Student
A Characterization of the Pressure-Viscosity and Compressibility Response of Five Oils for a Wide Range of Temperatures	Yes	Yes		Dr.	Scott	S	Bair		Georgia Institute of Technology	Regents' Researcher	School of Mechanical Engineering	Research - Senior Faculty

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
Adjustable Linkage Pump	No	No			Anthony		Knutson		University of Minnesota			Research - Doctoral Student
Adjustable Linkage Pump	No	No			Anirudh Reddy		Ravula		University of Minnesota			Research - Master's Student
Adjustable Linkage Pump	Yes	Yes		Dr.	James	D	Van de Ven		University of Minnesota	Assistant Professor	Mechanical Engineering	Research - Junior Faculty Curriculum - Junior Faculty Leadership/Administration - Education Program Leader
Adjustable Linkage Pump	No	Yes		Mr.	Shawn		Wilhelm		University of Minnesota	Research Assistant	Mechanical Engineering	Research - Doctoral Student
Advanced Hydraulic Systems for Next Generation of Skid Steer Loaders	No	No			Mrudula		Orpe		Purdue University			Research - Master's Student
Advanced Hydraulic Systems for Next Generation of Skid Steer Loaders	Yes	Yes			Monika	M	Ivantysynova		Purdue University			Leadership/Administration - Thrust Leader
Controllable Hydraulic Ankle Prosthesis	No	No			John		Skelton		University of Minnesota			Research - Master's Student
Controllable Hydraulic Ankle Prosthesis	Yes	Yes			William		Durfee		University of Minnesota	Professor	Mechanical Engineering	Curriculum - Senior Faculty
CPS: Synergy: Integrated Modeling Analysis and Synthesis of Miniature Medical Devices	Yes	Yes		Dr.	Pietro		Valdastri	PhD	Vanderbilt University		Mechanical Engineering	Curriculum - Junior Faculty
CPS: Synergy: Integrated Modeling Analysis and Synthesis of Miniature Medical Devices	No	Yes		Dr.	Robert	J	Webster	III	Vanderbilt University			Research - Junior Faculty
Development of a Gasoline Engine Driven Ultra High Pressure Hydraulic Pump	Yes	Yes		Dr.	Andrea		Vacca	PhD	Purdue University			Research - Junior Faculty Curriculum - Junior Faculty
Development of a Gasoline Engine Driven Ultra High Pressure Hydraulic Pump	No	No			Pulkit		Agarwal		Purdue University		Mechanical Engineering	Research - Master's Student
EFRI-RESTOR: Novel Compressed Air Approach for Off-shore Wind Energy Storage	No	Yes			Terrence	W	Simon		University of Minnesota			Research - Senior Faculty
EFRI-RESTOR: Novel Compressed Air Approach for Off-shore Wind Energy Storage	No	No		Mr.	Jacob		Wieberdink		University of Minnesota	Graduate Research Assistant	Mechanical Engineering	Research - Master's Student
EFRI-RESTOR: Novel Compressed Air Approach for Off-shore Wind Energy Storage	No	No			Farzad		Shirazi		University of Minnesota	Postdoctoral Research Associate	Mechanical Engineering	Research - Postdoc
EFRI-RESTOR: Novel Compressed Air Approach for Off-shore Wind Energy Storage	No	Yes		Dr.	James	D	Van de Ven		University of Minnesota	Assistant Professor	Mechanical Engineering	Research - Junior Faculty Curriculum - Junior Faculty Leadership/Administration - Education Program Leader
EFRI-RESTOR: Novel Compressed Air Approach for Off-shore Wind Energy Storage	Yes	Yes		Dr.	Perry	Y	Li		University of Minnesota			Curriculum - Senior Faculty Research - Senior Faculty
EFRI-RESTOR: Novel Compressed Air Approach for Off-shore Wind Energy Storage	No	No			Mohsen		Saadat		University of Minnesota			Research - Doctoral Student
EFRI-RESTOR: Novel Compressed Air Approach for Off-shore Wind Energy Storage	No	No			Chao		Zhang		University of Minnesota			Research - Doctoral Student
Energy Efficient Fluids	Yes	Yes		Mr.	Paul	W	Michael		Milwaukee School of Engineering	Research Chemist	Fluid Power Institute	Research - Research Staff
Energy Saving Hydraulic System Architecture Utilizing Displacement Control	No	No			Damiano		Padovani		Purdue University			Research - Doctoral Student
Energy Saving Hydraulic System Architecture Utilizing Displacement Control	Yes	Yes			Monika	M	Ivantysynova		Purdue University			Leadership/Administration - Thrust Leader
Evaluation And Design Improvements For A Hydraulic Pump	Yes	Yes			Monika	M	Ivantysynova		Purdue University			Leadership/Administration - Thrust Leader
Evaluation And Design Improvements For A Hydraulic Pump	No	No		Mr.	Lizhi		Shang		Purdue University			Research - Doctoral Student
Evaluation And Design Improvements For A Hydraulic Pump	No	No		Mr.	Rene		Chacon Portillo		Purdue University	Research assistant	Mechanical Engineering	Research - Master's Student
Evaluation and Design Study of the Piston/Cylinder Interface of a Swash Plate Type Hydraulic Motor	Yes	Yes			Monika	M	Ivantysynova		Purdue University			Leadership/Administration - Thrust Leader
High Pressure Compliant Material Development	Yes	Yes		Dr.	Kenneth	A	Cunefare	Ph.D.	Georgia Institute of Technology			Research - Senior Faculty
High Pressure Compliant Material Development	No	No			Tri		Nguyen		Georgia Institute of Technology			REU Student - NSF REU Site Award Curriculum - Undergraduate Student Research - Undergraduate Student
High Pressure Compliant Material Development	No	No		Mr.	Elliott		Gruber		Georgia Institute of Technology			Research - Master's Student
High Pressure Compliant Material Development	No	No		Mr.	John	D	Cavanaugh II		Georgia Institute of Technology			Curriculum - Undergraduate Student Research - Undergraduate Student
High Pressure Compliant Material Development	No	No		Mr.	Ryan		Salmon		Georgia Institute of Technology	Student	Mechanical Engineering	Research - Master's Student
High Pressure Compliant Material Development	No	No			John		McGrael		Georgia Institute of Technology			REU Student - ERC's Own REU Research - Undergraduate Student
Investigation of Alternative Cylinder Block Materials using Fluid Structure Interaction Modeling (FSTI).	No	No			Jeremy		Beale		Purdue University			Research - Doctoral Student
Investigation of Alternative Cylinder Block Materials using Fluid Structure Interaction Modeling (FSTI).	Yes	Yes			Monika	M	Ivantysynova		Purdue University			Leadership/Administration - Thrust Leader
Model Predictive Control of Pneumatic Actuators	No	No		Mr.	Hannes	G	Daepp		Georgia Institute of Technology		Mechanical Engineering	Research - Doctoral Student Curriculum - Doctoral Student
Model Predictive Control of Pneumatic Actuators	Yes	Yes		Dr.	Wayne	J	Book		Georgia Institute of Technology			Curriculum - Senior Faculty Leadership/Administration - Thrust Leader
Modeling and analysis of swash plate type piston motor	Yes	Yes			Monika	M	Ivantysynova		Purdue University			Leadership/Administration - Thrust Leader

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
Modeling of lubricating features of external gear machines and development of quieter solutions	Yes	Yes		Dr.	Andrea		Vacca	PhD	Purdue University			Research - Junior Faculty Curriculum - Junior Faculty
Modelling and analysis of swash plate axial piston pump	Yes	Yes			Monika	M	Ivantysynova		Purdue University			Leadership/Administration - Thrust Leader
Modulation of Anticipatory Postural Adjustments in Parkinson's disease Using a Portable Powered Ankle-Foot Orthosis	Yes	Yes		Dr.	Elizabeth	T	Hsiao-Wecksler	PhD	University of Illinois at Urbana-Champaign	Associate Professor	Department of Mechanical Science & Engineering	Curriculum - Senior Faculty Research - Senior Faculty
Modulation of Anticipatory Postural Adjustments in Parkinson's disease Using a Portable Powered Ankle-Foot Orthosis	No	No			Matt		Petrucci		University of Illinois at Urbana-Champaign			Research - Doctoral Student
MRI: Development of a Controlled-Trajectory Rapid Compression and Expansion Machine	No	Yes		Dr.	David	B	Kittelson		University of Minnesota	Professor	Mechanical Engineering	Research - Senior Faculty
MRI: Development of a Controlled-Trajectory Rapid Compression and Expansion Machine	Yes	Yes		Dr.	Zongxuan		Sun		University of Minnesota			Research - Junior Faculty Curriculum - Junior Faculty Leadership/Administration - Research Thrust Management and Strategic Planning
MRI: Development of a Controlled-Trajectory Rapid Compression and Expansion Machine	No	Yes			Kim	A	Stelson		University of Minnesota	Professor	Mechanical Engineering	Leadership/Administration - Director Curriculum - Senior Faculty Research - Senior Faculty
New Generation Of Green Highly Efficient Agricultural Machines Powered By High Pressure Water Hydraulic Technology	No	Yes		Dr.	Andrea		Vacca	PhD	Purdue University			Research - Junior Faculty Curriculum - Junior Faculty
New Generation Of Green Highly Efficient Agricultural Machines Powered By High Pressure Water Hydraulic Technology	Yes	Yes			Monika	M	Ivantysynova		Purdue University			Leadership/Administration - Thrust Leader
New Generation Of Green Highly Efficient Agricultural Machines Powered By High Pressure Water Hydraulic Technology	No	No		Ms.	Meike		Ernst		Purdue University			Research - Doctoral Student
New Generation Of Green Highly Efficient Agricultural Machines Powered By High Pressure Water Hydraulic Technology	No	No			Divya		Thiagarajan		Purdue University			Research - Doctoral Student
New Geometries for External Gear Machines towards the reduction of Noise Emissions	Yes	Yes		Dr.	Andrea		Vacca	PhD	Purdue University			Research - Junior Faculty Curriculum - Junior Faculty
Numerical Modeling of GEROTORs unit	Yes	Yes		Dr.	Andrea		Vacca	PhD	Purdue University			Research - Junior Faculty Curriculum - Junior Faculty
Rheology Modeling for Mechanical Face Seals	Yes	Yes		Dr.	Scott	S	Bair		Georgia Institute of Technology	Regents' Researcher	School of Mechanical Engineering	Research - Senior Faculty
Self-powered leak detection system for pipeline monitoring	Yes	Yes		Dr.	Kenneth	A	Cunefare	Ph.D.	Georgia Institute of Technology			Research - Senior Faculty
Static Dissipating Hydraulic Filters	Yes	Yes		Mr.	Paul	W	Michael		Milwaukee School of Engineering	Research Chemist	Fluid Power Institute	Research - Research Staff
Test bed 1: Heavy Mobile Equipment - High Efficiency Excavator	No	No		Mr.	Paul	W	Michael		Milwaukee School of Engineering	Research Chemist	Fluid Power Institute	Research - Research Staff
Test bed 1: Heavy Mobile Equipment - High Efficiency Excavator	No	No		Dr.	Andrew	G	Alleyne		University of Illinois at Urbana-Champaign			Curriculum - Senior Faculty Research - Senior Faculty Leadership/Administration - Thrust Leader
Test bed 1: Heavy Mobile Equipment - High Efficiency Excavator	No	No		Dr.	Wayne	J	Book		Georgia Institute of Technology			Curriculum - Senior Faculty Leadership/Administration - Thrust Leader
Test bed 1: Heavy Mobile Equipment - High Efficiency Excavator	No	No			Enrique		Busquets		Purdue University	Graduate Researcher	Mechanical Engineering	Research - Doctoral Student Curriculum - Doctoral Student
Test bed 1: Heavy Mobile Equipment - High Efficiency Excavator	No	No			Kim	A	Stelson		University of Minnesota	Professor	Mechanical Engineering	Leadership/Administration - Director Curriculum - Senior Faculty Research - Senior Faculty
Test bed 1: Heavy Mobile Equipment - High Efficiency Excavator	Yes	Yes			Monika	M	Ivantysynova		Purdue University			Leadership/Administration - Thrust Leader
Test bed 3: Highway Vehicles - Hyrdraulic Hybrid Passenger Vehicle	No	No			Thomas	R	Chase		University of Minnesota			Research - Senior Faculty
Test bed 3: Highway Vehicles - Hyrdraulic Hybrid Passenger Vehicle	No	No		Mr.	Kai Loon		Cheong		University of Minnesota		Mechanical Engineering	Research - Doctoral Student
Test bed 3: Highway Vehicles - Hyrdraulic Hybrid Passenger Vehicle	Yes	Yes		Dr.	Perry	Y	Li		University of Minnesota			Curriculum - Senior Faculty Research - Senior Faculty
Test Bed 4: Patient Transfer Device	No	No			James	D	Huggins		Georgia Institute of Technology	Research Engineer II	Mechanical Engineering	Leadership/Administration - Staff
Test Bed 4: Patient Transfer Device	No	No			Zachary		Siegel		Georgia Institute of Technology			Research - Undergraduate Student
Test Bed 4: Patient Transfer Device	No	No			Heather	C	Humphreys		Georgia Institute of Technology		Mechanical Engineering	Research - Doctoral Student Curriculum - Doctoral Student
Test Bed 4: Patient Transfer Device	Yes	Yes		Dr.	Wayne	J	Book		Georgia Institute of Technology			Curriculum - Senior Faculty Leadership/Administration - Thrust Leader
Test bed 6: Human Assist Devices -- Fluid Power Ankle-Foot Orthosis	No	No		Ms.	Morgan	K	Boes	MS	University of Illinois at Urbana-Champaign			Curriculum - Doctoral Student
Test bed 6: Human Assist Devices -- Fluid Power Ankle-Foot Orthosis	No	No			Timothy	J	Anderson		Mankato State Universtiy			REU Student - NSF REU Site Award
Test bed 6: Human Assist Devices -- Fluid Power Ankle-Foot Orthosis	Yes	Yes		Dr.	Elizabeth	T	Hsiao-Wecksler	PhD	University of Illinois at Urbana-Champaign	Associate Professor	Department of Mechanical Science & Engineering	Curriculum - Senior Faculty Research - Senior Faculty
Test bed 6: Human Assist Devices -- Fluid Power Ankle-Foot Orthosis	No	Yes			William		Durfee		University of Minnesota	Professor	Mechanical Engineering	Curriculum - Senior Faculty
Test bed 6: Human Assist Devices -- Fluid Power Ankle-Foot Orthosis	No	No			Mazharul		Islam		University of Illinois at Urbana-Champaign			Research - Doctoral Student
Test bed 6: Human Assist Devices -- Fluid Power Ankle-Foot Orthosis	No	No			Faith	F	Bradley		University of Minnesota			Curriculum - Undergraduate Student

