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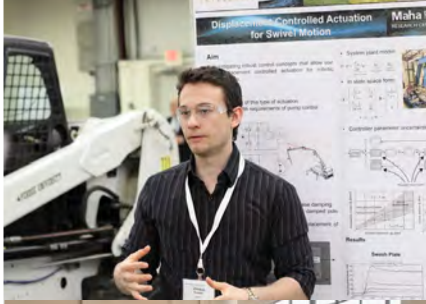
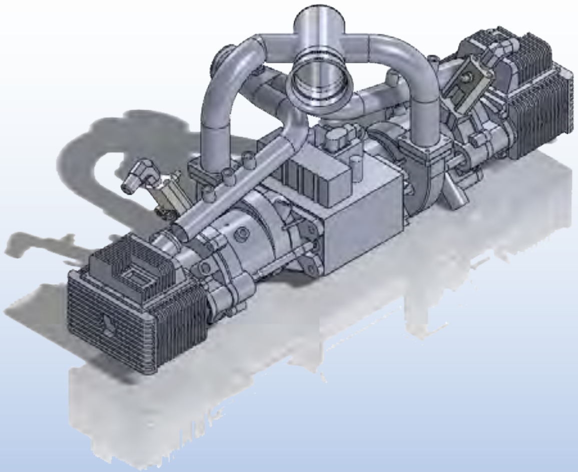
8th ANNUAL REPORT

VOLUME 1

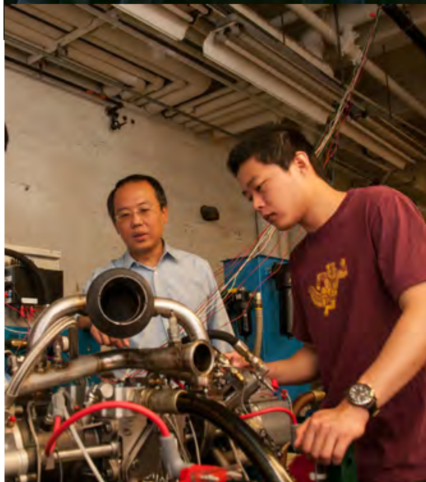
COOPERATIVE AGREEMENT #EEC 0540834 / DUE DATE: MARCH 18, 2014





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
				555917996	

EMPLOYER IDENTIFICATION NUMBER (EIN) OR TAXPAYER IDENTIFICATION NUMBER (TIN)
41-6007513

SHOW PREVIOUS AWARD NO. IF THIS IS
☐ A RENEWAL
☐ AN ACCOMPLISHMENT-BASED RENEWAL

IS THIS PROPOSAL BEING SUBMITTED TO ANOTHER FEDERAL AGENCY? YES ☐ NO ☒ IF YES, LIST ACRONYM(S)

NAME OF ORGANIZATION TO WHICH AWARD SHOULD BE MADE
University of Minnesota – Twin Cities

AWARDEE ORGANIZATION CODE (IF KNOWN)
0023879000

ADDRESS OF AWARDEE ORGANIZATION, INCLUDING 9 DIGIT ZIP CODE
University of Minnesota – Twin Cities
450 McNamara Alumni Center
Minneapolis, MN 55455-2070

NAME OF PERFORMING ORGANIZATION, IF DIFFERENT FROM ABOVE

PERFORMING ORGANIZATION CODE (IF KNOWN)

ADDRESS OF PERFORMING ORGANIZATION, IF DIFFERENT, INCLUDING 9 DIGIT ZIP CODE

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

TITLE OF PROPOSED PROJECT

REQUESTED AMOUNT	PROPOSED DURATION (1-60 MONTHS)	REQUESTED STARTING DATE	SHOW RELATED PREPROPOSAL NO., IF APPLICABLE
$ 2680000	12 months	06/01/2014	

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 08/21/2013
☐ INTERNATIONAL COOPERATIVE ACTIVITIES: COUNTRY/COUNTRIES ____
☐ FACILITATION FOR SCIENTISTS/ENGINEERS WITH DISABILITIES
☐ RESEARCH OPPORTUNITY AWARD (GPG V.H)

PI/PD DEPARTMENT
Mechanical Engineering

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CO-PI/PD				
CO-PI/PD				
CO-PI/PD				

NSF Form 1207 (10/99)

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Volume I Table of Contents

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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 nineteen 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 45 corporate members 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, with the exception of the CCEFP-GEM Partnership, can be found in Section 1.3 of this report. Information on the CCEFP-GEM partnership can be found in section 3.

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

High performance hydraulic hybrid system for Test Bed 1

Displacement controlled (DC) actuation has demonstrated more than 50% fuel savings and 70% performance improvement over traditional valve-controlled multi-actuator systems. A hybridized DC hydraulic system can further improved efficiency. Simulations of the new hybrid excavator system predict that the maximum engine power could be reduced by 50% for a truck loading cycle and fuel savings of greater than 50% are possible.

Pneumatic Strain Energy Accumulator implemented on Test Bed 6

In the past year the Strain Energy Accumulator (SEA) was demonstrated on TB6, the Ankle Foot Orthosis (AFO), as a way to recover exhaust gas from its pneumatic system. In these preliminary trials, the pneumatic SEA provided an energy savings of over 25% relative to operating the pneumatic actuation of the AFO in the conventional manner.

Patient Transfer Device at Georgia Tech

Test Bed 4, the patient transfer device, is in the first phase of operation. Untethered, valveless, electro-hydraulic pump control is attained for multiple degrees of freedom by using a reversible DC electric motor driving a bidirectional hydraulic gear pump for each degree of freedom. An advanced passivity-based human power amplifier control technique for collaborative manipulation was implemented on a pre-prototype hydraulic lift device.

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

Pressure Ripple Energy Harvester

The Hydraulic Pressure-Ripple Energy Harvester (HPEH) project set new benchmarks in terms of power generation performance, power density, and demonstration of viability. The project has been successful in pushing research and development such that HPEH powered devices could be viable across a broad range of power demands, available energy densities, form factors, static pressures, and target applications.

Pneumatic control of voluntary and Involuntary nerve impulses for hemiparesis rehabilitation and FMRI study

The ultimate goal of the research is to understand and characterize the neuromechanical mechanisms associated with facilitation techniques designed for functional recovery of hemiparetic limbs. The facilitation technique of interest, referred to as repetitive facilitation exercise or RFE. Studies have shown better results than conventional rehabilitation sessions applied to hemiparetic upper and lower limbs.

MEMS pneumatic valve

The MEMS Proportional Hydraulic Valve project successfully fabricated MEMS scale port plates and MEMS scale valve actuator arrays in the past year. These components comprise the two essential elements of MEMS valves. The two components will be "tuned" and combined to make complete prototype MEMS valves.

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

Regimes of friction in elastohydrodynamic lubrication

The prediction of friction from the measureable properties of a liquid lubricant has been an elusive goal of researchers in elastohydrodynamic lubrication since the 1960's. Past work employed fictitious properties, derived from measurements of the friction, and was therefore not predictive. Recent CCEFP research has defined the necessary properties through the identification of the dimensionless numbers which delineate the various friction regimes, thus making friction predictions possible.

Development of a novel gap-controlled tribo-rheometer

A novel gap-controlled tribo-rheometer has been built at UIUC that enables gap-controlled tests to systematically vary the appropriate dimensionless groups involved in the co-design of microtextured surfaces and lubricant fluids for reduced friction and leakage. Applications include friction and leakage reduction in fluid power systems; friction reduction has been measured and compares well with computational predictions.

New unique general FEA approach for contact and deformation analyses developed in the study of seals and rods with micro-patterned surface

A new unique general finite element analysis approach for contact analyses has been developed during research on hydraulic seals and rods with a micro-patterned surface. The approach is useful for the analysis of 2-D macroscopic bodies in contact with a surface containing 3-D micro/nano surface feature patterns, which normally requires a very large number of elements due to the necessity of capturing the micro/nano surface features.

iv. University education

CCEFP Fluid Power MOOC approved by University of Minnesota

University of Minnesota professors James Van de Ven and William Durfee will be offering 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 will introduce students to the fundamental principles of fluid power systems, circuits, and components. The six week course will be first offered during the fall of 2014.

CCEFP supports Three Parker Hannifin Chainless Challenge teams

The Parker Chainless Challenge is a national inter-university competition sponsored by Parker Hannifin, a corporate member of the CCEFP. The competition requires that a team of undergraduate students design and build a bicycle that uses fluid power as its main method power transmission. Three CCEFP schools participated in the competition and the University of Illinois at Urbana-Champaign was the overall competition winner.

CCEFP receives NSF REU Site Award

CCEFP was awarded the competitive NSF Research Experiences for Undergraduates (REU) Site Award for years 8-10. The REU program goal is to kindle interest of diverse participants in attending graduate school. Additionally, CCEFP’s goal also includes increasing the number of undergraduate students knowledgeable in fluid power. To date, more than 145 REU students have participated in the CCEFP program - more than in many REU site programs.

v. Pre-college education

Inaugural year of the EngrTEAMS Program

2013 was the inaugural year of the EngrTEAMS Program, “Engineering to Transform the Education of Analysis, Measurement, and Science in a Team-Based Targeted Mathematics-Science Partnership” a large NSF/MSP program developing state-of-the-art science education pedagogy and spreading this work through professional development activities to reach 150 4th-8th grade science teachers. CCEFP is a major project partner providing content experts and advisement on the advisory board.

CCEFP hosts NFPA Fluid Power Challenge - An 8th grade design competition

The Fluid Power Challenge is a skills based competition for eighth grade students that is promoted by the National Fluid Power Association and hosted by the CCEFP The program challenges students to solve real life engineering problems using fluid power (hydraulics and pneumatics). To date, the CCEFP has hosted three events, exposed over 300 students to fluid power technology. The CCEFP expects to expand efforts in the future.

NSF invites CCEFP to exhibit at *Change the World: Science and Engineering Careers Fair*

NSF invited CCEFP to exhibit at the Change the World: Science and Engineering Careers Fair in the nation’s capital in September. NSF was interested in displaying fluid power and CCEFP’s hands-on excavator demonstrator to be a hands-on tutorial at the event.

vi. General outreach

Twin Cities Public Television fluid power documentary

CCEFP, National Fluid Power Association and Twin Cities Public Television (TPT) created a one hour documentary on fluid power that is shown several times a month on TPT. Fluid power's strengths and potential are explained by CCEFP industry members, PIs and researchers.

vii. Diversity advances in the Center

CCEFP-GEM Partnership

The ERC-GEM-Industry partnership model has been developed and implemented. The specialized membership model includes cooperation between the ERC and the Industry member, who are both academic and corporate members of the National GEM Consortium, and who jointly sponsor the ERC GEM Fellow. The GEM Fellow receives over $150,000 in financial support in the form of an academic student stipend, tuition remission, and summer intern salary. The first GEM-ERC Fellow, Mr. Oscar Pena, was named for Fall 2013 under Professor Michael Leamy at Georgia Institute of Technology. The CCEFP submitted an informal proposal to NSF and was invited to discuss the program, in person, November 2013. NSF ERC leaders were strongly supportive and agreed to provide supplemental funding to extend the CCEFP's pilot program into another year.