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 6: Human Assist Devices -- Fluid Power Ankle-Foot Orthosis	No	No			Matt		Petrucci		University of Illinois at Urbana-Champaign			Research - Doctoral Student
Test bed 6: Human Assist Devices -- Fluid Power Ankle-Foot Orthosis	No	No			Jonathan	D	Nath		University of Minnesota	Undergraduate	Mechanical Engineering	REU Student - ERC's Own REU Curriculum - Undergraduate Student
Test bed 6: Human Assist Devices -- Fluid Power Ankle-Foot Orthosis	No	No		Mr.	Brett	C	Neubauer		University of Minnesota			Research - Doctoral Student
Test bed 6: Human Assist Devices -- Fluid Power Ankle-Foot Orthosis	No	No		Mr.	Ziming		Wang		University of Illinois at Urbana-Champaign		Mechanical Engineering	Research - Master's Student Curriculum - Master's Student
Test bed 6: Human Assist Devices -- Fluid Power Ankle-Foot Orthosis	No	No			Faith	F	Bradley		University of Illinois at Urbana-Champaign			REU Student - NSF REU Site Award Curriculum - Undergraduate Student Research - Undergraduate Student
Test bed 6: Human Assist Devices -- Fluid Power Ankle-Foot Orthosis	No	No			Timothy	J	Anderson		University of Illinois at Urbana-Champaign			REU Student - NSF REU Site Award Curriculum - Undergraduate Student Research - Undergraduate Student
Test bed 6: Human Assist Devices -- Fluid Power Ankle-Foot Orthosis	No	No			Katie	M	Neville		University of Illinois at Urbana-Champaign		Mechanical Engineering	Curriculum - Undergraduate Student
Test bed 6: Human Assist Devices -- Fluid Power Ankle-Foot Orthosis	No	Yes		Dr.	Geza	F	Kogler	PhD.	Georgia Institute of Technology			Research - Research Staff
Wearable eMbots to Induce Recovery of Function	No	No		Mr.	Saeed		Hashemi		University of Minnesota			Research - Doctoral Student
Wearable eMbots to Induce Recovery of Function	Yes	Yes			William		Durfee		University of Minnesota	Professor	Mechanical Engineering	Curriculum - Senior Faculty

APPENDIX II

Glossary and Acronyms

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GLOSSARY OF ACRONYMS AND SPECIAL TERMS

ABET …………..	Accreditation Board for Engineering and Technology
AC ……………...	alternating current
AGEP …………..	Alliances for Graduate Education and the Professoriate
AISES ………….	American Indian Science and Engineering Society
ASEE …………..	American Society for Engineering Education
ASME ………….	American Society of Mechanical Engineers
BRIDGE.............	Building Resources and Innovative Designs for Global Energy
CCEFP …………	Center of Compact and Efficient Fluid Power
CFD ……………	Computational Fluid Dynamics
CNT ……………	carbon nano-tubes
DC ……………...	direct current
DOF...................	degree of freedom
E & O …………	Education and Outreach
EC ……………...	Executive Committee
EngrTEAMS.......	Engineering to Transform the Education of Analysis, Measurement, and Science in a Team-Based Targeted Mathematics-Science Partnership
EON ……………	Education and Outreach Network
ERC ……………	Engineering Research Center
FDLTCC ……….	Fon du Lac Tribal and Community College
FIRST ………….	For Inspiration and Recognition of Science and Technology
fMRI	functional Magnetic Resonance Imaging
FP ………………	fluid power
FPE …………….	free piston engine
FPEF..................	Fluid Power Educational Foundation
FPIRC	Fluid Power Innovation and Research Conference
FY ……………...	fiscal year
gidaa…………..	gidakiimanaaniwigamig (*"Our Earth Lodge"*, in Anishinaabe)
GT ……………..	Georgia Institute of Technology
GRDS…………..	Graduate Research Diversity Supplement
H & P …………..	hydraulics and pneumatics
HAFO	hydraulic ankle foot orthosis
HBCU ………….	Historically Black College and University
HCCI …………..	homogeneous charge compression ignition
HMT ……………	hydro-mechanical drive train
HP ……………...	horsepower
HPEH................	Hydraulic Pressure Energy Harvesters
HST...................	hydro-static transmission
IAB …………….	Industrial Advisory Board
IFPE……………	International Fluid Power Expo
IC ………………	internal combustion
kW ……………..	kilowatt
LSAMP ………..	Louis Stokes Alliance for Minority Participation
ME ……………..	Mechanical Engineering

MEMS................	Micro-Electro Mechanical Systems
MOOC	Massive Online Open Course
MRI....................	magnetic resonance imaging
MSOE ………….	Milwaukee School of Engineering
MW …………….	megawatt
NCAT ………….	North Carolina Agricultural and Technical State University
NCED ………….	National Center for Earth-Surface Dynamics
NFPA …………..	National Fluid Power Association
NSBE.................	National Society of Black Engineers
NSF …………….	National Science Foundation
ORNL	Oak Ridge National Laboratory
PC ……………...	Project Champion
PFPD…………..	Portable Fluid Power Demonstration
PLTW ………….	Project Lead The Way
PWM …………..	pulse width modulation
PZT...................	lead zirconate titanate
QED……………	Quality Evaluation Design
RET …………….	Research Experiences for Teachers
REU ……………	Research Experiences for Undergraduates
RFE	repetitive facilitation exercise
SAB ……………	Scientific Advisory Board
SACNAS ………	Society for Advancement of Chicanos and Native Americans in Science
SLS...................	selective laser sintering
SLC …………….	Student Leadership Council
SMM …………..	Science Museum of Minnesota
STEM ………….	Science Technology Engineering and Mathematics
SWOT ………….	Strengths, Weaknesses, Opportunities and Threats
TB ……………...	test bed
TCUP …………..	Tribal Colleges and Universities Program
TMS	transcranial magnetic stimulation
TPT …………….	Twin Cities Public Television
UCD ……………	user-centered design
UIUC …………..	University of Illinois at Urbana-Champaign
UMN …………..	University of Minnesota
UDRS………….	Undergraduate Research Diversity Supplement
W ………………	watt

APPENDIX III

Agreements and Certifications

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NFPA
Education and
Technology
Foundation

This Agreement (the "Agreement") is made effective July 1, 2014, between Regents of the University of Minnesota (hereinafter, "Lead University"), a Minnesota state constitutional corporation, on behalf of the Engineering Research Center for Compact and Efficient Fluid Power (hereinafter, the "CCEFP"), a multi-party, collaborative research venture, located at the Lead University, and the NFPA Education and Technology Foundation (hereinafter, the "Foundation"), an Illinois not-for-profit corporation, with principal offices at 6737 W. Washington Street, Milwaukee, Wisconsin.

RECITALS

WHEREAS, the Foundation is committed to supporting outreach, education and research programs in fluid power that achieve the following objectives: (i) actively engage students at all grade levels in learning about fluid power; (ii) encourage the development of new teaching resources—fluid power laboratories as well as online, print and hands-on instruction tools; (iii) support research in motion control through fluid power at the two-year, four-year and graduate school levels; and (iv) foster on-going forums between educators and industry so that ideas and priorities of mutual interest can be shared and set; and

WHEREAS, for the past eight years, Lead University has operated the CCEFP with support from the National Science Foundation (NSF) under an Engineering Research Center (ERC) grant and with membership support from over 40 companies; and

WHEREAS, for the past eight years, Lead University has operated the CCEFP in cooperation with six other universities; namely: University of Illinois at Urbana-Champaign, Purdue University, Vanderbilt University, Georgia Institute of Technology, Milwaukee School of Engineering, and North Carolina Agricultural and Technical University (hereinafter, each university individually is "University" or "Participating University", and the universities collectively are "Universities" or "Participating Universities"), with Lead University bearing responsibility for administrative coordination among the Universities; and

WHEREAS, for the next two years Lead University will continue to operate the CCEFP in collaboration with the Universities (and potentially other universities) and with NSF ERC and industry support; and

WHEREAS, over the past year, the Lead University and the Foundation have been planning for the continuation of the CCEFP after the NSF ERC grant ends, and agree that increasing industry support is one necessary component of the CCEFP's long-term viability, and further agree that the Foundation should assume responsibility for obtaining necessary financial support for the CCEFP from the fluid power industry, and further agree that this change in the CCEFP's industry funding model should be implemented in the final two years of NSF ERC funding.

AGREEMENT

NOW, THEREFORE, in consideration of the premises hereof and the mutual covenants and agreements contained herein, the parties hereto agree as follows:

1. <u>Recitals</u>

(a) The recitals are incorporated herein by reference.

2. <u>Industry Support</u>

(a) The Foundation shall be responsible for actively seeking and effectively securing support for the CCEFP from the fluid power industry.

(b) Lead University shall be responsible for assisting the transition of these responsibilities. Among other steps, Lead University shall: (i) Provide Foundation with complete available information concerning current and former CCEFP industry members, including membership dates, levels and contacts; (ii) Develop and implement in cooperation with Foundation a joint communication plan to inform current CCEFP industry members of the change in the industry funding model and to encourage companies to provide support for the CCEFP through the Foundation; and (iii) As part of (ii), provide current CCEFP industry members with timely notice that all existing industry membership agreements with Lead University will terminate effective June 30, 2014. Thereafter, so long as Foundation is meeting metrics established through CCEFP Operating Procedures (hereinafter referred to as "COP"), Lead University will not enter into new CCEFP industry membership agreements and, instead, will refer companies that wish to contribute to the CCEFP to the Foundation.

(c) If a current CCEFP industry member informs the Lead University that it does not wish to provide funding through the Foundation, the Lead University may accept funding support for the CCEFP directly from the company during the first two years of this Agreement, provided (i) the Lead University does not provide the company any rights to CCEFP intellectual property created or discovered after the effective date of this Agreement; (ii) the funds will be pooled with funds provided by the Foundation; (iii) decisions about use of funds will be made in accordance with the COPs; and (iv) opportunities for the company to serve on industry oversight, advisory and management committees of the CCEFP will be determined in a manner mutually agreeable to both parties and consistent with the Foundation's charitable status. The Lead University will notify the Foundation of funds received under this subparagraph (c), and the Foundation's support commitment will be reduced by a corresponding amount. This subparagraph (c) applies to general support for the CCEFP and does not apply to company support for specific fluid power research projects or programs conducted at Lead University or at other Universities.

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(d) During the first two years of this Agreement (July 1, 2014, through June 30, 2016), Foundation shall provide support of at least $655,000 per year to the CCEFP. The level of annual Foundation support for each succeeding year, and the date on which the commitment for the additional year's support will be made, shall be determined in accordance with Section 8(a) of this Agreement, and any subsequent metrics and procedures established through CCEFP Operating Procedures.

(e) Support from the Foundation in the first two years will be dependent on the CCEFP fulfilling a set of effort-based metrics associated with government grant acquisition. Specifically, the CCEFP will work with industry to identify and pursue government grant opportunities that align with its fluid power research strategy and which could reasonably result in at least $3 million in support of the CCEFP's pre-competitive fluid power research program. Support from the Foundation in each succeeding year will be dependent on the CCEFP fulfilling a set of outcome-based metrics associated with government grant acquisition, which will be specified in the CCEFP Operating Procedures.

(f) Payment of Foundation support shall be made in four quarterly installments, which shall be due and payable on July 1, October 1, January 1, and April 1 of each year. Checks should be made payable to University of Minnesota and mailed to "Regents of the University of Minnesota" at NW 5957, P.O. Box 1450 Minneapolis, MN 55485-5957.

3. <u>Goals and Administration of the CCEFP</u>

(a) The goals of the CCEFP shall remain the development of fundamental knowledge about fluid power and the education of the next generation of scientific and engineering leaders in the field. These goals will be accomplished in several ways, including by engaging students in the performance of meaningful, pre-competitive fluid power research, sustained over a period of years.

(b) The overall administrative functions and operations of the CCEFP shall be the responsibility of the Lead University, which shall provide appropriate faculty, staff and students to fulfill these obligations.

(c) To lead the administrative functions of the CCEFP, the Lead University shall select a full professor as CCEFP Director. In making this selection, the Lead University will consult with the Foundation and its Board of Directors. The duties and responsibilities of the CCEFP Director shall be described in the CCEFP Operating Procedures, and will include authority on the selection of research projects and the apportionment of resources.

(d) The Lead University will provide administrative and financial support for a qualified professional to serve as an industry liaison officer for the CCEFP. The level of support,

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as well as the duties and responsibilities of this individual, shall be described in the CCEFP Operating Procedures.

4. <u>Industry Engagement</u>

(a) There will be a set of CCEFP Operating Procedures ("COPs") to define the industry oversight, advisory and management committees of the CCEFP, as well as key processes such as strategy development and project selection. The COPs shall be consistent with the NSF ERC grant, with this Agreement, with sub-awards to the Universities, with any Foundation agreements with its industry supporters, and with applicable federal regulations and policies.

(b) The COPs will function as the primary means for defining how the CCEFP interacts with industry and the supporters of the Foundation. They will establish opportunities for industry to participate on oversight, advisory and management committees, as well as opportunities to interact with faculty and graduate students.

(c) The parties intend that the Foundation's status as a Section 501(c)(3) organization will not be adversely affected through its support for the CCEFP and the provision of participation opportunities to its industry supporters. Lead University shall reasonably cooperate with the Foundation with regard to any matter that the Foundation identifies as a concern to its tax-exempt status.

(d) The COPs shall provide for the creation of a steering committee with both industry and university members, who may or may not be members of the NFPA, that shall at least be responsible for: (i) Establishing and maintaining the CCEFP strategic plan; (ii) Ensuring that the research strategy of the CCEFP is aligned with the pre-competitive research needs of the fluid power industry, as determined and described in the NFPA Technology Roadmap; and (iii) Working with the CCEFP Director to identify and pursue government grant opportunities that align with the CCEFP research strategy.

(e) The COPs shall provide for the creation of an industry engagement committee, with industry members, who may or may not be members of the NFPA, that shall at least be responsible for: (i) Prioritizing the areas of research study most beneficial to the pre-competitive needs of the fluid power industry; (ii) Working with the CCEFP Director to identify principal investigators and universities with the expertise and resources needed to address the prioritized areas of research study; (iii) Working with the CCEFP Director to design and distribute a call for research project proposals aligned with the prioritized areas of research study; (iv) Reviewing the resulting research project proposals and participating in selection of those that will be funded; (v) Monitoring the progress of funded research project proposals, interacting frequently with the principal investigators and students; (vi) Mentoring and coaching principal investigators and students to ensure that an industry perspective is taken into consideration as research project progress; and (vii) Determining when to graduate research projects.

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(f) The COPs shall provide a role for NFPA's roadmap committee, which will include industry members, who may or may not be members of the NFPA, that shall at least be responsible for developing and maintaining a Technology Roadmap for the fluid power industry that identifies the areas of pre-competitive research necessary to meet the future needs of fluid power customers, expand fluid power into new customer markets, and attract the best and brightest young engineers to fluid power. Members of this roadmap committee will also participate in the research project selection process managed by the industry engagement committee, specifically, reviewing the research project proposals and helping to select those that will be funded.

(g) Opportunities for industry to serve on these committees will be determined in a manner that is consistent with the Foundation's charitable status.

5. <u>University Participation</u>

(a) Any federal research and development organization, or any government-owned contractor-operated laboratory, located in the United States, may become a Participating University in the CCEFP, consistent with applicable state and federal laws and statutes, and pending the approval of the Lead University and the Foundation.

(b) Each Participating University shall enter into a sub-award or subcontract with the Lead University that obligates the Participating University and its researchers to comply with the obligations of Universities and researchers set forth in this Agreement. These sub-awards or subcontracts will provide for a maximum indirect cost charge of 10% for research projects funded through the industry support mechanism of the Foundation.

(c) Individual researchers at Participating Universities retain academic freedom to propose specific fluid power research projects to individual companies, and to accept projects proposed by a company outside of the CCEFP. Correspondingly, a company is free to sponsor individual projects as Participating Universities, irrespective of the company's status as a contributor to the Foundation.

(d) Participating Universities will be responsible for providing information (as may be reasonably available to the Participating University) to the Lead University regarding fluid power funding applications, fluid power research awards, and non-sponsored fluid power research funding, for consideration in connection with the CCEFP's metrics and goals. Confidential information (such as certain information in funding applications) may be withheld.

(e) Participating Universities are individually and jointly responsible for actively seeking and effectively securing support for CCEFP research from sources other than the fluid

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power industry support provided through the Foundation—primarily through government grants and contracts.

6. Intellectual Property

(a) As detailed in Section 3(a), the creation of commercially valuable intellectual property is not a primary goal of the CCEFP.

(b) Each party recognizes that the CCEFP will be funded by the NSF ERC program for, at most, a term ending May 30, 2016, subject to NSF continued approval and support. It is the intent of this Agreement to help establish the means through which the CCEFP may become self-supporting thereafter. Any disposition of funds and Intellectual Property upon the possible termination of operations of the CCEFP shall be the responsibility of the Lead University and of any Universities that have taken title to CCEFP inventions, and shall be in full compliance with law, including the regulations and rules governing NSF supported research programs.

(c) The students, faculty and staff conducting research through the CCEFP (the "Researchers") shall have the right to publish the results of any research performed through the CCEFP in accordance with scholarly norms. Researchers are responsible for sharing research results with the Foundation and its industry supporters in accordance with CCEFP Operating Procedures. Universities will encourage Researchers to interact with industry supporters in any manner they consider appropriate, considering that direct interactions between Researchers and industry supporters may help supporters more fully appreciate both the implications of the discoveries made during CCEFP research and the intellectual and personal qualification of the next generation of science and engineering leaders in the field of fluid power.

(d) Pursuant to 35 U.S.C. § 200 et. seq. (the "Bayh-Dole Act"), the University or Universities whose Researchers are inventors under U.S. Patent law (the "Inventing University") shall have the right to retain title to all patents developed from this work, subject to the rights of the U.S. Government as set forth in the Bayh-Dole Act and implementing regulations. The provisions of Part 730, "Intellectual Property", of the NSF Grants Policy Manual shall also govern rights and responsibilities regarding intellectual property created with NSF funding. This section shall apply to all CCEFP inventions conceived or reduced to practice during the period of NSF ERC funding.