Reformulated coalition with the White Earth Indian Reservation

This program is a major outreach effort designed to expose native students to the ways that science and technology can impact society. The program introduces the native high school students to native and non-native engineering students and them pathways to a future in STEM and related fields. A reboot of the program came about through the commitment of students and staff from the Innovative Engineers, the National Society of Black Engineers, and the American Indian Society for Engineering and Science.

Bridges Program

The Bridges Program is a collaboration between the Universidad Nacional de Ingenieria (UNI), the Universidad Tecnologica LaSalle, Villanova University, and the University of Minnesota dedicated to building relationships and empowering people and communities, in the United States and Nicaragua. This is done through the initiation, support, and coordination of community-based projects.

viii. Innovation achievements

Post-stroke patient testing with the PPAFO at the Rehab Institute of Chicago

In collaboration with researchers at the Rehabilitation Institute of Chicago, testing has begun to explore the advantages of the PPAFO compared to a range of other assistive devices (e.g., tibial stimulators and commercially-available passive AFOs) in a post-stroke subject population. The devices are being compared by asking each participant to complete a set of clinically-accepted walking tasks with both the PPAFO and their personal device.

High efficiency variable displacement linkage pump

A novel variable displacement pump has been developed that is driven by an adjustable linkage that moves the ground pivot of a link through an arc with a linear actuator and reaches true zero displacement. The compressibility energy loss is minimized by the pistons reaching the same top dead center position, regardless of displacement.

Pressure ripple energy harvester

The Hydraulic Pressure-Ripple Energy Harvester (HPEH) project set new benchmarks in terms of power generation performance, power density, and demonstration of viability. The project has been successful in pushing research and development such that HPEH powered devices could be viable across a broad range of power demands, available energy densities, form factors, static pressures, and target applications.

B. High-Level Response and Status to SWOT Findings of Previous Year Site Visit

SVT: Planning and project selection and review could benefit from greater involvement of the Scientific Advisory Board.

CCEFP response: We plan to restructure the SAB, moving toward a smaller and more engaged group. We have a core of roughly a half dozen SAB members who actively participate in Center activities. A similar number rarely participate. We plan to retire the non-participants from the SAB and replace some of them with subject matter experts who have an interest in actively supporting the Center.

The SAB and the IAB met formally for the first time at the 2012 CCEFP Annual Meeting. The focus of the meeting was Center sustainability. There was a strong interaction and sharing of ideas and both Boards agreed that joint meetings should be done on an ad hoc basis to help resolve key challenges facing the Center. We plan to have another joint IAB-SAB meeting at the 2013 CCEFP Annual Meeting in October.

CCEFP update: We had a joint IAB-SAB meeting at the 2013 CCEFP Annual Meeting in October. The topic was sustainability and a very useful discussion ensued. Since then, inactive members of the SAB have been removed as planned, and the remaining group has been more intensely engaged. Two of the SAB members with extensive fluid power industry experience in high-level technical management have been retained as consultants. These two have been actively working with the leadership team on industry commitment, government grants and commercialization of CCEFP inventions.

SVT: Student engagement in the biweekly webinars is inadequately emphasized by faculty, given the strong interest in them of and participation by industry engineers.

CCEFP response: We agree that we need to strengthen the student engagement in the biweekly webinars. To that end, we will be doing the following:

1. The Center Director will contact Center PIs to urge them to tell their students that the biweekly webinars should be a priority and to set an example by regularly attending themselves.
2. We plan to expand these webinars to include topics of interest beyond Center projects and test beds. We believe a reasonable mix of topics would be approximately 50-60% project and test bed updates, 20-25% presentations from CCEFP faculty, students and staff, non-CCEFP researchers, and 20-25% presentations from industry. This last group would focus on fluid power related or associated topics and would need to be technical in nature and not marketing focused.
3. CCEFP's E&O team has offered supplemental grants to all Center schools to allow them to bring in lunch for students and faculty during the biweekly webinars. Two schools, Georgia Tech and Purdue, have used these grants to bring in food during the webinars and they have seen their attendance rise. The Center Director will encourage all schools to take advantage of the grants to foster greater attendance by students and faculty at the webinars.

CCEFP update: All three steps above have been taken. Student involvement in webinars has increased. Rather than using grants, CCEFP now directly orders pizza lunches for all of our schools to be served during webcasts. This is probably the most important reason that attendance has increased.

SVT: Intellectual property training is needed for all students.

CCEFP response: We agree our students need intellectual property training. Our Center ILO has been tasked with providing mandatory training for all CCEFP students by the end of 2013. Future students will be required to take this training as well. The training will cover all aspects of properly managing Center IP including when and how to file and be in compliance with the CCEFP Membership Agreement (MA).

CCEFP update: During one of our webcasts last fall a representative from the University of Minnesota Office of Technology and Commercialization (OTC) explained the recent changes in patent law due to the America Invents Act. The webinar included a highly relevant presentation on confidentiality including the details of what constitutes public disclosure. The most important change from the America Invents Act is that precedent is now established by the "first to file" rather than the "first to invent" rule. Awareness of patent issues has increased greatly, but we still must implement the mandatory training process.

SVT: It is unclear whether test bed 4 provides opportunities for advancement of fluid power technology.

CCEFP response: We believe the new test bed 4, the patient transfer device (PTD), holds strong potential for the advancement of fluid power technology. In particular, the control aspects of the PTD represent significant challenges that could be broadly applicable in fluid power. One example is the use of passivity control to ensure stable and safe operation of the device. In addition, collaborating with Carnegie Mellon provides the opportunity to determine if the symbiotic autonomy technology (or features of it) being researched in their CoBot robots could provide benefits on the test bed and in a broader range of fluid power application. Finally, fluid power-enabled medical devices is a research area we believe can help the Center thrive in its post-NSF existence. The PTD test bed complements the suite of medical applications using fluid power that the Center is creating. These medical devices have generated a great deal of industry interest. Thus, we believe there are both solid research and commercial opportunities associated with the new test bed 4.

CCEFP update: Recent discussions with industry have confirmed the interest in more bio-medical fluid power research activity and the appropriateness of the patient handler to move us in this direction.

SVT: The following are considered threats to the Center's success:

- *Potential for disintegration of CCEFP, due to increased reliance on associated projects as NSF funding winds down.*
- *Failure of universities to step up to support the CCEFP after graduation.*
- *Failure of industry to substantially increase support for precompetitive research after graduation.*
- *Technologies that are competitive with fluid power may prevail if fluid power advances do not come to market in a timely fashion.*

CCEFP response to Threats: We view our greatest threat to long term sustainability as funding. We believe that we have prioritized our efforts accordingly. A challenging but viable plan has been established with three major elements: 1) industry consortium dues with reduced university indirect overhead to fund pre-competitive research and administration, 2) large grants from strategically aligned government agencies 3) associated research projects from both industry and government agencies. Our goal is to raise roughly $3 million funding from each of these areas.

Since the Site Visit in April 2013, we have made considerable progress. We recognize that maintaining a pre-competitive research critical mass is crucial to Center viability and thus raising industry consortium funds is our highest priority. Meetings have been held with industry and NFPA leaders to establish recruiting goals and revenue targets. We plan to visit all key industry members to raise awareness at all organizational levels. Marketing campaigns are being developed to target industry CEOs directly with what we believe to be our considerable value proposition. All Center universities have agreed to cap indirect overhead rates at 10% on the industry consortium funds.

Similar progress is being realized in securing future large government grants. Two meetings were held at the DOE to explore government funding opportunities. Associated research projects are already quite established in the Center. Our actions plans must focus on ways to better expose more researchers to industry members to attract more widespread funding.

CCEFP update: Since the last site visit, two meetings with the Advanced Manufacturing Office (AMO) have been held. A proposal was submitted to the NIST Advanced Manufacturing Technology (AMT) program to create a manufacturing roadmap for the fluid power industry. Both initiatives will position us to be competitive for a future center in the NNMI (National Network for Manufacturing Innovation) program.

Two cross-functional committees focusing on sustainability funding have been formed and have held their organizing meetings. Both committees have a mix of industry and academic members. The Government Relations Committee is focused on garnering large, multi-site grants that will be focused on pre-competitive fluid power research. The Industry Relations Committee is focused on gaining commitment from industry for using pooled funds for pre-competitive fluid power research. These two areas are the most important ones to create a sustainable post-NSF CCEFP.

The CCEFP and NFPA are on the verge of signing a landmark Memorandum of Understanding (MOU). The goal is to eliminate gaps and overlaps by having each organization do what it does best. CCEFP will take primary responsibility for research, higher education and government grants. NFPA will take primary responsibility for working with industry, publicity, event planning and K-12 education. One feature of the arrangement is that instead of contributing industry membership dues to CCEFP, industry will provide contributions to the NFPA Foundation that will in turn provide the funds to CCEFP. Since the NFPA Foundation is tax exempt, the contribution are gifts and intellectual property rights will not be granted.

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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	Paul Imbertson	Electrical 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
Project Lead The Way	Clifton Park	New York
The National GEM Consortium	Alexandria	Virginia

EDUCATION AND OUTREACH PERSONNEL

Name	Title	Department	Institution
Cherie Bandy	E&O Administrative Specialist	ERC Staff	University of Minnesota
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
Elizabeth Hsiao-Wecksler	Faculty Researcher	Mechanical Sci. and Eng.	University of Illinois at UC
Marcus Huggans	Education Partner	External Relations	The National GEM Consortium
Paul Imbertson	Education Director	Electrical Engineering	University of Minnesota
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
Cameron Lindner	gidaa Robotics Program Coordinator	K12 STEM Teacher	Cloquet Middle School, MN
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
Holly Pellerin	gidaa Program Coordinator	ERC Staff	University of Minnesota
Andrew Schenk	SLC President	Agricult. / Biological Eng.	Purdue University
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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 is currently the dominant method of energy transmission in applications ranging from off-road vehicles, such as agricultural, construction and mining equipment to manufacturing systems. The vision of the Engineering Research Center for Compact and Efficient Fluid Power (CCEFP) has been consistent since its inception: to transform fluid power by making it more compact, efficient and effective. The Center's work continues to make progress towards reducing our Nation's energy usage and increasing the ways in which fluid power, for example in human-scale applications, will improve our quality of life. 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 eighth 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 has become recognized as a thought leader in the fluid power research community internationally.

While CCEFP's vision has remained constant, its strategy has continued to evolve and mature. The Center's leadership in the international fluid power research community and our close relationships with most of the major companies in the fluid industry provides us with an ever-improving understanding of the critical needs in fluid power. The relevance of the Center's strategy is validated by the strong industry support it enjoys and by the adoption of similar strategies in the international fluid power research community.

The CCEFP has turned its undivided attention to sustainability. 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 grants from federal agencies. The NFPA Foundation support model is described in section 5.3. Government and industry relations committees have been formed to focus on the other major elements of the sustainability plan. These committees are also described in section 5.3.