(e) Each University shall ensure that it has obtained all necessary rights to the Intellectual Property from its Researchers to grant the rights provided to the United States under this Agreement.

(f) This Agreement does not grant the Foundation or any industry supporter any rights to CCEFP intellectual property created or discovered after the effective date. Each of the Universities remains free, at its sole discretion, to license inventions to any party it selects, including any industry supporter.

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(g) Any royalties and fees received by any of the Universities under this Agreement, over and above expenses incurred, will be distributed in accordance with the policies of the University or Universities that have taken title to the invention.

7. Reporting

(a) The CCEFP shall provide the Foundation and its industry supporters with periodic reports of the progress of research supported by the CCEFP, including information regarding the students engaged in the research projects and any intellectual property that has been developed. The frequency and nature of these reports will be defined in the CCEFP Operating Procedures and will include an annual meeting of the CCEFP, at which the results of CCEFP research will be presented and displayed.

(b) The CCEFP shall provide the Foundation with periodic reports detailing its use of the funds offered under this Agreement. The frequency and nature of these reports will be defined in the CCEFP Operating Procedures.

8. Term and Termination

(a) Beginning on or before April 1, 2015, and each April 1 thereafter, the Foundation and the Lead University must agree to extend this Agreement in writing, including the amount of financial support provided to the CCEFP by the Foundation, for one additional year. If not extended, the Agreement will terminate without fault to either party at the end of the then-current term of the Agreement.

(b) If either party commits a substantial and material breach or default with respect to any of the terms or conditions of this Agreement and fails to remedy such breach or default within ninety (90) days after receipt of written notice from the other party, the party giving notice of breach may, at its option and in addition to any other remedies it may have, terminate this Agreement by sending notice of termination in writing to the other party's contractual and administrative contact. Unless the party receiving notice of termination requests arbitration within sixty (60) days, the final termination shall be effective as of the date of the receipt of such notice.

(c) Termination of this Agreement for any reason shall not affect the rights and obligations of the parties accrued prior to the effective date of termination. Any term that, by its sense, context and common usage would ordinarily survive termination, shall survive.

(d) The exclusive method for adjudicating any dispute that is not resolved informally is binding arbitration under the Rules of Conciliation and Arbitration of the American Arbitration Association. For disputes that do not involve a claim of a material breach of this Agreement, unless the parties agree otherwise, (i) the arbitration will be conducted by one arbitrator, selected by the parties or, absent agreement, appointed in accordance with the Rules of the American Arbitration Association and (ii) the arbitration will be conducted on a

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documentary record of affidavits, exhibits, statements of position, and similar submissions. For disputes that involved a claim of a material breach, there shall be three (3) arbitrators, and the parties shall be afforded an opportunity for limited discovery and presentation of witnesses. Each party shall be responsible for its own costs and fees and for one-half of the arbitrator's fee.

9. Contacts

(a) Contacts for the Agreement may be changed by written notice. The original contacts are as follows:

	Lead University	**Foundation**
Technical	Prof. Kim A. Stelson Mechanical Engineering 111 Church Street SE Minneapolis, MN 55455 612-625-6528 kstelson@umn.edu	Eric Lanke NFPA Foundation 6737 W. Washington Street, Suite 2350 Milwaukee, WI 53214 414-778-3351 elanke@nfpa.com
Contractual/ Administrative	Amy Rollinger Sponsored Projects Administration 200 Oak Street SE, Suite 450 Minneapolis, MN 55355 612-625-1359 amyg@umn.edu	Eric Lanke NFPA Foundation 6737 W. Washington Street, Suite 2350 Milwaukee, WI 53214 414-778-3351 elanke@nfpa.com
Financial	Julia Steinkopf Sponsored Financial Reporting 200 Oak Street SE, Suite 450 Minneapolis, MN 55455 612-624-7033 gordo091@umn.edu	Eric Lanke NFPA Foundation 6737 W. Washington Street, Suite 2350 Milwaukee, WI 53214 414-778-3351 elanke@nfpa.com

10. Standard Terms and Conditions

(a) This Agreement is the complete and exclusive statement of the understanding between the parties regarding the subject matter hereof, and it supersedes all prior written or contemporaneous communications.

AC | [initials]

(b) This Agreement shall be governed and construed in accordance with the laws of the State of Minnesota. The Minnesota State District Court for Hennepin County shall have exclusive jurisdiction to enforce an arbitral award or entertain any other legal proceeding against Lead University.

(c) It is expressly understood that Lead University and Foundation are independent contractors and not the agent, partner, or employee of the other. A party shall not have the authority to enter into any contract or agreement to bind the other, and a party shall not represent to anyone that it has such authority, nor shall the respective employees of a party be entitled to any benefits applicable to employee of the other party.

(d) Each party represents that it has and will continue to have at least the following levels of insurance or self-insurance during the term of this Agreement: (i) as to the Lead University, Workers' Compensation in statutory compliance with Minnesota State Law; and (ii) as to both parties, General Liability Insurance in an amount not less than one million dollars ($1,000,000) each claim/three million dollars ($3,000,000) each aggregate occurrence. Lead University represents that the Lead University has and will continue to have Professional Liability insurance in an amount not less than one million dollars ($1,000,000) each claim/three million dollars ($3,000,000) each aggregate occurrence.

(e) Each party shall be responsible for its own acts and the results thereof and not for the acts of the other party. Liability of the Lead University is subject to the terms and limitations of the Minnesota Tort Claims Act, Minnesota Statutes Section 3.736. Liability of the Foundation will be limited to the economic value of the commitments described in this Agreement.

(f) Lead University makes no warranties, express or implied, as to any matter whatsoever, including without limitation, the condition, originality or accuracy of the research or any invention(s) or product(s), whether tangible or intangible, conceived, discovered, or developed under this Agreement; or the ownership, merchantability, or fitness for a particular purpose of the research or any such invention or product.

(g) IN NO EVENT SHALL EITHER PARTY'S LIABILITY FOR BREACH OF CONTRACT INCLUDE DAMAGES FOR WORK STOPPAGE, LOST DATA, OR INDIRECT, SPECIAL OR CONSEQUENTIAL DAMAGES (INCLUDING LOST PROFIT), OF ANY KIND. EITHER PARTY'S LIABILITY TO THE OTHER FOR BREACH OF THIS AGREEMENT SHALL NOT EXCEED THE MONETARY CONSIDERATION DUE UNDER THIS AGREEMENT.

(h) The parties may not assign any rights or obligations of this Agreement without the prior written consent of the other party, which shall not be unreasonably withheld. Any assignment attempted to be made in violation of this Agreement shall be void.

(i) This Agreement shall be amended only in writing duly executed by all the parties to this Agreement. The parties will work together in good faith regarding any amendments that

AC / SE

may be needed to achieve the goals of the CCEFP as stated in paragraph 3a of this agreement. No waiver by any party of any default or nonperformance shall be deemed a waiver of any subsequent default or nonperformance.

SO AGREED:

REGENTS OF THE UNIVERSITY OF MINNESOTA

Signature: [signature]

Print Name: April Coon
Assistant Director
Sponsored Projects Administration

Title:

Date: 8/14/14

NFPA EDUCATION AND TECHNOLOGY FOUNDATION

Signature: [signature]

Print Name: Eric Lanke

Title: CEO

Date: 8/14/14

AC | [initials]

CCEFP Operating Procedure (COP)

COP No: 001 Rev 0
Title: CCEFP Operating Procedures

	NAME	TITLE	SIGNATURE	DATE
Authored by	Michael Gust	ILO - CCEFP		03-24-2014
Approved by	Eric Lanke	CEO - NFPA Foundation		09-19-2014
Approved by	Kim Stelson	Director - CCEFP		09-19-2014

Release Date	09-19-2014
Latest Review Date	09-19-2014

READ AND COMMENTED BY			
NAME	**TITLE**	**SIGNATURE**	**DATE**
various	CCEFP Industry Advisory Board	N/A	07-17-2014

PURPOSE

The purpose of this CCEFP Operating Procedure is to identify the key processes for efficient and effective operation of the Center for Compact and Efficient Fluid Power (CCEFP) and its collaboration with industry through the NFPA Education and Technology Foundation (NFPA Foundation). It is advantageous to have key procedures clearly documented so that industry supporters, participating universities, researchers and students of the CCEFP understand how best to interact with the CCEFP.

INTRODUCTION

The goals of the CCEFP are the development of fundamental knowledge about fluid power and the education of the next generation of scientific and engineering leaders in the field. These goals will be accomplished in several ways, including by engaging students in the performance of meaningful, pre-competitive fluid power research, sustained over a period of years. The University of Minnesota has entered into a renewable grant agreement with the NFPA Foundation on behalf of the CCEFP to fund these pre-competitive fluid power research projects. The grant agreement references the COPs as the primary means for defining how the CCEFP will interact with industry and the supporters of the NFPA Foundation in its use of the research funds awarded.

SCOPE

Key processes for CCEFP research, workforce development and industry collaboration are identified in this COP and are listed below. Processes associated with the operation of the NFPA Foundation are out of scope and are managed by the leadership of the NFPA Foundation. Amendment and addition of COPs is outside of scope and is covered by COP-001-02.

CCEFP Operating Procedure (COP)

COP No: 001 Rev 0
Title: CCEFP Operating Procedures

A. COP-001: CCEFP Operating Procedures

  A.1. COP-001-01: COP Documentation Instructions

  A.2. COP-001-02: CCEFP COP Amendment Instructions

B. COP-002: CCEFP Management Team and Industry Oversight Committees

C. COP-003: CCEFP Research Strategy and Resource Alignment

  C.1. COP-003-01: NFPA Technology Roadmap

  C.2. COP-003-02: CCEFP Research Strategy

D. COP-004: CCEFP Call for Project Proposals

  D.1. COP-004-01: CCEFP call for project proposals template

  D.2. COP-004-02: CCEFP budget template

E. COP-005: CCEFP Project Selection

  E.1. COP-005-01: CCEFP project selection criteria template

F. COP-006: CCEFP Project Progress Reporting and Monitoring

  F.1. COP-006-01: CCEFP Progress Review template

G. COP-007: Performance Metrics

DEFINITIONS

Not applicable.

RESPONSIBILITIES

CCEFP Director is responsible for assuring that CCEFP maintains the official record of all COPs and changes to COPs.

PROCEDURE

CCEFP Director delegates responsibility for maintenance of the official record to an appropriate CCEFP official, who maintains an official file in both hard copy and electronic format. The current COPs are available to CCEFP stakeholders on-line; the historical file is available to CCEFP stakeholders upon request.

CCEFP Operating Procedure (COP)

COP No: 001 Rev 0
Title: CCEFP Operating Procedures

FORMS and TEMPLATES USED

COP-001-01: COP Documentation Instructions

COP-001-02: COP Amendment Instructions

REFERENCES

Not applicable.

REVISION CONTROL

Revision No.	Significant Changes	Release Date
0	Initial document release	09-19-2014

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CCEFP Operating Procedure (COP)

COP No: 002 Rev 0
Title: CCEFP Management Team and Industry Oversight Committees

	NAME	TITLE	SIGNATURE	DATE
Authored by	Michael Gust	ILO - CCEFP	Michael A. Gust	03-24-2014
Approved by	Eric Lanke	CEO - NFPA Foundation	Eric Lanke	09-19-2014
Approved by	Kim Stelson	Director - CCEFP	Kim A. Stelson	09-19-2014

Release Date	09-19-2014
Latest Review Date	09-19-2014

READ AND COMMENTED BY			
NAME	**TITLE**	**SIGNATURE**	**DATE**
various	CCEFP Industrial Advisory Board	N/A	07-17-2014

PURPOSE

The purpose of this CCEFP Operating Procedure is to define the management structure of the CCEFP and its key industry oversight committees.

INTRODUCTION

It is important for all CCEFP participants and stakeholders to clearly understand how the CCEFP operates. This helps the organization operate efficiently, and it helps with recruitment of CCEFP industry supporters.

SCOPE

Definition and responsibilities of key CCEFP Management Team positions are within scope of this COP. Definition, membership eligibility, leadership selection, and responsibilities of industry oversight committee are also within the scope of this COP.

DEFINITIONS

"Pascal Society" is the annual giving and recognition society within the NFPA Foundation that is dedicated to meeting the technology and workforce development needs of the U.S. fluid power industry.

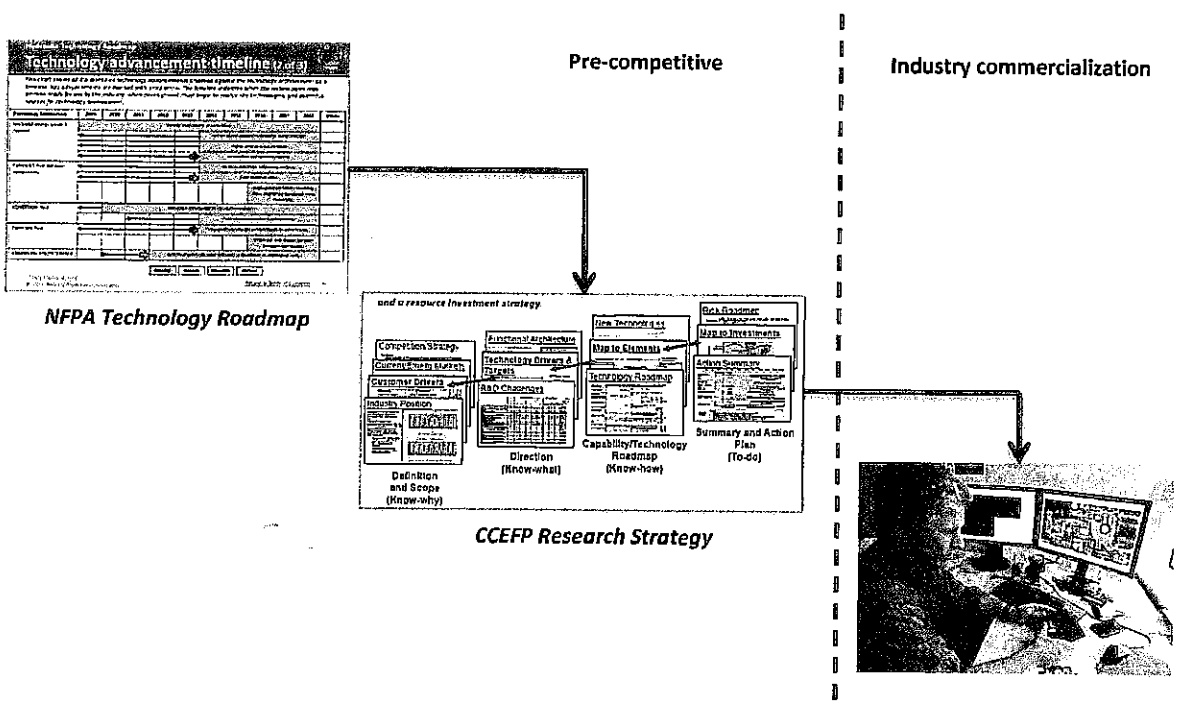
"NFPA Technology Roadmap" is an industry consensus-based document, organized and published by the NFPA, which identifies the areas of pre-competitive research needed to increase fluid power's competitive position in the marketplace, open up new markets for fluid power, and attract the best and brightest students to the field.

CCEFP Operating Procedure (COP)

COP No: 002 Rev 0
Title: CCEFP Management Team and Industry Oversight Committees

"CCEFP Research Strategy" is the document which defines the research areas of need and associated education programs necessary to achieve the CCEFP's goals of developing fundamental knowledge about fluid power and educating the next generation of scientific and engineering leaders in the field.

The interaction between the NFPA Technology Roadmap, the CCEFP Research Strategy, and industry technology/product roadmaps is shown below. The wants and needs of industry are collected from industry experts and summarized in the NFPA Technology Roadmap which is shared with the CCEFP. The CCEFP uses this information to formulate its CCEFP Research Strategy which then drives the organization's research priorities. All of these efforts are focused on pre-competitive research. Industry can utilize the outcomes of the CCEFP pre-competitive research programs to formulate their own technology and product roadmaps which they intend to commercialize.



RESPONSIBILITIES

CCEFP Management Team

1. The **CCEFP Director** is responsible for leading the strategic and administrative functions of the CCEFP, including:

    a. Engaging the appropriate industry oversight committees to help establish and maintain the CCEFP Research Strategy.

b. Engaging the appropriate industry oversight committees to ensure that the CCEFP Research Strategy is aligned with the pre-competitive research needs of the fluid power industry, as determined and described in the NFPA Technology Roadmap.

c. Seeking out other subject matter experts in emerging fluid power markets and applications to further augment the CCEFP Research Strategy.

d. Identifying principal investigators and universities with the expertise and resources needed to address the CCEFP Research Strategy.

e. Identifying and pursuing government grant opportunities that align with the CCEFP Research Strategy.

f. Managing the established processes for CCEFP research project selection, monitoring, and graduation.

g. Preparing an annual budget for the CCEFP and apportioning resources as needed to fulfill its obligations, including the establishment of supporting staff positions.

h. Ensuring that all contractual obligations of the CCEFP are fulfilled.

2. The **CCEFP Industry Liaison Officer** is responsible for ensuring productive industry collaboration with the CCEFP, including:

a. Building and maintaining a coalition of industry partners interested in the development of new fluid power technologies.

b. Working with the coalition and other pertinent subject matter experts to define, maintain and supplement the NFPA Technology Roadmap, identifying the areas of pre-competitive research needed to increase fluid power's competitive position in the marketplace, open up new markets for fluid power, and attract the best and brightest students to the field.

c. Working with the CCEFP leadership and industry partners to develop and maintain a CCEFP Research Strategy that addresses one or several of the areas of pre-competitive research needs identified by the NFPA Technology Roadmap.

d. Assisting in the development and execution of a fundraising strategy which results in the industry, academic and governmental funding necessary to implement the CCEFP Research Strategy.

e. Working with the CCEFP leadership, industry and research partners to identify, support and track research projects that align with the CCEFP Research Strategy.

f. Connecting members of the industry coalition with research project outcomes, including new knowledge, technology development opportunities and candidates for the industry workforce.

g. Ensuring the successful alignment of CCEFP research activities with NFPA's work on industry executive engagement, marketing of fluid power technology, international fluid power standards, and fluid power education for the broader industry.

Industry Oversight Committees

1. The **NFPA Foundation Board of Directors:**

   a. Determines the membership levels, recognition and participation opportunities, and programs supported by The Pascal Society.

   b. Determines annual budget amounts allocated to each program supported by The Pascal Society.

   c. Selects the lead university of the CCEFP and determines the terms of the grant agreement between it and the NFPA Foundation.

2. The **CCEFP Steering Committee:**

   a. Establishes and maintains the CCEFP Research Strategy.

   b. Ensures that the CCEFP Research Strategy is aligned with the pre-competitive research needs of the fluid power industry, as determined and described in the NFPA Technology Roadmap.

   c. Works with the CCEFP Director to seek out other subject matter experts in emerging fluid power markets and applications to further augment the CCEFP Research Strategy.

   d. Works with the CCEFP Director to identify and purpose government grant opportunities that align with the CCEFP Research Strategy.

3. The **CCEFP Industry Engagement Committee:**

   a. Prioritizes the areas of research study most beneficial to the pre-competitive needs of the fluid power industry.

   b. Works with the CCEFP Director to identify principal investigators and universities with the expertise and resources needed to address the prioritized areas of research study.

c. Works with the CCEFP Director to design and distribute a call for research project proposals that results in project proposals aligned with the prioritized areas of research study.

d. Reviews the resulting research project proposals and recommends those that will be funded.

e. Monitors the progress of funded research project proposals, interacting frequently with the principal investigators and students.

f. Mentors and coaches principal investigators and students to ensure that an industry perspective is taken into consideration as research projects progress.

g. Determines when to graduate research projects.

4. The **NFPA Roadmap Committee**:

a. Develops, maintains and supplements the NFPA Technology Roadmap, identifying the areas of pre-competitive research necessary to meet the future needs of fluid power customers, expand fluid power into new customer markets, and attract the best and brightest young engineers to fluid power.

b. Participates in the research project selection process managed by the CCEFP Industry Engagement Committee. Specifically, reviews the research project proposals and helps identify those that will be recommended for funding.

PROCEDURE

CCEFP Management Team

1. The **CCEFP Director:**

a. The CCEFP lead university will select an employed, tenured professor to serve as the CCEFP Director.

b. The CCEFP lead university will provide office space and administrative support for the activities of the CCEFP Director.

2. The **CCEFP Industry Liaison Officer:**

a. The CCEFP lead university will employ a qualified individual to serve as the CCEFP Industry Liaison Officer.

b. The CCEFP lead university will provide office space and administrative support for the activities of the CCEFP Industry Liaison Officer.

c. The NFPA will provide the lead university with financial support to help offset the salary, benefits and overhead costs associated with the CCEFP Industry Liaison Officer. In recognition of this support, and at the discretion of the NFPA, the CCEFP Industry Liaison Officer will also serve as the NFPA Director of Research & Technology.

Industry Oversight Committees

1. The **NFPA Foundation Board of Directors**:

   a. The membership and leadership of the NFPA Foundation Board of Directors will be determined in accordance with the bylaws and established policies and practices of the NFPA Foundation.

   b. NFPA will provide administrative support for the activities of the NFPA Foundation Board of Directors.

2. The **CCEFP Steering Committee**:

   a. Gold-level donors of The Pascal Society will be invited to nominate a CEO, division president or other senior executive to serve as a member of the CCEFP Steering Committee. These nominees for the industry members of the CCEFP Steering Committee must be approved by the NFPA Foundation Board of Directors.

   b. Participating CCEFP universities will be invited to elect a number of deans, tenured professors or other academic thought leaders to serve as members of the CCEFP Steering Committee. The number of these positions will be not greater than 20% of the number of industry members of the CCEFP Steering Committee.

   c. The CCEFP Director may appoint additional CCEFP Steering Committee members, up to 20% of the number of industry members, to represent perspectives and knowledge sets that may otherwise be missing. Among the potential candidates for these nominations will be thought leaders from government agencies and national labs.

   d. In order to ensure continuity of leadership between the industry members of the existing CCEFP Executive Committee and the CCEFP Steering Committee, industry members serving on the CCEFP Executive Committee as of July 1, 2014 will assumes roles as industry members of the CCEFP Steering Committee for the length of their natural three year terms on the CCEFP Executive Committee.

   e. The CCEFP Director will chair the CCEFP Steering Committee.

   f. The CCEFP lead university will provide administrative support for the activities of the CCEFP Steering Committee.