1.1 SYSTEMS VISION

The CCEFP systems vision has been continuously modified and refined over the last eight years. Its test beds provide a real world opportunity to demonstrate the systems vision. 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 a very broad range 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 these 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. 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): Orthosis (Test Bed 6)
6. Micro Medical Devices (≤10W): Precision Pneumatics for MRI Guided Surgery (Test Bed Beta)

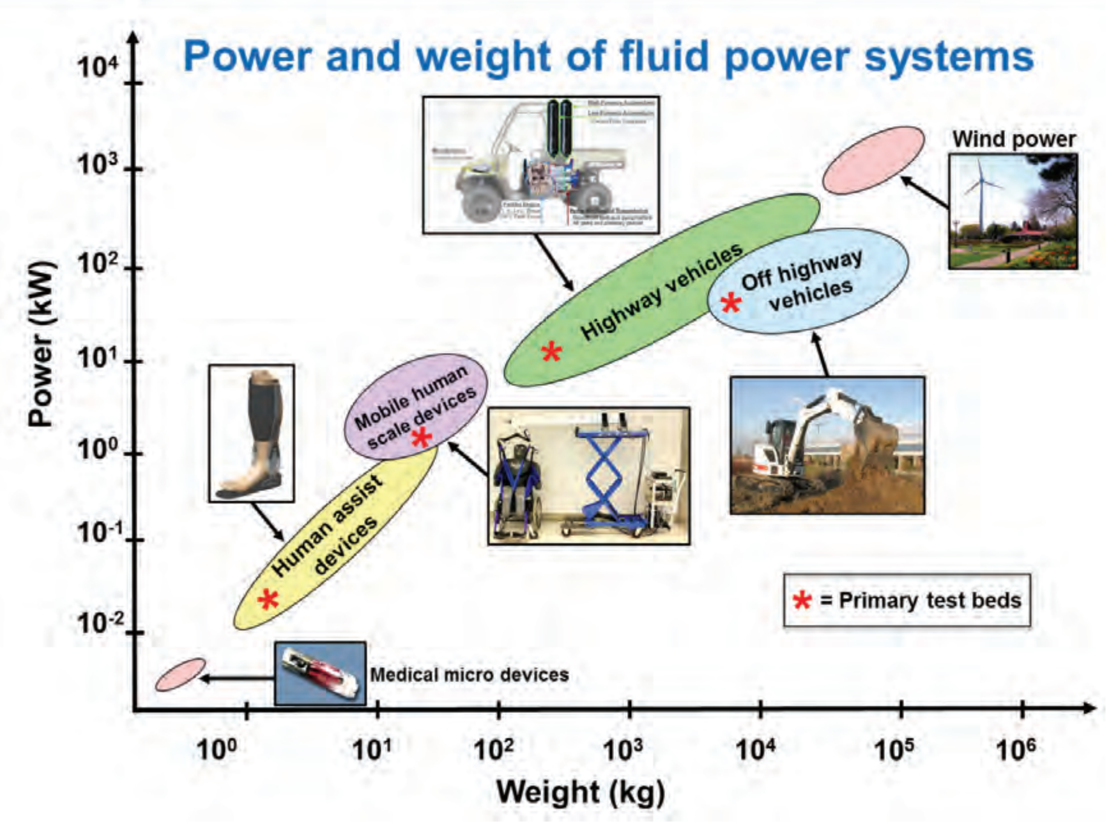

Figure 1-1: Size range of CCEFP Test Beds

The test beds chosen represent applications where fluid power is the best solution. They span six orders of magnitude of power and weight. They encompass current and future applications of fluid power, influence neighboring applications and solve important societal problems.

The CCEFP has identified the following transformational goals necessary to realize our vision:

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 Center's three thrusts flow out of its transformational goals. Thrust 1, efficiency, primarily addresses transformational goal 1. The thrusts aim is to create more efficient components and systems. Thrust 2, compactness, primarily addresses transformational goals 2 and 3. Its aim is creating components and systems that are significantly smaller and lighter than those currently available. Thrust 3, effectiveness, addresses transformational goal 4 by seeking solutions that make fluid power that is clean, quiet, safe and easy to use.

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.

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.

One 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 is 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 to be 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.

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.

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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).

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 breadth of size and weight of the Center's test beds, fluid power can be applied over many orders of magnitude of weight and power, but 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 also is 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 environment 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 on these areas, the research results will 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 are wind power, a stationary 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.

Our strategic planning process identified nine important fluid power attributes listed in Table 1-1. These attributes define the technical barriers of the Center. 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 control Energy management Compact power supplies Compact energy storage Compact integrated systems Safe and easy to use Leak-free Quiet	Efficient components & systems Compact power supplies Compact energy storage

Overcoming the technical and transformation barriers facing fluid power is the basis of the Center's vision which is to make fluid power compact, efficient, and effective. Compact means smaller and lighter for the same function. Efficient means saving energy. Effective means clean, quiet, safe and easy to use. These key components of the CCEFP vision are also the foci of the Center's three thrusts: efficiency, compactness and effectiveness.

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. Clear communicating the strategy is essential and the three-thrust structure has stood the test of time for providing a clear, concise and accurate guide for achieving our mission. 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.

CCEFP's projects are given a number 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. Nearly all of the projects in the Center combine elements of all three thrusts. Further, every test bed requires contributions from all three thrusts to succeed. Take 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 more compact replacement for the conventional accumulator, or replacing a conventional engine and pump with a HCCI free-piston engine-pump are two examples of how compactness enables a more efficient vehicle. Effectiveness also plays a key role. No one will buy a vehicle that is noisy, leaks oil, or is unsafe or difficult to drive.

CCEFP uses the tools of strategic planning, systems engineering and project management to guide research. Over time these tools have strengthened, but it is recognized that improvement is possible. Important strategic elements are evaluated in seeking and selecting proposals, and in monitoring progress. The call for proposals explicitly lists desired areas based on a gap analysis related to the barriers to be overcome. Experts in industry and academia extensively evaluate candidate proposals on all essential aspects, with the final decision being made by the CCEFP Executive Committee. All funded proposals are within the scope of the Center, overcome one of the nine barriers, and can be demonstrated on one of the test beds.

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 is 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 PI has submitted a proposal for FY9-10 funding to continue the research.

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. Vehicle engines are sized to provide sufficient torque and power for transient operation, such as during acceleration from a stop or during a passing maneuver. This leads to vehicles having engines that have roughly an order of higher power than is required for highway cruising. Hybridization can allow the excess power to be stored for later use, allowing the engine to be turned off when not needed, thus increasing fuel efficiency. Among other advantages, the free-piston engine pump has instantaneous on-off capability, meaning it has no need to idle. Several small engines could 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.

Although there are a number of compact energy storage projects being funded, the Center recognizes that it is an enabling technology for a major transformation of the fluid power industry and, thus, more research in the area is needed. To that end, we organized an ideation and prototyping workshop focused on generating novel ideas for fluid power energy storage solutions and creating simple, non-functional prototypes of the best ideas. The workshop was facilitated by Prof. Barry Kudrowitz from the University of Minnesota's College of Design. There were roughly 30 participants fairly evenly split between industry, PIs and students divided into three teams. Participants received, did some creativity-enhancing exercises and first brainstormed concepts for approaches for storing fluid power energy. Each idea was written on a post-it note along with an image of the concept. As the ideas were generated, the inventor told their team the concept name and provided a brief explanation. The ideas were then posted on an adjacent wall by the team's facilitator. After roughly ½ hour of brainstorming, the teams sorted the ideas into groups. Interestingly, this step was done in silence so that the sorting was done mainly using the right (creative) side of the participant's brain. Once the ideas were sorted, team members voted for their top three choices in two categories: (1) ideas that can be developed in the near term (2-5 years) and (2) those which require a longer term for development. The teams then created a simple prototype of their top vote getter in each category and presented them to the entire workshop. A total of 186 ideas were generated. The results were compiled and sent to CCEFP's industry members and researchers.

The evolution of test beds is an ongoing challenge that has been carefully guided by the Center. The original six test beds supported by core funding have been reduced over time to four. Test bed 4 has been 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. The two MRI guided test beds have increased our medically oriented test beds to four, and the wind power test bed provides an entrée into renewable energy research.

Response to Site Visit Team SWOT Report

SVT: Planning and project selection and review could benefit from greater involvement of the Scientific Advisory Board.

CCEFP response: We agree that the Scientific Advisory Board is a unique and valuable resource whose role should be expanded. To that end, we plan to restructure the SAB, moving toward a smaller and more engaged group. We have a core of roughly a half dozen SAB members who have actively participated in Center activities when asked. There are roughly the same number who have rarely participated. We plan to retire the non-participants from the SAB and replace some of them with subject matter experts who have expressed or shown a strong interest in actively supporting the Center. Two such additions have been made in the past 15 months. Sohan Uppal, retired VP and CTO of Eaton's Fluid Power Group, joined the SAB in the Spring of 2012 as the SAB Chairman. Dr. Joe Kovach, Engineering VP at Parker Hannifin, joined the SAB in the Fall of 2012. We will work with Chairman Uppal and the SAB to increase involvement in areas including strategic planning, research agenda, funding opportunities and proposal review.

The SAB and the IAB met formally for the first time at the 2012 CCEFP Annual Meeting. The focus of the meeting was Center sustainability. There was a strong interaction and sharing of ideas and both Boards agreed that joint meetings should be done on an ad hoc basis to help resolve key challenges facing the Center. We plan to have another joint IAB-SAB meeting at the 2013 CCEFP Annual Meeting in October.

CCEFP update: We had a joint IAB-SAB meeting at the 2013 CCEFP Annual Meeting in October. The topic was sustainability and a very useful discussion ensued. Since then, inactive members of the SAB have been removed as planned, and the remaining group has been more intensely engaged. Two of the SAB members with extensive fluid power industry experience in high-level technical management have been retained as consultants. These two have been actively working with the leadership team on industry commitment, government grants and commercialization of CCEFP inventions.

SVT: Student engagement in the biweekly webinars is inadequately emphasized by faculty, given the strong interest in them of and participation by industry engineers.

CCEFP response: We agree that we need to strengthen the student engagement in the biweekly webinars. To that end, we will be doing the following:

1. The Center Director will contact all Center PIs to urge them to tell their students that participating in the biweekly webinars should be a priority and to set an example by regularly attending the webinars themselves.
2. We plan to expand these webinars to include topics of interest beyond Center projects and test beds. New webinar topics should have relevance to both the researchers and our industry members. We believe a reasonable mix of topics would be approximately 50-60% project and test bed updates, 20-25% presentations from CCEFP faculty, students and staff, non-CCEFP researchers, and 20-25% presentations from industry. This last group would focus on fluid power related or associated topics and would need to be technical in nature and not marketing focused.
3. CCEFP's E&O team has offered supplemental grants to all Center schools to allow them to bring in lunch for students and faculty during the biweekly webinars. Two schools, Georgia Tech and Purdue, have used these grants to bring in food during the webinars and they have seen their attendance rise. The Center Director will encourage all schools to take advantage of the grants to foster greater attendance by students and faculty at the webinars.

CCEFP update: All three steps above have been taken. Student involvement in webinars has increased. Rather than using grants, CCEFP now directly orders pizza lunches for all of our schools to be served during webcasts. This is probably the most important reason that attendance has increased.

SVT: Intellectual property training is needed for all students.

<u>*CCEFP response*</u>: We agree that it would be beneficial to train our students on intellectual property. Our Center ILO has been tasked with providing mandatory training for all CCEFP students by the end of 2013. Future students will be required to take this training as well. The training program will cover all aspects of properly managing Center IP including how to file and protect it in compliance with the CCEFP Membership Agreement. This is particularly important due to the fact our Membership Agreement does not include a blanket NDA. We have discussed this aspect extensively with the CCEFP IAB. Several of our largest members have indicated they would never agree to such a blanket requirement in our Membership Agreement and would rather make these decisions on a case by case basis. For this reason, most of our communication with our industry members is considered public disclosure making intellectual property training of our students all the more important.

<u>*CCEFP update*</u>: During one of our webcasts last fall a representative from the University of Minnesota Office of Technology and Commercialization (OTC) explained the recent changes in patent law due to the America Invents Act. The webinar included a highly relevant presentation on confidentiality including the details of what constitutes public disclosure. The most important change from the America Invents Act is that precedent is now established by the “first to file” rather than the “first to invent” rule. Awareness of patent issues has increased greatly, but we still must implement the mandatory training process.

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

<u>*CCEFP response*</u>: We believe the new test bed 4, the patient transfer device (PTD), holds strong potential for the advancement of fluid power technology. In particular, the control aspects of the PTD represent significant challenges that could be broadly applicable in fluid power. One example is the use of passivity control to ensure stable and safe operation of the device. In addition, collaborating with Carnegie Mellon provides the opportunity to determine if the symbiotic autonomy technology (or features of it) being researched in their CoBot robots could provide benefits on the test bed and in a broader range of fluid power application. Also, the test bed is human scale and fits well in the six order of magnitude range of power and weight of the Center test beds. Finally, fluid power-enabled medical devices are one of the research areas we believe can help the Center thrive in its post-NSF existence and the PTD test bed complements the suite of medical applications using fluid power that the Center is creating. These medical devices have generated a great deal of industry interest. Thus, we believe there are both solid research and commercial opportunities associated with the new test bed 4.

<u>*CCEFP update*</u>: Recent discussions with industry have confirmed the interest in more bio-medical fluid power research activity and the appropriateness of the patient handler to move us in this direction.

SVT: The following are considered threats to the Center’s success:

- ***Potential for disintegration of CCEFP, due to increased reliance on associated projects as NSF funding winds down.***
- ***Failure of universities to step up to support the CCEFP after graduation.***
- ***Failure of industry to substantially increase support for precompetitive research after graduation.***
- ***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 to Threats*</u>: We view our greatest threat to be long term sustainability after NSF funding ceases. We believe that we have prioritized our efforts accordingly. A challenging but viable plan has been established with three major elements: 1) industry consortium dues with reduced

university indirect overhead to fund pre-competitive research and administration, 2) large grants from strategically aligned government agencies such as DOE, DOD, NIH, NSF, etc. and 3) associated research projects from both industry and government agencies. Our goal is to raise roughly $3 million funding from each of these areas even though we believe that the Center could continue at two thirds of this funding level.

Since the Site Visit in April 2013, we have made considerable progress. The Center Director and key members of his staff meet weekly to review progress on sustainability and drive results. We recognize that maintaining a pre-competitive research critical mass is crucial to Center viability and thus raising industry consortium funds is our highest priority. Face to face meetings have been held with industry and NFPA leaders to help establish recruiting goals and revenue targets. A new dues structure has been evaluated with modifications proposed for FY11 and beyond. Plans are underway to visit all key industry members to raise awareness at all organizational levels. Promotional marketing campaigns are being developed to target industry CEOs directly with what we believe to be our considerable value proposition. We strongly believe that the fluid power industry needs the CCEFP to help drive much needed innovation. One of the reasons that industry will support the Center long term is that technologies that are competitive with fluid power may prevail if fluid power advances do not come to market in a timely fashion. All seven universities in the Center have stepped up and agreed to cap indirect overhead rates at 10% maximum on these industry consortium funds.

Similar progress is being realized in securing future large government grants. A face to face meeting was recently held at the DOE with key agency, Center, national lab and industry leaders in attendance to explore future government funding opportunities. These discussions were positive with many opportunities identified. Follow up meetings are planned. Associated research project efforts are already quite established in the Center although funding tends to be focused in the hands of a few PI’s. Our actions plans must focus on ways to better expose more researchers to industry members to attract more widespread funding.

CCEFP update: Since the last site visit, two meetings with the Advanced Manufacturing Office (AMO) have been held. A proposal was submitted to the NIST Advanced Manufacturing Technology (AMT) program to create a manufacturing roadmap for the fluid power industry. Both initiatives will position us to be competitive for a future center in the NNMI (National Network for Manufacturing Innovation) program.

Two cross-functional committees focusing on sustainability funding have been formed and have held their organizing meetings. Both committees have a mix of industry and academic members. The Government Relations Committee is focused on garnering large, multi-site grants that will be focused on pre-competitive fluid power research. The Industry Relations Committee is focused on gaining commitment from industry for using pooled funds for pre-competitive fluid power research. These two areas are the most important ones to create a sustainable post-NSF CCEFP.

The CCEFP and NFPA are on the verge of signing a landmark Memorandum of Understanding (MOU). The goal is to eliminate gaps and overlaps by having each organization do what it does best. CCEFP will take primary responsibility for research, higher education and government grants. NFPA will take primary responsibility for working with industry, publicity, event planning and K-12 education. One feature of the arrangement is that instead of contributing industry membership dues to CCEFP, industry will provide contributions to the NFPA Foundation that will in turn provide the funds to CCEFP. Since the NFPA Foundation is tax exempt, the contribution are gifts and intellectual property rights will not be granted.

Under the “List of Significant Achievements”, the SVT requested an update on the new Parker Hannifin Hybrid Drive Systems division that designs and manufactures hydraulic hybrid systems for commercial vehicles. The information in the update below is from May 2013.

Hybrid Drive Systems is located in Columbus, OH. It has approximately 60 employees, about 40% of which are engineers (many are former CCEFP students).

RunWise:

- This is an "advanced series” hybrid hydraulic system. It has a two-speed hydrostatic drive (low speed 0-25 mph and high speed 26-45 mph) for urban driving and switches to a mechanical direct drive for efficient operation at highway speeds (46-60+ mph).
- Initially targeted at heavy duty refuse vehicles.
- Approximately 100 units operating today.
- Real world results:
    - 98% fleet up time
    - 43-44% fleet average fuel savings
    - Brake life extended ~20x (from 3-4 brake jobs per year to one every 6 years)
    - 10-15% increase in productivity (revenue stops/day)
    - As little as 2 year payback in private fleets, 4-4½ years in municipal fleets
    - Drivers love it (no shifts until 25 mph, creep mode to 5 mph, extra power)
- CNG engine versions available soon

Hydromechanical (power split) hybrid:

- Prof. Monika Ivantysynova and her team at Purdue helped Parker Hannifin develop this product under a CCEFP associated project.
- Initially targeted at medium duty package delivery vehicles.
- Chassis rolls testing at the US EPA documented ≈50% fuel savings (duty cycle dependent).
- 48 pre-production units are about halfway through their two year test period.
    - UPS has 40. 20 are in Baltimore and 20 are in Atlanta.
    - FedEx has six. Two are in Michigan and four are in California.
    - Purolator Courier (Canada’s largest package delivery company) has two.
- System performance and reliability has been as expected.

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 future fluid power applications. The primary purposes of these test beds are as follows:

- Test Bed 1, the 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.

Test Bed 1, the compact excavator, employed throttle-less hydraulic actuation technology since 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. A patent on the DC technology was applied for in 2011. 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 a 50% engine downsizing. The goals for the project are 50% fuel savings over current state-of-the-art excavator systems, meeting current exhaust emission standards and no degradation in machine performance.

The compact excavator 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. Displacement controlled actuation has demonstrated more than 50% fuel savings and 70% performance improvement over traditional valve-controlled multi-actuator systems. The basis for the advantages of DC actuation reside in the complete elimination of resistance control. DC actuation uses a variable displacement pump to control actuator motion. An additional advantage is the ability to recapture energy from overrunning and breaking loads. As a consequence of the displacement-controlled actuation improved efficiency, the average engine power required for the mobile machine is dramatically reduced. Furthermore, the new hydraulic hybrid swing architecture allows for the recuperation of the swing breaking loads. The energy is recaptured in a hydraulic accumulator and can be immediately distributed to the rest of the working actuators through the engine shaft. As a result, it is possible to use a smaller and less powerful engine to do the same work. Simulations of the new hybrid excavator system predict that the maximum engine power could be reduced by 50% for a truck loading cycle and fuel savings of greater than 50% are possible. The figure below shows a schematic of the hydraulic architecture energy flows.

The overall goal of Test Bed 3 is to realize hydraulic hybrid powertrains for passenger vehicles demonstrating both dramatic improvements in 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:

- 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 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.

As was stated above, to focus resources, the CCEFP has concentrated its effort of the Gen 1 vehicle with the Gen 2 vehicle becoming an industry led test bed with the CCEFP provided control support. Progress on the Gen 1 vehicle includes transmission continuously variable transmission (CVT) testing to optimize powertrain efficiency. The results for the Gen 1 vehicle was 50 mpg for the city driving schedule (EPA UDDS) and 62 mpg for the EPA highway schedule. Hybrid system optimization algorithms from project

1A.1 were implemented in the high level controller resulting in an additional 3% fuel efficiency improvement. Testing with other 1A.1 algorithms is ongoing. Three core controllers were designed and successfully implemented on the vehicle-dynamometer system to obtain consistent and reliable drive cycle test results. Firstly, the hybrid powertrain controller utilizes the three-level hierarchical strategy developed in previous years. Secondly, the dynamometer controller, completed this year, applies a novel “virtual vehicle” concept to exert correct load on the vehicle based upon the torque applied by the power-train. Lastly, the “virtual driver” controller is designed to eliminate the need of an actual driver during drive cycle tests.

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 ~100W~1kW. 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. It provides a system for testing component technologies, as well as developing intuitive control and expanding the use of fluid power 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. Current patient lifts are typically electrically actuated, or have a manual hydraulic pump; with only one actuated degree of freedom, they 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 make possible 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.

As a new test bed the PTD provides an excellent opportunity to embrace systems engineering and project management. An extensive needs assessment using focus groups and one-on-one interviews has been completed to identify specifications for maneuverability, caretaker interface, capacity, sling design and cost. Problem understanding has also been enhanced through the use of a pre-prototype.

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

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

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

Pneumatic AFO: To improve efficiency a regenerative scheme using the pneumatic strain energy accumulator from project 2C.2 was tested on the pneumatic resulting a 25% reduction in energy consumption. This is significant for an untethered device where the user must carry the “fuel” for the AFO. In collaboration with researchers at the Rehabilitation Institute of Chicago, testing has begun to explore the advantages of the PPAFO compared to a range of other assistive devices (e.g., tibial stimulators and commercially-available passive AFOs) in a post-stroke subject population. The devices are being compared in this population by asking each participant to complete a set of clinically-accepted walking tasks with both the PPAFO and their personal device.