CCEFP Operating Procedure (COP)

COP No: 002 Rev 0
Title: CCEFP Management Team and Industry Oversight Committees

3. The **CCEFP Industry Engagement Committee**

   a. Gold- and Silver-level donors of The Pascal Society will be invited to appoint a CTO or other senior-level technology expert with significant fluid power experience to serve as a member of the CCEFP Industry Engagement Committee.

   b. The members of the CCEFP Industry Engagement Committee will each year elect a vice-chair, who will serve one year as vice-chair followed automatically by one year as chair of the CCEFP Industry Engagement Committee.

   c. The CCEFP lead university will provide administrative support for the activities of the CCEFP Industry Engagement Committee.

4. The **NFPA Roadmap Committee**:

   a. Gold-, Silver- and Bronze-level donors of The Pascal Society will be invited to nominate a senior-level engineer or technology expert with significant fluid power experience to serve as a member of the NFPA Roadmap Committee.

   b. The NFPA CEO may nominate additional NFPA Roadmap Committee members to represent perspectives and knowledge sets that may otherwise be missing.

   c. The NFPA will select the chair of the NFPA Roadmap Committee.

   d. The NFPA will provide administrative support for the activities of the NFPA Roadmap Committee.

FORMS and TEMPLATES USED

Not applicable.

REFERENCES

Not applicable.

REVISION CONTROL

Revision No.	Significant Changes	Release Date
0	Initial document release	09-19-2014

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CCEFP Operating Procedure (COP)

COP No: 003 Rev 0
Title: CCEFP Research Strategy Development and Resource Alignment

	NAME	TITLE	SIGNATURE	DATE
Authored by	Michael Gust	ILO - CCEFP	[signature]	03-24-2014
Approved by	Eric Lanke	CEO - NFPA Foundation	[signature]	09-19-2014
Approved by	Kim Stelson	Director - CCEFP	[signature]	09-19-2014

Release Date	09-19-2014
Latest Review Date	09-19-2014

READ AND COMMENTED BY			
NAME	**TITLE**	**SIGNATURE**	**DATE**
various	CCEFP Industrial Advisory Board		07-17-2014

PURPOSE

The purpose of this CCEFP Operating Procedure is to outline the process for developing the CCEFP's overall research strategy and for the alignment of resources in support of this strategy.

INTRODUCTION

It is crucial that the CCEFP be responsive to the pre-competitive research needs of the entire fluid power industry. The primary vehicle to communicate the pre-competitive research needs of industry to the CCEFP is the NFPA Technology Roadmap, which will be reviewed and updated regularly by the NFPA Roadmap Committee. The CCEFP Director and the CCEFP Steering Committee will translate the content of the Roadmap into an overall research strategy for the CCEFP. Furthermore the CCEFP Management Team will actively seek out and prioritize CCEFP projects that align with the research strategy.

SCOPE

The process for developing and maintaining the CCEFP Research Strategy is within scope of this COP. Aligning CCEFP resources with the research strategy is also within scope. Development of the NFPA Technology Roadmap is not within scope.

DEFINITIONS

"CCEFP Research Strategy" is the document which defines the research areas of need and associated education programs necessary to achieve the CCEFP's goals of developing fundamental knowledge about fluid power and educating the next generation of scientific and engineering leaders in the field.

CCEFP Operating Procedure (COP)

COP No: 003 Rev 0
Title: CCEFP Research Strategy Development and Resource Alignment

"Resource Alignment" is the methods and process utilized by the CCEFP Management Team to assure that the areas of need identified by the CCEFP Research Strategy are being addressed.

RESPONSIBILITIES

The CCEFP Director is responsible for oversight of the CCEFP Research Strategy.

PROCEDURE

1. NFPA Technology Roadmap is reviewed, updated and/or supplemented by the NFPA Roadmap Committee.

2. Updates and/or supplements to the Roadmap are communicated to CCEFP Director.

3. After consultation with the CCEFP research community and other fluid power thought leaders, the CCEFP Director reviews updates and/or supplements to the Roadmap with the CCEFP Steering Committee and makes any necessary changes to the CCEFP research strategy.

4. CCEFP Director communicates changes to the CCEFP research strategy to the CCEFP Industry Engagement Committee and works with them to prioritize the areas of research study most beneficial to the pre-competitive needs of the fluid power industry.

5. CCEFP Director or his designee works with the CCEFP Industry Engagement Committee to identify principal investigators and universities with the expertise and resources needed to address the prioritized areas of research study.

FORMS and TEMPLATES USED

COP-003-01: NFPA Technology Roadmap

COP-003-02: CCEFP Research Strategy

REFERENCES

Not applicable.

CCEFP Operating Procedure (COP)

COP No: 003 Rev 0
Title: CCEFP Research Strategy Development and Resource Alignment

REVISION CONTROL

Revision No.	Significant Changes	Release Date
0	Initial document release	09-19-2014

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CCEFP Operating Procedure (COP)

COP No: 004 Rev 0
Title: CCEFP Call for Project Proposals

	NAME	TITLE	SIGNATURE	DATE
Authored by	Michael Gust	ILO - CCEFP	[signature]	03-24-2014
Approved by	Eric Lanke	CEO - NFPA Foundation	[signature]	09-19-2014
Approved by	Kim Stelson	Director - CCEFP	[signature]	09-19-2014

Release Date	09-19-2014
Latest Review Date	09-19-2014

READ AND COMMENTED BY			
NAME	**TITLE**	**SIGNATURE**	**DATE**
various	CCEFP Industrial Advisory Board	N/A	07-17-2014

PURPOSE

The purpose of this CCEFP Operating Procedure is to outline the process for requesting CCEFP researchers to submit projects to address critical areas of pre-competitive research need for the fluid power industry.

INTRODUCTION

The primary vehicle for driving the research undertaken by the CCEFP is the CCEFP Research Strategy. Based on that strategy, the CCEFP Management Team and the CCEFP Industry Engagement Committee will develop a biennial call for pre-competitive research proposals to the appropriate researchers at participating and newly-identified universities.

SCOPE

Communicating the pre-competitive research needs and project areas derived from the CCEFP Research Strategy to the CCEFP principal investigators, and soliciting their proposals, is in scope.

DEFINITIONS

"CCEFP Call for Project Proposals" is the vehicle for the CCEFP Management Team to request proposals from participating and newly-identified principal investigators.

"PI" is an abbreviation for "principal investigator."

"Participating University" is an academic institution that has agreed to the CCEFP terms and conditions for funded research or workforce development projects.

CCEFP Operating Procedure (COP)

COP No: 004 Rev 0
Title: CCEFP Call for Project Proposals

"Newly-Identified University" is an academic institution that has been selected to receive the CCEFP Call for Proposals because it possesses the expertise and/or resources needed to address the CCEFP research strategy, although it has not yet agreed to the CCEFP terms and conditions for funded research or workforce development projects.

RESPONSIBILITIES

The CCEFP Director is responsible for oversight of the CCEFP Call for Project Proposals.

PROCEDURE

1. The CCEFP Research Strategy is reviewed and updated per COP-003.
2. CCEFP Director or his designee works with the CCEFP Industry Engagement Committee to design and distribute a CCEFP Call for Project Proposals to the Participating and Newly-Identified Universities that will result in project proposals aligned with the prioritized areas of research study.
3. PIs from participating and newly-identified universities respond to call for proposals by completing appropriate templates.
4. For an existing project to be considered for renewal it is required that a continuation proposal be submitted.

FORMS and TEMPLATES USED

COP-004-01: CCEFP call for project proposals template

COP-004-02: CCEFP budget template

REFERENCES

Not applicable.

REVISION CONTROL

Revision No.	Significant Changes	Release Date
0	Initial document release	09-19-2014

CCEFP Operating Procedure (COP)

SOP No: 005 Rev 0
Title: CCEFP Project Selection

	NAME	TITLE	SIGNATURE	DATE
Authored by	Michael Gust	ILO - CCEFP		03-24-2014
Approved by	Eric Lanke	CEO - NFPA Foundation		09-19-2014
Approved by	Kim Stelson	Director - CCEFP		09-19-2014

Release Date	09-19-2014
Latest Review Date	09-19-2014

READ AND COMMENTED BY			
NAME	**TITLE**	**SIGNATURE**	**DATE**
various	CCEFP Industrial Advisory Board	N/A	07-17-2014

PURPOSE

The purpose of this CCEFP Operating Procedure is to define the criteria and overall process for the selection of the CCEFP research project proposals that are funded through the NFPA Foundation.

INTRODUCTION

A balanced research portfolio that addresses the pre-competitive needs of the fluid power industry is the most important feature in helping the CCEFP achieve its goals of developing fundamental knowledge about fluid power and the education of the next generation of scientific and engineering leaders in the field. A well balanced portfolio will support both hydraulic and pneumatic projects and will span the risk/reward spectrum from fundamental research representative of technology readiness level (TRL) 1 to nearer term technology efforts of a TRL 4 or 5. Industry participation in the selection of projects is paramount to ensuring that the CCEFP is responsive to meeting industry needs. Academic perspective is critical to pushing the boundaries of new ideas and concepts.

All projects should have a beginning and an end and not continue indefinitely. CCEFP projects are typically authorized funding for a 2-year time period, although the second year of funding is not awarded until the next fiscal year, at which point it is guaranteed. At the end of this 2-year time period it is acceptable to submit a new proposal to continue the research. However this new project must still be recommended for funding by the CCEFP Industry Engagement Committee and approved by the CCEFP Director to receive funding. Projects that are not selected for renewal are sun-set. The CCEFP Management Team strives to be as supportive as possible during the transition phase, especially with regard to any affected students.

SCOPE

CCEFP Operating Procedure (COP)

SOP No: 005 Rev 0
Title: CCEFP Project Selection

The criteria and process for selection of project proposals funded through the NFPA Foundation are within the scope of this COP. The same criteria will be applied to NSF-funded research or other government funded research.

DEFINITIONS

Project selection criteria descriptions for Strategic Alignment, Risk and Reward are shown in the table below and further defined in SOP-004-01.