Hydraulic AFO: The research objective of the HAFO project within TB6 has been to understand the capabilities and limits of small-scale hydraulics. The research motivation of the project has been the need for small, light, untethered, wearable robots. The development objective of the project was to create an untethered HAFO that meets demanding specifications. The results of the project have been a better understanding of hydraulic systems at small scale from a theoretical perspective and the creation of a physical prototype that is the highest power, untethered AFO. With the computational models informing the design, we determined that the best system architecture is a power transmission chain that is battery > motor controller > DC electric motor > tiny hydraulic pump > hose > cylinder > linear-to-rotary transmission > ankle torque. It was also determined that the best configuration is to place the power supply at the waist and the cylinder at the ankle with thin hoses connecting the two. The power supply is complete and the powered ankle component is being fabricated. The University of Minnesota filed a provisional patent application for the HAFO and an NIH R21 application has been submitted to use the HAFO as an AFO emulator in a project to optimize fitting of AFOs to children with cerebral palsy.

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 is of the opinion 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. Approximately forty fluid power manufacturers and distributors are Center members. Time and time again they have stated that the education outcomes (i.e. intellectual capital) of the Center are as important to them as the outcomes of research. These Center partners share in a common goal--the Center will foster deep understandings of fluid power technology and its applications among its students. Toward 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; 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, IAB summits, NFPA workforce summits, the CCEFP Annual Meeting and the recently initiated CCEFP-Industry GEM Fellowship program.

Highlights of the Y8 CCEFP Education and Outreach Program include:

- CCEFP is granted an NSF REU Site Award for three years.
- Over 150 REU students have participated in CCEFP research.
- 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
- The first fluid power Massive Open Online Course (MOOC), to be offered Fall 2014, through Coursera, approved by the University of Minnesota.
- Student Retreat hosted by Caterpillar, Inc., August 2013.
- GEM-ERC-Industry Fellowship program has a bright future, support and buy-in from NSF leadership.
- CCEFP has successfully supported more than ten undergraduate and graduate students in fluid power through its internal Research Diversity Supplemental award program.
- Fluid Power Exhibits are now on permanent display at the Science Museum of Minnesota.
- CCEFP hosts a variety of networking opportunities between industry and students at events.
- 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.

Industrial Collaboration and Tech Transfer Interactions

Industry membership in the CCEFP grew by five new companies in the past year due to a reinvigorated membership drive focus. While this validates the Center's value to the fluid power industry, it also highlights just how diligent we must be to maintain and grow our membership base. One of our members, the National Fluid Power Association (NFPA.org), knows this challenge all too well as its mission is to serve the needs of the entire fluid power industry. By sharing best practices from their 50+ years of experience and leveraging their 225 member base we expect to grow our industry support base significantly as we implement our sustainability plan. In the past year we held numerous discussions with the NFPA with a focus on long term Center sustainability. In its role as an industry consortium, the NFPA is uniquely positioned to provide insight to the needs of the entire fluid power industry. This insight will benefit the CCEFP in many ways. One tangible example is the industry research roadmap which the NFPA helped to create. Going forward, we envision this roadmap as the primary vehicle for channeling the needs of industry to the Center.

The Industrial Advisory Board (IAB) also continues to be an extremely active participant in the CCEFP providing invaluable input to the Center research strategy, project selection and project progress. The IAB 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 IAB members. There are monthly IAB conference calls where topics of particular interest are discussed. These meetings cover a wide range of topics from research projects areas of interest to sustainability planning. Approximately three times per calendar year IAB "summits" are held on site at a member university on a rotating schedule. These meetings typically last a day and a half providing ample time and opportunities for industry to engage with faculty and students. The first day is dedicated to technical presentations by the Center researchers and a tour of the university laboratory facilities. An informal dinner, with all PIs and students invited to join the industry visitors, is held during the evening and is an excellent venue to get to know one another better. 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 also with the research team. It is common to invite potential members to these site meetings as it provides them with an excellent opportunity to experience firsthand the value of a membership in the CCEFP and is a great recruiting tool. These site meetings have proven to be very successful and have greatly increased awareness of our activities on the part of industry.

With the CCEFP in its eighth year, some of our most successful 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 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 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 89% 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 engineering. Comparing CCEFP with national averages, the percentage of women was 11.1% for faculty with 27.3% for the leadership as compared to 14.1% for faculty nationally and 35.3% for undergraduate non-REU students and 41.2% for REU students compared to 18.9% for undergraduates nationally. Underrepresented racial minorities are near or exceeding national averages, retaining the representation in this area. The percentage for underrepresented racial minorities was 9.1% for faculty compared to 3% nationally, 12.5% for doctoral students compared to 4.7% nationally, and 47.1% for non-REU students and 29.4% 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. 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. The most important metrics and comparisons are given below.

The number of publications in peer-reviewed technical journals increased from 22 from 24. Additional efforts in this area are still needed, since the average for this figure is 28 among all ERCs.

Inventing and patenting continues at a steady pace. Patent applications remained unchanged at 6, and disclosures increased from 3 to 6.

Doctoral degrees granted decreased slightly from 12 to 11. The continued high number of doctoral students shows that they are completing their degrees in a timely manner. Education impact is significant with 29 courses containing ERC content, compared to the ERC average of 16. CCEFP's extensive K-12 education and outreach activities help the Center to exceed most norms in these categories.

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1.3 HIGHLIGHTS OF SIGNIFICANT ACHIEVEMENT AND IMPACT

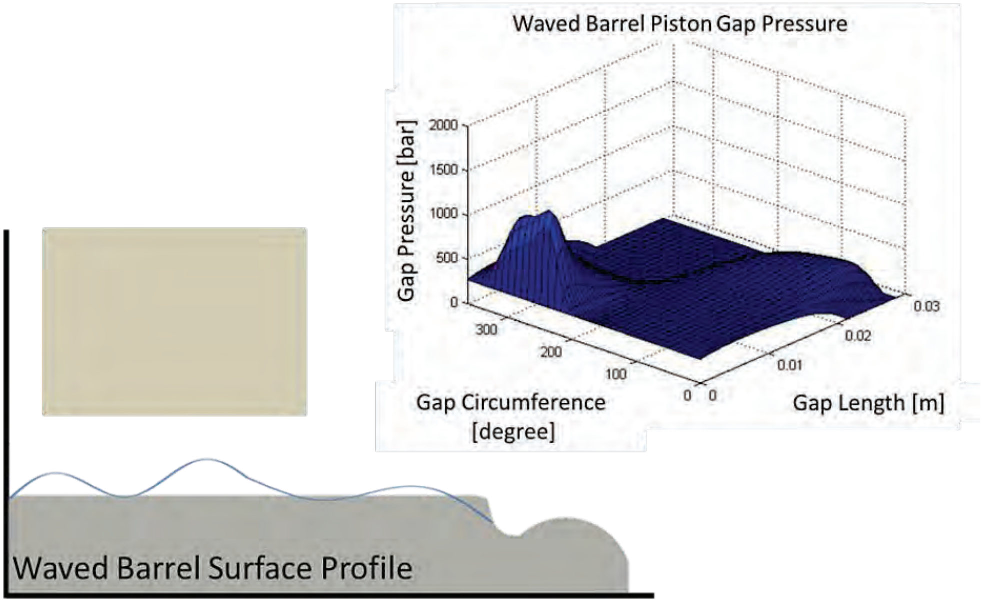
RESEARCH / TECHNOLOGY ADVANCEMENT HIGHLIGHTS

Novel waved pistons reduce pump power loss by 60%

Swash plate axial piston pumps and motors are widely used in today's hydraulic systems. Thin fluid films separate highly loaded movable pump and motor surfaces from each other and prevent wear and fatal machine failures. Although these lubricating films are essential to prevent failure, they also represent the largest source of power loss inside the hydraulic units. Despite many decades of worldwide intensive research, experts and pump designers still lack a complete understanding of the complex and physical behavior of these thin critical fluid films.

CCEFP researchers have combined experimental research with multi-domain modeling to develop an understanding of the physics in those thin fluid film interfaces of pumps and motors. It was discovered that the elasto-hydrodynamic and thermal effects is fundamentally important to the film generation and stability; these phenomena are responsible for substantial modification of the fluid film thickness and must be considered to correctly predict the fluid film behavior. With this understanding, a very complex fully-coupled fluid-structure interaction and multi-body dynamics simulation model that considers thermal deformation of the main interfaces and their influence on the fluid film behavior was created.

This state-of-the-art numerical model is now used to further understand the physics enabling the lubricating films and to propose new design methods to reduce the power loss coming from these gaps. Using this model, investigation is being done on the impact of micro-surface shaping on the piston surface along with varying gap heights on the overall performance of the machine. From this model that is able to provide accurate predictions along with a combination of various micro-surface shapes and a decrease in the clearance between the piston and cylinder, simulations have demonstrated potential improvements of overall power loss up to 50% at full displacement and 65% at partial displacements at higher pressures and even still an improvement of up to 20% and 60% respectively at lower pressures. These results represent a major breakthrough in this research direction and suggest an even deeper study of the possible new technology that will lead to a new generation of pumps and motors.

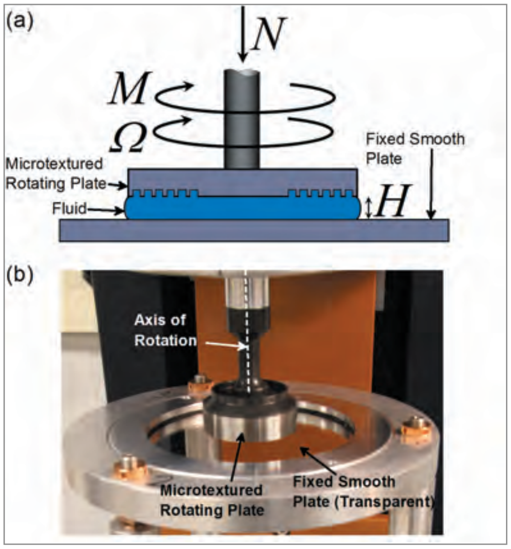


Micro-Surface Shape on the Piston Surface (Left); Unwrapped Pressure Profile (Right)

Development of a novel gap-controlled tribo-rheometer

This instrument enables gap-controlled tests to systematically vary the appropriate dimensionless groups (which include gap thickness) involved in the co-design of microtextured surfaces and lubricant fluids for reduced friction and leakage. The instrument employs a transparent precision-aligned glass plate as a lower boundary for visualizing flow. Applications include friction and leakage reduction in fluid power systems; friction reduction has been measured and compares well with computational predictions.

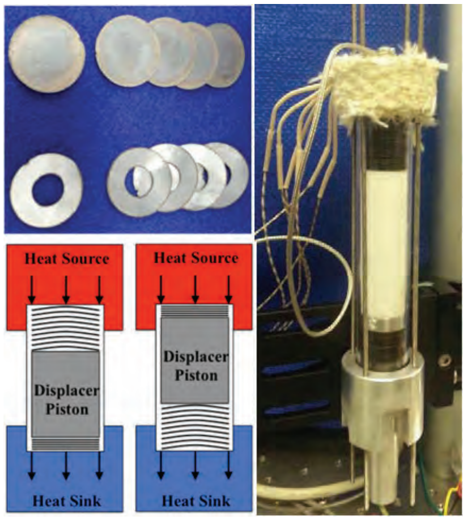
This precision instrumentation has also impacted other scientific disciplines, in the context of small gap shear responses of liquids. Striking observations have been reported elsewhere for elastic shear modulus of water, glycerol, and other simple liquids at low frequency and small gaps. Research was done to measure, and theoretically explain, that these results may actually arise from surface tension line forces that are amplified at small gaps. Such effects must be considered for any small gap measures including, but not limited to, fluid power applications.



(a) Rotational rheometer where gap height H, angular velocity Ω, torque T and normal force N are measured or controlled. (b) Custom precision-aligned glass bottom plate with top custom microtextured plate attached.

Novel In-cylinder Heat Exchangers that Increase Heat Transfer by Nearly Four Times

A Stirling thermocompressor is intended to serve as a compact and quiet, untethered 50 W, pneumatic power supply for an ankle foot orthosis. Portable sources of energy that can be used efficiently for robotic actuation are currently not available. If such a technology were available, untethered robotic systems could become more powerful, and ultimately be more useful. The best batteries and motors typically result in underpowered systems that are heavy and/or do not operate for long periods of time. What is needed is an energy carrier that stores more energy per unit weight than batteries. Hydrocarbon fuels such as butane, propane, natural gas or methane offer this high energy density. A device that efficiently converts this stored energy into a form that can be used for actuation is also needed and a Stirling thermocompressor is just such a device.



A Stirling engine uses the Stirling cycle to convert heat energy into mechanical work. In a Stirling thermocompressor, a small compressor maintains the pressure in a reservoir that can be used to power pneumatic actuators. In order to produce enough power efficiently, the Stirling cycle needs to be able to transfer heat into and out of the engine quickly. The prototype shown has stacks of small thin metal disks acting as heat exchangers that increase the heat transfer surface area by over 100 times. This allows heat transfer at a rate nearly four times that which occurs without them. Research is currently underway to enhance this effect even more. In-cylinder heat exchangers could be used in conventional compressors to increase their efficiency. An improvement in industrial compressor used for pneumatic industrial automation could save billions of dollars each year.

Hydraulic Ankle Foot Orthosis

The goal of the hydraulic ankle foot orthosis (HAFO) is to demonstrate the capabilities and advantages of tiny hydraulics for untethered powered human assist machines. System and component level modeling to predict the efficiency and weight of small hydraulic systems was a key part of this work. The models 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 is a transformer whose transmission ratio as 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 degrees/second, weighs < 1 kg at the ankle and fits under a pair of loose-fitting pants. The HAFO is the lightest, high torque, untethered, powered ankle orthosis that has ever been developed.

HAFO prototype with waist-worn power supply (left) and ankle component (right).

Orthosis enters clinical trials on post-stroke patients

Walking impairment presents major personal, social and economic burdens among stroke victims. One method for improving the impairment of walking among post-stroke persons involves the application of ankle-foot orthoses (AFOs). Researchers have reported mixed results when evaluating the clinical and biomechanical advantages of patient-specific, physician-prescribed, custom AFOs in post-stroke persons.

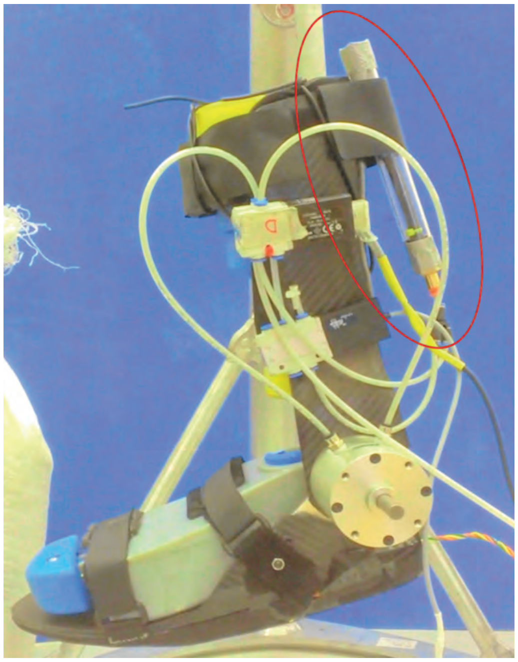
Current, commercially-available AFOs are passive or semi-active devices that provide joint stability and motion control, with the primary goal of holding the foot in a neutral position during the swing phase of gait to correct for foot drop. We are exploring whether the pneumatic Portable Powered Ankle-Foot Orthosis (PPAFO) that is being developed in Test bed 6 at the University of Illinois can be used as a successful gait assistance device.

Pneumatic ankle-foot orthosis in clinical trial

In collaboration with researchers at the Rehabilitation Institute of Chicago, testing has begun to explore the advantages of the PPAFO compared to a range of other assistive devices (e.g., tibial stimulators and commercially-available passive AFOs) in a post-stroke subject population. The devices are being compared in this population by asking each participant to complete a set of clinically-accepted walking tasks with both the PPAFO and their personal device. During each walking task, the subject's oxygen consumption is being measured as well as the standard outcome measures of the task.

Pneumatic Strain Energy Accumulator

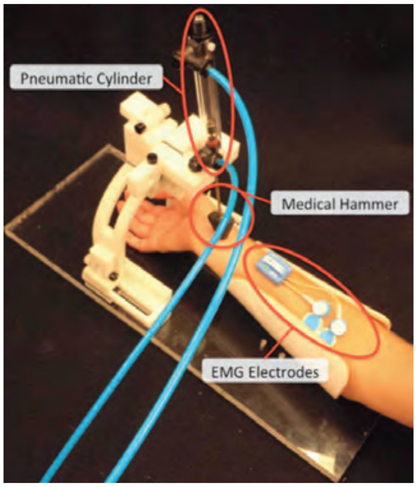
In the past year the Strain Energy Accumulator was demonstrated on TB6, the Ankle Foot Orthosis (AFO), as a way to recover exhaust gas in its pneumatic system. In these preliminary trials, the use of the pneumatic strain energy accumulator resulted in an energy savings of over 25% relative to operating the pneumatic actuation of the AFO in the conventional manner. This is an important milestone since the orthosis is representative of a typical pneumatic actuator task. The typical method of pneumatic actuation is only 23% to 30% efficient since a large amount of the energy is exhausted when the actuator changes direction. The pneumatic strain energy accumulator is able to store a portion of this exhaust gas and then reuse it to assist the powered return motion of the actuator. A recent report from Oak Ridge National Lab ("Estimating the Impact (Energy, Emissions and Economics) of the U.S. Fluid Power Industry" published December 2012) states that the recovery of exhaust gas from pneumatic systems could increase their efficiency by 14% to 23%. The demonstration on the AFO increased efficiency by 25%. Given that about 0.5% of the energy consumed in the United States is for industrial pneumatics, an application of this technology for pneumatic devices on assembly lines could save $1.4B to $2.5B per year.



Pneumatic strain energy accumulator implemented on ankle-foot orthosis

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

The ultimate goal of the research is to understand and characterize the neuromechanical mechanisms associated with facilitation techniques designed for functional recovery of hemiparetic limbs. The facilitation technique of interest, referred to as repetitive facilitation exercise or RFE, was designed by Dr. Kawahira of Kagoshima University, Japan. Studies have shown better results than conventional rehabilitation sessions applied to hemiparetic upper and lower limbs. The project will include analysis of the facilitation exercise paradigm and re-implementation with the addition of a pneumatically driven MRI-compatible robotic device. The hypothesized mechanism of RFE is that this specific exercise overlaps the afferent myotatic reflex with descending nerve impulses and hence facilitates a myotatic reflex in synchronization with the patient's intention to move the hemiparetic limb.

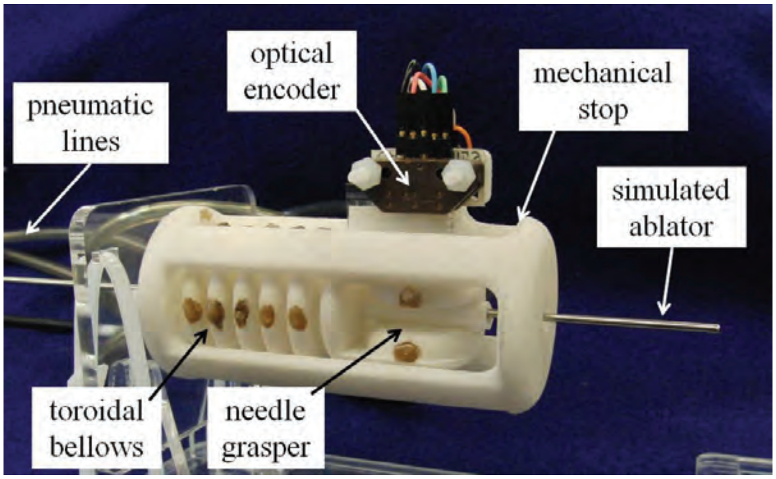


Tele-operated pneumatic system

The specific goal of this project is to build a fully automated RFE rehabilitation device to help validate the hypothesized mechanism of the RFE. To achieve the goal, the project will establish methodologies to establish precise impact timing control of a pneumatic robotic hammer and multimodal instruction cues to realize the robotic RFE procedure that is capable of being used in the magnetic resonance imaging (MRI) environment. A tele-operated pneumatic system requires 5-7 meters long transmission lines that complicate the system dynamics and add a significant time lag and pressure attenuation in pneumatic actuation. This project studies a new model that accounts for the complexity observed in experimental data that could not be captured by conventional models. The transmission line is modeled as an intermediate chamber serially connected between the air source and the actuator. The fluid flows into and out of the transmission line are represented as orifices. As a result, the responses of the pneumatic device become predictable and controllable. A provisional patent has been filed through Georgia Tech Office of Industry Engagement.

Intrinsically Safe, Nonmagnetic Flexible Fluidic Actuator for MRI-Guided Interventions

Magnetic resonance imaging (MRI) offers many benefits to image-guided interventions. They include excellent soft tissue distinction, little to no repositioning of the patient, and zero radiation exposure. The closed, narrow bore of a high field MRI scanner limits clinician access to the patient, so an MRI-compatible robot is essentially required for many potential interventions. Fluid power is an ideal form of robotic actuation inside the scanner's magnetic field because actuators can be designed free of magnetic and electrical components. However, there are no fluid power actuators readily available that offer the safety, sterilizability and precision performance required for medical robotic systems. Toward breaking this transformational barrier to fluid power solutions for health care, CCEFP researchers) have recently invented a fluid powered actuator for MRI-guided interventions. With a compact design made possible by additive manufacturing, a first prototype was made. Employing an inchworm-like behavior, the device is intrinsically safe. The linear actuator can advance or retract a needle in small, discrete steps. The device's pneumatic bellows and pinching mechanism are hermetically sealed for clean performance in sterile environments. A model-based controller was developed and tested. In experiments, the mean steady-state positioning error was 0.025 mm. The device is a promising solution for robotic actuation in MRI-guided interventions.