		Score					
	Scoring Parameter	1	2	3	4	5	Enter score (Integers only)
Alignment	Fundamental nature of project	Largely technology development	Extension of known technology into new space.	Some level of fundamental research apparent	Largely fundamental research (extension of current or past work)	Largely fundamental research (novel direction)	
	Systems approach	Little or no opportunity for demonstration on a fluid power system	A slight possibility of demonstration in a fluid power system has been established.	Provides a basis for demonstration on a fluid power system.	A clear path for demonstration on a fluid power system has been established.	Demonstration of one or more fluid power systems is planned during this project proposal time frame.	
	Strategic fit	Strategic fit not apparent	Some level of strategic fit	Aligned with CCEFP strategy	Aligned with transformational goals of CCEFP	Strong alignment with transformational goals of CCEFP	
	Alignment with test bed	Little or no alignment	Partial alignment, but research not consistent with main focus of test bed	Partial alignment and research is consistent with main focus of test bed	Completely aligned and consistent with scope of test bed	Completely and expands scope of test bed in a manner consistent with Center's goals	
	Center goals focused	No or weak alignment	Slight alignment with one of the CCEFP major goals	Alignment with more than one of the CCEFP major goals	Strong alignment with one of the CCEFP major goals	Strong alignment with more than one of the CCEFP major goals	
Risk	Project metrics	Limited definition of scope, deliverables, resources, and timeline	Some definition of scope, deliverables, resources, and timeline, but <50% defined	Scope, deliverables, resources, and timeline >50% defined	Project 80% scoped including deliverables, resource allocations, and timeline	Project completely scoped including deliverables, resource allocations, and timeline	
	Deliverables	Vague deliverables	Not well defined and/or SMART (Specific, Measureable, Attainable, Realistic & Time-bound)	Not well defined and/or SMART, but includes benchmarking of competitive technologies	Fully defined and SMART	Full defined, SMART and competitive benchmarks are part of deliverables	
	Likelihood of success	Unclear	Moderate - est. 25%	Good - est. 50%	Very good - est. >67%	High - est. >80% (e.g., builds on past successes)	
	Team assessment	It is apparent that the team is missing numerous critical skillsets for project success	It is likely that the team is missing one or more critical skillsets for project success	The team is missing some critical skillsets for project success but a plan is in place to secure them	It is likely that the team possesses all critical skillsets for project success	It is apparent that the team possesses all critical skillsets for project success	
	Budget Assessment	It is apparent that the proposed budget is dramatically too high or dramatically insufficient to meet project scope or well outside of specified guidelines	The proposed budget is questionable with respect to project scope or specified guidelines	The proposed budget is adequate	The proposed budget is reasonable based on project scope and specified guideleines	It is apparent that the proposed budget is appropriate to meet project scope and within specified guidelines	
Reward	Industry participation	No industry partners identified	Potential partners indentified but not yet committed	Letter of support from industry partner	Letter of support and commitment of resources from industry partner	Letters of support and commitment of resources from multiple industry partners	
	Addressing CCEFP technical barrier(s)	Weak or no link to technical barriers	Addresses one non-transformational technical barrier	Addresses multiple non-transformational technical barrier	Addresses a transformational technical barrier	Addresses multiple technical barriers including at least one transformational barrier	
	Breadth of applicability	Project's potential impact is narrow	Project's potential impact is limited to the sponsoring test bed	Project's potential impact covers more than one test bed	Potential impact benefits a broad segment of fluid power applications	Project's potential impact benefits essentially all fluid power applications	
	External support	No additional external support is likely	Nominal external support, such as in-kind donations, is possible	Some level of external support (<$50K) is expected	Government or industry sponsored research projects > $100K are likely to result from this research	Government or industry sponsored research projects > $500K are likely to result from this research	
	Original nature of project	Little or no novel contribution is likely to occur	Some novel contributon is likely to occur	Typical novel contribution is likely to occur	Novel contribution resulting in publications and/or IP is likely to occur	Novel contribution resulting in prestigious publications and/or marketable IP is likely to occur	

TRL – Technology readiness level. A measurement of the maturity of a technology developed by the US Department of Defense (DoD). TRL values range from TRL 1 to TRL 9. Corresponding CCEFP definitions are provided in the table below.

Technology Readiness Level	DoD Description	CCEFP Description
TRL 1: Basic principles observed and reported	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development. Example might include paper studies of a technology's basic properties.	Basic fundamental research that could lead to future improvements in many different areas which have yet to be defined. (Ex: nano particles or texturing that reduces friction)
TRL 2: Technology concept and/or application formulated	Invention begins. Once basic principles are observed, practical applications can be invented. The application is speculative and there is no proof or detailed analysis to support the assumption. Examples are still limited to paper studies.	Next logical step from fundamental research. Typically this would include early stage investigation of the optimal application for the fundamental insight gained in a TRL 1 project. The goal is to determine which specific fluid power challenge or barrier on which to focus.

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TRL 3: Analytical and experimental critical function and/or characteristic proof of concept	Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.	The mathematical analysis, modeling and/or early experimental verification associated with the focused TRL 2 effort above. Most likely to include an associated bench prototype.
TRL 4: Component and/or breadboard validation in laboratory environment	Basic technological components are integrated to establish that the pieces will work together. This is "low fidelity" compared to the eventual system. Examples include integration of "ad hoc" hardware in a laboratory.	Concept has been demonstrated in a lab environment. Case can be made for improvement over existing approaches. Industry input for an on-purpose design is highly desirable before continued any further development.
TRL 5: Component and/or breadboard validation in relevant environment	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so that the technology can be tested in a simulated environment. Examples include 'high fidelity' laboratory integration of components.	On purpose prototype has demonstrated the desired product feature or benefit in the lab or on a test bed. An industry partner has been involved in developing the test plan. Next step is to begin commercialization.
TRL 6: System/subsystem model or prototype demonstration in a relevant environment	Representative model or prototype system, which is well beyond the breadboard tested for TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high fidelity laboratory environment or in simulated operational environment.	A CCEFP project or test bed at this level would be nearing the end of Center support. An industry partner is likely to have assumed the lead role for further efforts (as a sponsored project) or the project is in the final stages of graduating as a Center-funded project.
TRL 7: System prototype demonstration in an operational environment	Prototype near or at planned operational system. Represents a major step up from TRL 6, requiring the demonstration of an actual system prototype in an operational environment, such as in an aircraft, vehicle or space. Examples include testing the prototype in a test bed aircraft.	Possible CCEFP involvement, but only as an associated/sponsored project and not a Center-funded project. An industry partner or start-up is now leading the effort.
TRL 8: Actual system completed and qualified through test and demonstration	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the system in its intended weapon system to determine if it meets design specifications.	Not applicable to CCEFP. Technologies at this level would normally fall under industry development programs. CCEFP may play a supportive role.
TRL 9: Actual system proven through successful mission operations	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. In almost all cases, this is the end of the last "bug fixing" aspects of true system development. Examples include using the system under operational mission conditions.	Not applicable to CCEFP. Technologies at this level would normally fall under industry development programs. CCEFP may play a supportive role.

RESPONSIBILITIES

1. The CCEFP Director, with support from the CCEFP Industry Liaison Officer, is responsible for administering the overall project selection process.
2. The CCEFP Industry Engagement Committee will be responsible for recommending which proposals are funded.

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3. The CCEFP Industry Engagement Committee will identify a number of proposal review teams to provide appropriate and knowledgeable reviews of all proposals. In addition to the members of the CCEFP Industry Engagement Committee, these proposal review teams will include the members of the NFPA Roadmap Committee.
4. The CCEFP Director has final responsibility for determining which projects will be funded.

PROCEDURE

1. Responses to the CCEFP strategic call for proposals will be posted on a secure website two weeks before the CCEFP Annual Meeting to allow sufficient time for the proposal review teams to familiarize themselves with the proposals. Access instructions to the website will be provided to each individual representative.
2. A 1/2 day session at the CCEFP Annual Meeting will be dedicated for PIs to present an overview of their project proposals to the CCEFP Industry Engagement Committee and proposal review team attendees along with Q & A.
3. Following the October CCEFP Annual Meeting but before the end of the year each proposal review team representative will assess and rank order project proposals based on the selection criteria. Ranking results from multiple representatives will be combined and compared using appropriate statistical methods and forwarded to the CCEFP Director and CCEFP Industry Liaison Officer.
4. The CCEFP Director and CCEFP Industry Liaison Officer will review the project rankings to ensure proper distribution and strategic alignment, and prepare a final list of rank-ordered projects to be funded.
5. The final list of projects to be funded will be presented to the CCEFP Industry Engagement Committee. Any deviations from the received ranked order due to concerns about distribution or strategic alignment will be described and explained by the CCEFP Director.
6. Projects will be awarded in the final ranked order up to the available funding limit. Typically projects will be funded for two years unless otherwise specified.
7. PIs will be notified of the awards per the lead university Sponsored Projects Administration organization.
8. Existing CCEFP projects that are discontinued qualify for bridge funding per CCEFP guidelines.

FORMS and TEMPLATES USED

COP-004-01: CCEFP project selection criteria template

REFERENCES

Not applicable.

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SOP No: 005 Rev 0
Title: CCEFP Project Selection

REVISION CONTROL

Revision No.	Significant Changes	Release Date
0	Initial document release	09-19-2014

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CCEFP Operating Procedure (COP)

COP No: 006 Rev 0
Title: CCEFP Project Progress Reporting and Monitoring

	NAME	TITLE	SIGNATURE	DATE
Authored by	Michael Gust	ILO - CCEFP	[signature]	03-24-2014
Approved by	Eric Lanke	CEO - NFPA Foundation	[signature]	09-23-2014
Approved by	Kim Stelson	Director - CCEFP	[signature]	09-23-2014

Release Date	09-23-2014
Latest Review Date	09-23-2014

READ AND COMMENTED BY			
NAME	**TITLE**	**SIGNATURE**	**DATE**
various	CCEFP Industrial Advisory Board	N/A	07-17-2014

PURPOSE

The purpose of this CCEFP Operating Procedure is to describe the process for reporting and monitoring progress on CCEFP research projects.

INTRODUCTION

Keeping projects on track and progressing is important to the CCEFP and its industry supporters. To ensure that expected progress is realized the CCEFP Management Team will utilize two project progress review sessions per year, one of which will be held face to face with industry at the annual conference The CCEFP will also publish an annual report one month after its fiscal year ends.

SCOPE

Only CCEFP projects funded through the NFPA Foundation are in scope. Other affiliated industry or government agency funded projects are not in scope.

DEFINITIONS

"RFP" is an abbreviation for "request for proposal."

"CCEFP Funded Project" is a project that has been selected to be funded from a strategic RFP.

"PI" is an abbreviation for "principal investigator."

RESPONSIBILITIES

The lead PI, or designee, is responsible for reporting progress.

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Title: CCEFP Project Progress Reporting and Monitoring

The CCEFP Management team, or designees, is responsible for evaluating progress and recommending actions to resolves issues and delays.

PROCEDURE

1. Each CCEFP project or test bed will have a review committee of faculty and industry representatives assigned by the CCEFP Management Team.
2. The review committee will conduct two reviews per year, one in the fall at the CCEFP annual conference and another at one of the two other industry summits held at a CCEFP participating university during the remainder of the year.
3. PIs or their designees will complete the progress review template defined in COP-006-01 one week prior to the upcoming review session and forward to the CCEFP Director for distribution to the assigned committee representatives.
4. PIs or their designees will present their progress reviews to the CCEFP Industry Engagement Committee and the other invited industry representatives at the review session. Feedback as defined in COP-006-02 will be solicited from these industry attendees and forwarded to the assigned review committees, research project PI and the CCEFP Director.
5. Committee representatives will assess progress and report back to the PI and the CCEFP Director who will implement corrective measures on an as-needed basis.
6. The annual report of the CCEFP, published one month after the end of the CCEFP fiscal year, will contain the latest progress report available on each CCEFP project or test bed. The annual report will be made available to the public at-large through the CCEFP and NFPA Foundation websites.

FORMS and TEMPLATES USED

COP-006-01: CCEFP Progress Review template

COP-006-02: Industry Feedback on CCEFP Progress Review

REFERENCES

Not applicable.

REVISION CONTROL

Revision No.	Significant Changes	Release Date
0	Initial document release	09-23-2014

CCEFP Operating Procedure (COP)

COP No: 007 Rev 0
Title: Performance Metrics

	NAME	TITLE	SIGNATURE	DATE
Authored by	Michael Gust	ILO - CCEFP	[signature]	03-24-2014
Approved by	Eric Lanke	CEO – NFPA Foundation	[signature]	09-23-2014
Approved by	Kim Stelson	Director - CCEFP	[signature]	09-23-2014

Release Date	09-23-2014
Latest Review Date	09-23-2014

READ AND COMMENTED BY			
NAME	**TITLE**	**SIGNATURE**	**DATE**
various	CCEFP Industry Advisory Board	N/A	09-23-2014

PURPOSE

The purpose of this CCEFP Operating Procedure is to define performance metrics for the CCEFP and the NFPA Foundation.

INTRODUCTION

As the CCEFP transitions its pre-competitive research program from primarily NSF funding to primarily industry consortium funding through the NFPA Foundation, the metrics for assessing and driving performance will similarly change. These metrics will be reviewed and mutually agreed upon with the NFPA Foundation annually.

Some of the existing metrics, such as students graduated, technical papers published, etc., will remain unchanged. Other metrics will be selected to drive focused efforts particularly in the area of securing new government grants to replace the current NSF grant as it reduces in size and eventually ends altogether. During an initial transition period the CCEFP performance metrics regarding additional government grants will be "effort-based" and then migrate to "results-based" over time. Effort-based metrics examples may include proposals written, government agencies visited, participation on panels, etc. Results-based metrics may include funds awarded, etc.

Agreed metrics for the CCEFP for NSF years 9 and 10 are set out in the NFPA Foundation Grant Agreement, section 2(e).

Similar metrics are in order for NFPA Foundation performance. Some examples may include funds awarded, funding forecast, industry members visited, industry members committed, etc. Agreed metrics for NFPA Foundation performance for NSF years 9 and 10 are set out in the NFPA Foundation Grant

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Title: Performance Metrics

Agreement, section 2(d). Term and termination details for establishing ongoing funding support are describe in NFPA Foundation Grant Agreement, section 8(a).

SCOPE

Metrics associated with the NFPA Foundation award are in scope. Other award metrics are not in scope.

DEFINITIONS

Not applicable.

RESPONSIBILITIES

The CCEFP Director is responsible for identifying, approving and tracking any CCEFP-owned metrics. The NFPA CEO is responsible for identifying, approving and tracking any NFPA Foundation-owned metrics.

PROCEDURE

1. Agreed upon metrics will be tracked quarterly and reported to ensure expected progress is realized.
2. An annual report will be written and published by the CCEFP Management Team one month after the end of each fiscal year. The report will include performance against approved metrics.
3. During the fall quarter of each year a planning session for the upcoming year will be held between the CCEFP Director and the NFPA Foundation CEO. Additional attendees approved by both parties may participate.
4. Appropriate performance metrics for both organizations, funding levels realized and funding level forecasts will be discussed and a joint recommendation for a draft addendum to the Grant Agreement finalized.
5. The draft addendum will be reviewed and approved by the appropriate oversight individual or committee for each organization.
6. If the addendum is approved, the level of NFPA Foundation committed support for an additional year (the following year, plus 1) will be established by April 1. To illustrate, during NSF year 8, the NFPA Foundation has committed to levels of support for NSF years 9 and 10. By April 1 of year 9, the NFPA Foundation will commit to the level of support for year 11.

FORMS and TEMPLATES USED

Not applicable.

REFERENCES

Not applicable.

CCEFP Operating Procedure (COP)

COP No: 007 Rev 0
Title: Performance Metrics

REVISION CONTROL

Revision No.	Significant Changes	Release Date
0	Initial document release	09-23-2014

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CENTER FOR COMPACT AND EFFICIENT FLUID POWER
ANTITRUST POLICY

Active industry participation in the Center for Compact and Efficient Fluid Power (CCEFP) is an important aspect of support for the CCEFP. Participation adds to the vitality and energy of the organization, and furthers CCEFP's vision of accomplishing together what can't be done alone in the fluid power industry.

CCEFP is committed to strict compliance with all laws applicable to carrying out its objectives, and in the conduct of its activities. Its programs involve cooperative efforts to accomplish those objectives, including the frequent meeting of competitors and their distributors and suppliers. It is therefore important to emphasize the ongoing responsibility of CCEFP and its volunteers to comply fully with federal and state antitrust laws.

The CCEFP Industrial Engagement Committee (IEC), Educational Advisory Board (EAB) and Steering Committee (SC) officers, as governing representatives of industry to the CCEFP, are aware of their responsibility and conduct their meetings and adopt programs and activities in strict compliance with all laws applicable to not-for-profit organizations. An equal responsibility for antitrust compliance rests with all those participating in CCEFP activities such as research Project Mentors (PM's). Your corporate employer and CCEFP depend on you as a participant to use your good judgment to avoid all discussions and activities which may involve improper subject matter, or discussions which may have unintended implications, and avoidance of even an appearance of improper activity. You, who are directly involved in the industry either as a manufacturer, distributor or supplier, must take every precaution to assure that your conduct at CCEFFP meetings or with competitors at any time will not have implications of an antitrust nature.

The industry representatives associated with the CCEFP are undertaking activities similar to that of an association. While the positive contributions of associations are well recognized and encouraged by government, association activities also are subject to close scrutiny under both federal and state antitrust laws. The single most significant law affecting associations is the Sherman Antitrust Act, which makes unlawful every contract, combination or conspiracy in restraint of trade. Because an association is, by nature, a group of competitors joined together for a common business purpose, an association satisfies what would ordinarily be a difficult element in proving an antitrust violation.

CCEFP industry member meetings and discussions are, in general, to be industry-CCEFP-promotion, industry-CCEFP issues, and educationally or technically oriented. Discussions may generally cover matters concerning fluid power related research developments, advancing "technical know-how", identifying future market needs on a general (i.e., non-specific company) basis, generic terms, technology transfer and education/outreach related topics.

Historically, the most significant area of antitrust concern for associations has been price fixing. Price fixing is a very broad term which includes any concerted effort or action that has an effect on prices, terms or conditions of trade, or on competitors. Accordingly, CCEFP members should refrain from any discussion which may provide the basis for an inference that they agreed to take any action relating to prices, services, production, allocation of markets or any other matter having a market effect. These discussions should be avoided both at formal meetings and informal gatherings. In addition, CCEFP members should be sensitive to other matters that may raise particular antitrust concern: membership restrictions, codes of ethics or other forms of self-regulation, and product standardization or certification.

The following are guidelines participants should follow at CCEFP meetings and related informal gatherings:

- **DON'T** discuss your own or competitors' prices or fees for service, or anything that might affect prices or fees, such as costs, discounts, terms of sale, profit margins or future marketing plans.
- **DON'T** stay at a meeting where any such price talk occurs – state why you are leaving.
- **DON'T** make public announcements or statements about your own prices or fees, or those of competitors, at any CCEFP meeting.

- **DON'T** talk about what individual companies plan to do in particular geographic or product markets or with particular customers.
- **DON'T** disclose to others at meetings or otherwise any competitively sensitive information.
- **DON'T** speak or act on behalf of CCEFP unless specifically authorized to do so.
- **DO** have a staff person from CCEFP present at any meetings you conduct and insist on the agenda being followed and minutes kept.
- **DO** send copies of all CCEFP-related correspondence to CCEFP's office.
- **DO** alert CCEFP staff or legal counsel to any sensitivities or inaccuracies in proposed statements to be made by or on behalf of CCEFP.
- **DO** consult with your own legal counsel or CCEFP staff before raising any matter or making any statement that you think may involve competitively sensitive information.
- **DO** be alert to improper activities, and don't participate if you think something is improper.

Adherence to these guidelines involves not only avoidance of antitrust violations, but avoidance of behavior which might be so construed. Bear in mind, however, that the antitrust laws are stated in general terms, and that this policy only provides an overview of prohibited actions. It is intended only to highlight and emphasize the principal antitrust standards which are relevant to CCEFP programs and activities. You must, therefore, seek the guidance of either your own legal counsel or CCEFP's legal counsel if antitrust questions arise.

CENTER FOR COMPACT AND EFFICIENT FLUID POWER
EXPORT CONTROL STATEMENT OF COMMITMENT

U.S. export controls consist of a broad, diverse, and complicated array of regulatory requirements that have varying and often surprising impacts on the activities of university personnel. There are three areas in particular that give rise to most export control issues in the university setting.

First, the Export Administration Regulations (EAR) and International Traffic in Arms Regulations (ITAR) prohibit the unauthorized disclosure or transfer of controlled software, technology, and technical data to non-U.S. persons, both abroad *and in the United States*. Second, export controls regulate the shipment, transmission, carriage, or provision of certain goods, software, technology, and services outside of the United States. The items subject to the regulations include the EAR-controlled items on the Commerce Control List (CCL) and the ITAR-controlled items on the U.S. Munitions List (USML). And finally, the Foreign Assets Control Regulations impose economic sanctions against several countries as well as the individuals and organizations on the Specially Designated Nationals List (a U.S. Government official list of the bad guys). The country-wide sanctions include robust restrictions on travel and trade to and from the targeted countries, affecting the ability of University personnel to study, teach, or conduct research in those locations.

Each participant in any CCEFP-funded project or activity must comply with the export control policy of his or her home institution. Any CCEFP-funded project personnel facing a potential export controls issue should not hesitate to seek guidance from their respective university's official responsible for export controls compliance. Some general guidelines for such circumstances are listed below.

When should I consult my university's export controls compliance official?

- Whenever you face a potential export controls issue, such as in the following circumstances: Whenever sponsors attempt to impose publication or personnel access restrictions on research activities.
- Before receiving export-controlled technical information from an outside party, such as an industry or U.S. Government research sponsor.
- Whenever documents from sponsors or other parties refer to the Export Administration Regulations, the International Traffic in Arms Regulations (ITAR), the Foreign Assets Control Regulations, or export controls and economic sanctions generally.
- Before accepting hardware, software, technology, or technical data from an outside party (such as an industry sponsor) to be used in a project as part of an instructional course.
- Before preparing to export from the U.S. any technology, equipment, materials, or chemical or biological agents (including toxins and genetic elements) on the Commerce Control List.
- Before handling or preparing to export from the U.S. any goods, technical data, or services subject to the ITAR.
- Before traveling to an embargoed country.

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