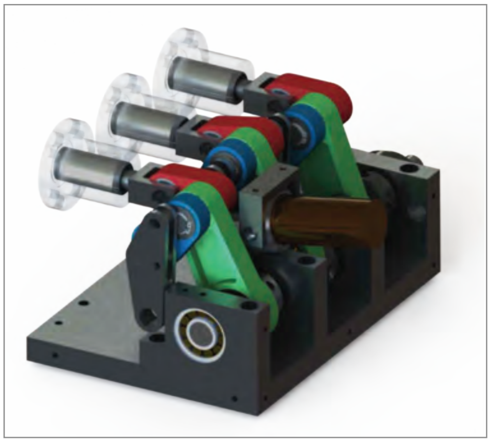
Non-magnetic flexible fluidic actuator for MRI-guided interventions device prototype

Energy harvesting for self-powered sensors

The Hydraulic Pressure-Ripple Energy Harvester (HPEH) project set new benchmarks in terms of power generation performance, power density, and demonstration of viability. The project has greatly benefited from contributions from REU students, who have designed and tested every one of the 9 prototype devices, representing six distinct generations of designs. Advancement in the energy harvesting circuit incorporating inductance matched to the piezoelectric energy conversion element within an HPEH yielded a prototype with peak power output of 3.3 mW. Another prototype was developed for compact, low-power sensing applications, and achieved its required target output of at least 67 mW. The first HPEH-powered, wireless temperature sensor was demonstrated. A single-crystal piezoelectric variant HPEH prototype yielded twice the power density as compared to variants using co-fired multi-layer piezoelectric elements. A prototype was developed with a flexible design enabling the use of combinations of commercially available piezoelectric elements, permitting ease of configuration of the device for different target power demands. The project has been successful in pushing research and development such that HPEH powered devices could be viable across a broad range of power demands, available energy densities, form factors, static pressures, and target applications.

Six generations of High Pressure Energy Harvester prototypes

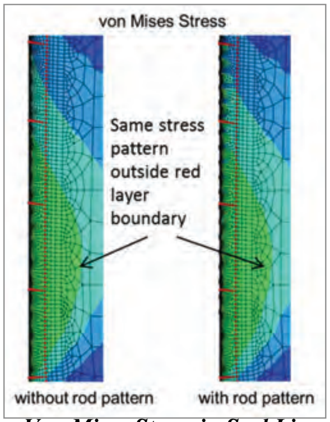
High Efficiency Variable Displacement Linkage Pump



Variable displacement linkage pump

Aa novel variable displacement pump that is driven by an adjustable linkage has been developed. The linkage is adjusted by moving the ground pivot of a link through an arc with a linear actuator and reaches true zero displacement. The compressibility energy loss is minimized by the pistons reaching the same top dead center position, regardless of displacement. The architecture employs rolling element bearings in its pin joints, minimizing mechanical losses, especially at low displacements. The pump pistons are supported by a crosshead bearing, eliminating side-loading and allowing operating with a variety of fluids, by separating the working fluid and the pump lubrication. The efficiency model has been experimentally validated with a low-power single-cylinder pump. A 10kW three-cylinder prototype has been designed and is currently being fabricated. The predicted efficiency of the pump exceeds 90% for displacements above 15%. A utility patent on this pump architecture is pending.

New unique general FEA approach for contact analyses

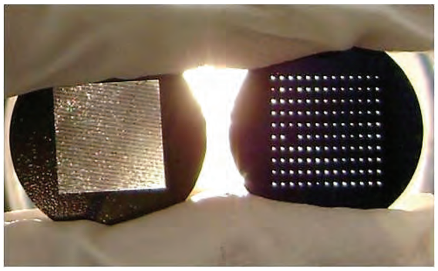


Von Mises Stress in Seal Lip

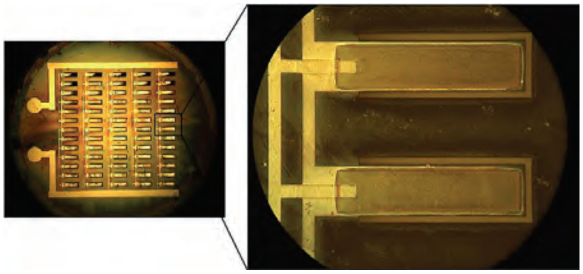
A new unique general finite element analysis (FEA) approach for contact analyses has been developed in our study of hydraulic seals and rods with a micro-patterned surface. This approach is useful for the analysis of 2-D macroscopic bodies in contact with a surface containing 3-D micro/nano surface feature patterns, which normally requires a very large number of elements due to the necessity of capturing the micro/nano surface features. The approach is based on the fact that the material within the body farther than a short distance (typically100 μm) from the contact surface is substantially unaffected by the surface features. Therefore, a 3-D FEA is performed only on a thin (typically 100 μm) layer adjacent to the contact surface. Displacement boundary conditions on the layer boundary are obtained from a 2-D FEA of the entire seal in contact with a smooth surface with no surface features. The 3-D FEA of the thin layer yields the contact pressure distribution. In our seal analysis, this technique requires 10^5 elements (possible) vs. 10^6-10^9 elements (impossible) required for a full 3-D model of the seal.

MEMS Proportional Pneumatic Valve

The MEMS Proportional Hydraulic Valve project successfully fabricated MEMS scale port plates and MEMS scale valve actuator arrays in the past year. These components comprise the two essential elements of MEMS valves. Two port plates are below. The port plate on the left contains 6900 orifices of 29 micron diameter. The right port plate contains 130 orifices of 86 micron diameter. The right port plate withstood the full design pressure of 7 bar without fracture. Novel etching procedures were required due to the large aspect ratio of plate thickness to orifice diameter. A piezoelectric actuator array is shown at right below. A similar array was made with cantilevered actuators having dimensions of 2000 x 700 x 17 microns. Tip deflections of over 20 microns were measured. They were fabricated using "PZT" for the piezoelectric layers, which has the best known piezoelectric properties of any material. The work was a collaboration with the Nanofabrication Lab at Penn State University to fabricate the PZT layers, as this is the only domestic facility of which we are aware that is available to fabricate PZT at the MEMS scale. Now that fabrication procedures have been baselined, the two components will be "tuned" and combined to make complete prototype valves.



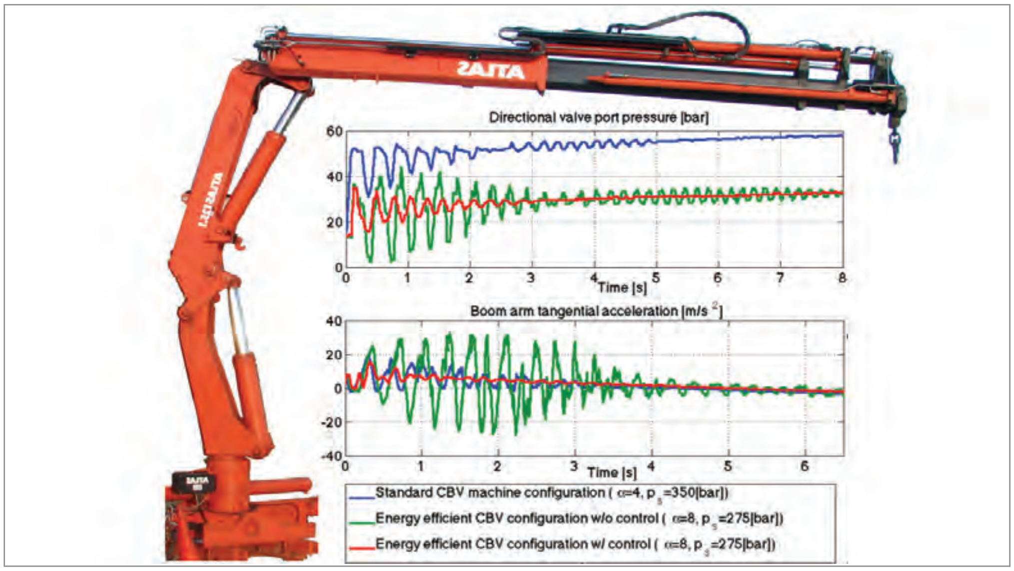
Port plates



Piezoelectric actuator array

Active Vibration Damping of Mobile Machines

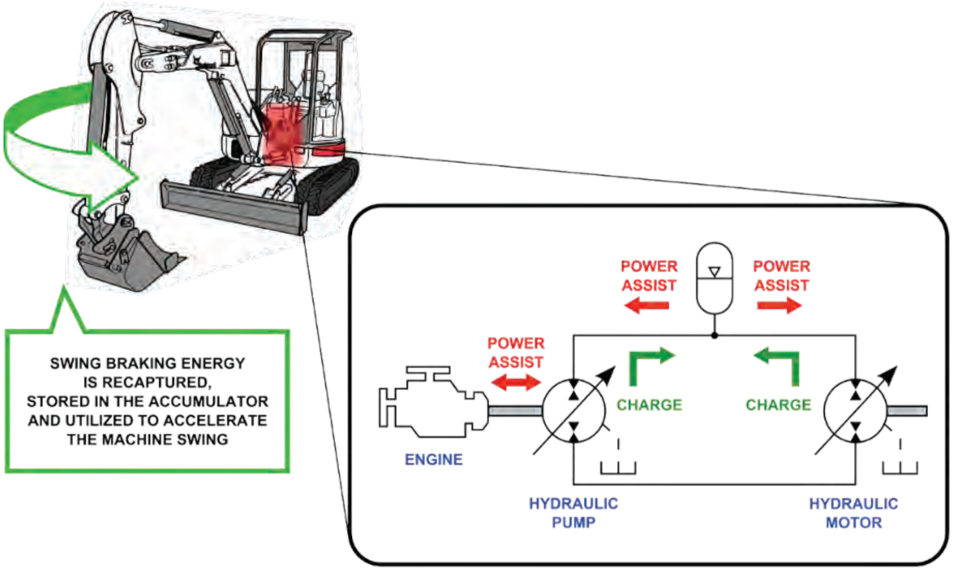
In Project 3B.3, the hydraulic circuit of a mid-size hydraulic crane was modified with the aim of achieving a reduction of fuel consumption of about 40% for a typical loading and unloading cycle. The modification is based on the use of a different setting for counterbalance valves installed in the crane. This setting, very aggressive as concerns energy consumption, is never utilized in commercial applications due to the high instabilities it introduces. Using the novel adaptive control techniques, the crane dynamics was brought a better level respect the commercial configuration, without introducing system slow-downs.



The hydraulic crane used for CCEFP project 3B.3. The plots show the typical pressure and vertical acceleration of the main boom during a typical operation of the crane.

High Performance Hydraulic Hybrid Excavator Requires only 50% Engine Power

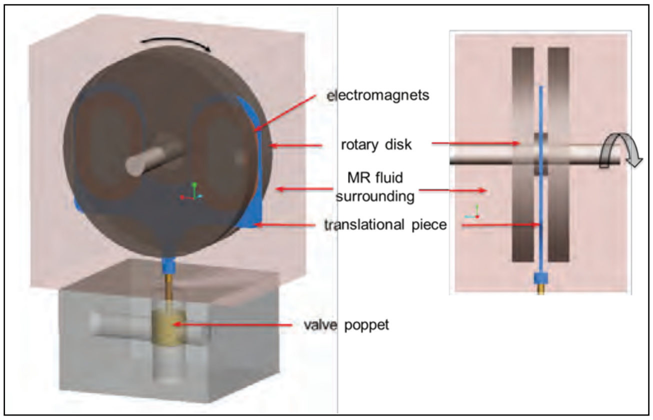
Displacement controlled actuation has demonstrated more than 50% fuel savings and 70% performance improvement over traditional valve-controlled multi-actuator systems. The basis for the advantages of DC actuation reside in the complete elimination of resistance control. DC actuation uses a variable displacement pump to control actuator motion. An additional advantage is the ability to recapture energy from overrunning and breaking loads. As a consequence of the displacement-controlled actuation improved efficiency, the average engine power required for the mobile machine is dramatically reduced. Furthermore, the new hydraulic hybrid swing architecture allows for the recuperation of the swing breaking loads. The energy is recaptured in a hydraulic accumulator and can be immediately distributed to the rest of the working actuators through the engine shaft. As a result, it is possible to use a smaller and less powerful engine to do the same work. Simulations of the new hybrid excavator system predict that the maximum engine power could be reduced by 50% for a truck loading cycle and fuel savings of greater than 50% are possible. The figure below shows a schematic of the hydraulic architecture energy flows.



Hydraulic Hybrid Excavator Architecture

High Speed Valve with Energy Coupler Actuator (ECA) using MR fluid

Project 1E.6 has developed and tested a novel high-speed valve actuation system capable of proportional and bidirectional operation. It can be used to actuate poppet or spool type valves, does not require a source of pilot pressure, and multiple actuators/valves can be compactly stacked on a single rotating shaft. The proof-of-concept actuator using magnetorheological (MR) fluid as the coupler between the rotary and translational pieces experimentally achieved a 1.5mm stroke in 4.5ms (equivalent to the design target of 100L/min @5bar) and scales favorably, achieving a 7mm stroke in 10ms, enabling the actuator to be used in large flow rate valves. The simulation model accurately predicted the measured response, and the validated model is being used to optimize the design. With an improved coil design the valve will have a faster response while using less power per switch.



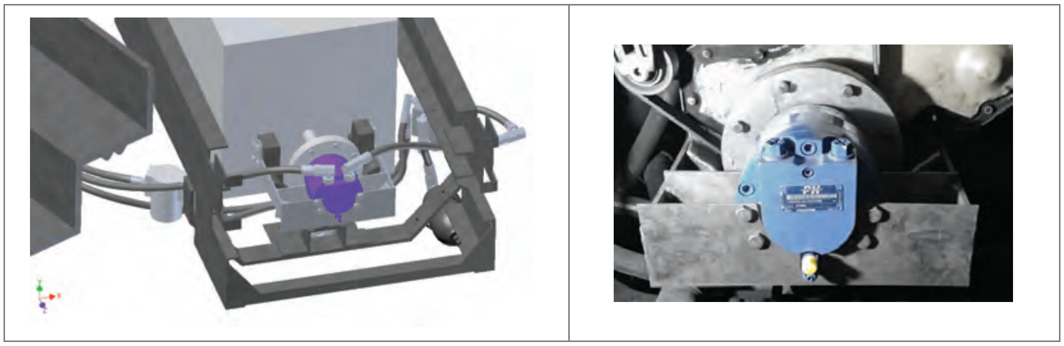
High Speed Valve with Energy Coupler Actuator (ECA) using MR fluid

Hydraulically Powered Start-Stop Systems for Use in Diesel-Powered School Buses

This research explores a start-stop system (termed ‘CleanStart’ by Poclain Hydraulics) for increasing fuel efficiency and decreasing emissions of a public school bus donated by Atlanta Public Schools. A significant problem with using diesel fuel to power school buses is that it emits pollutants that are not only harmful to the environment, but also extremely detrimental to the health of school children and their developing lungs. Additionally, the high cost of diesel fuel means that cash-strapped state budgets have to maintain a large transportation budget. One of the primary causes of inefficiency and unnecessary emissions arises from excessive idling. This occurs when stopping to pick up and deliver children, at bus stops, and in front of schools. The current project seeks to decrease excessive idling through an automated start-stop system based on a hydraulic motor attached to the buses’ crankshaft.

The start-stop research project builds on the team’s existing hydraulic hybrid school bus. It is in cooperation with Poclain Hydraulics, who has provided the team of undergraduate students with hydraulic components, an ECU, and technical assistance. Implementing the start-stop has required the installation of a reservoir, pump, motor, accumulator, valves, hoses, supporting brackets, and a control unit. Simple algorithms have been developed to control the components using an NI-sourced single-board RIO controller. The work has been carried out primarily by two undergraduate students over the course of two semesters. Following completion of the installation, the team will assess the system’s impact on the fuel economy and emissions of the school bus, and will analyze the system’s return on investment and commercial viability. Progress to date includes:

- Completion of all mounting brackets and component preparation: Welding of reservoir, design and construction of reservoir bracket, welding and mounting of motor, fabrication of modified radiator fan brackets.
- The following components have been mounted and connected: Reservoir, pump, accumulator, motor, junction box, and hydraulic hosing.
- The electrical system has been configured, a pump relay was designed and fabricated, and work began on fuel pump control and engine operation via micro-controller (NI single-board RIO).

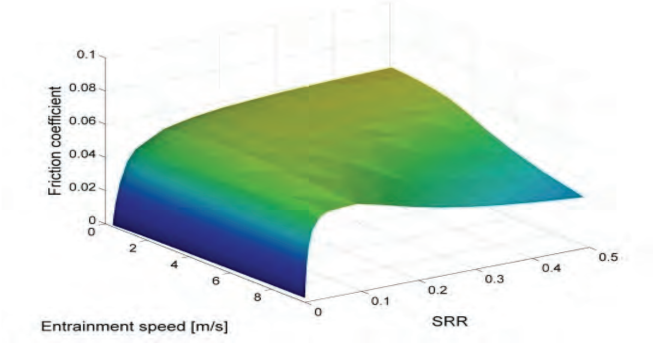


CAD drawings of planned installation on bus (left); Hydraulic pump installed on crankshaft (right).

A significant portion of the necessary work has already been completed with the remainder of the work and final installation, testing, and documentation scheduled for completion by the end of Spring 2014.

Regimes of Friction in Elastohydrodynamic Lubrication

The prediction of friction from the measureable properties of a liquid lubricant has been an elusive goal of researchers in elastohydrodynamic lubrication since the 1960's. Past work employed fictitious properties, derived from measurements of the friction, and was therefore not predictive. Recent CCEFP research has defined the necessary properties through the identification of the dimensionless numbers which delineate the various friction regimes, thus making friction predictions, such as below, possible.



Experimentally validated friction predictions

The prediction has been experimentally validated as follows. The linear regime is found where the Weissenberg number,

$$Wi = \frac{\text{shear stress}}{\text{effective modulus}} < 1$$

The non-linear viscous regime occurs for limiting stress number,

$$Li = \frac{\text{shear stress}}{\Lambda \cdot \text{pressure}} < 1$$ and Wi>1 and Ti<100.

The thermoviscous regime dominates friction when the thermoviscous number,

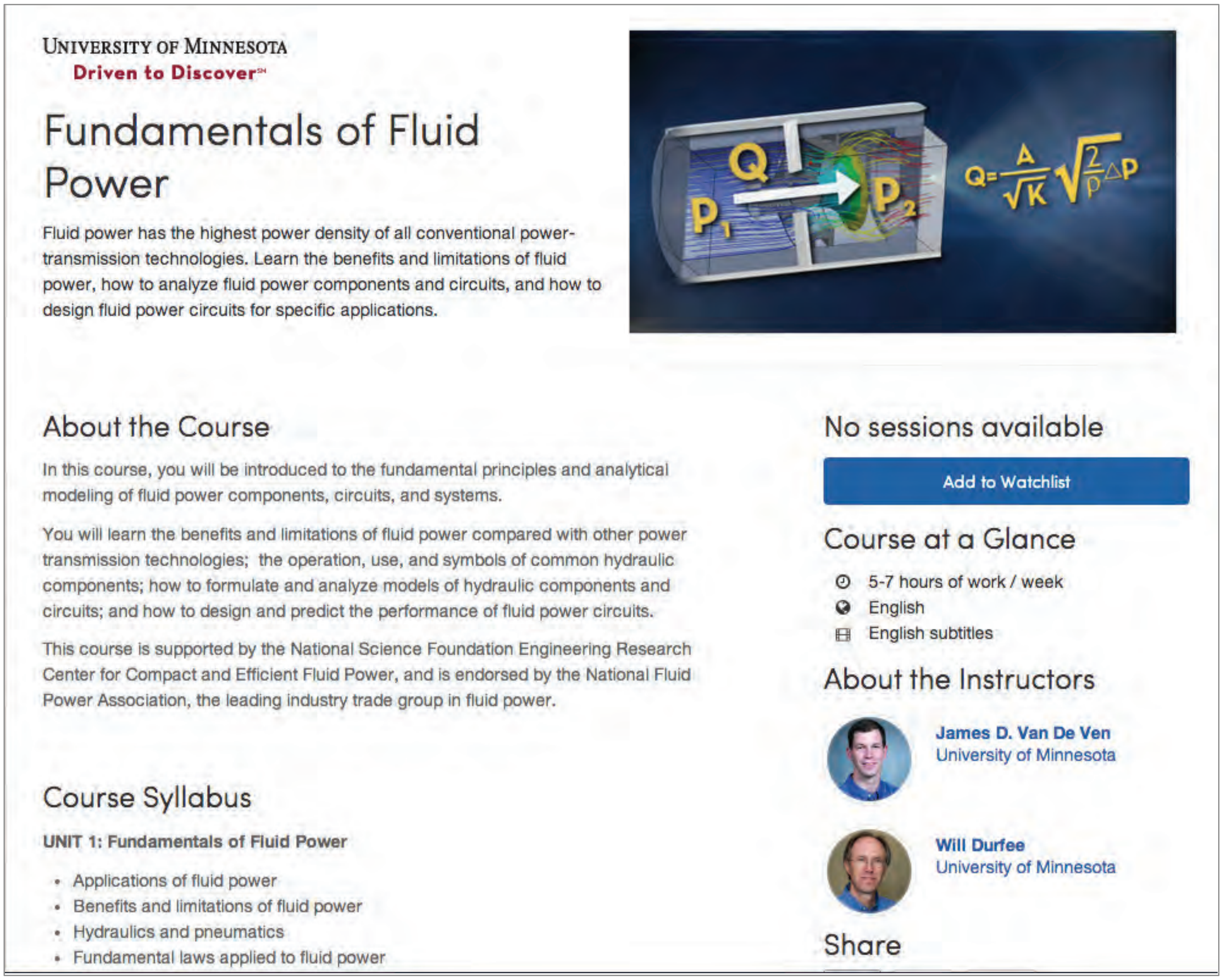
$$Ti = \frac{\text{Nahme-Griffith number g}\, Wi}{Li} > 100$$

The prediction of friction from measureable properties will allow the engineering of liquids for reduced mechanical energy loss.

EDUCATION HIGHLIGHTS

CCEFP Fluid Power MOOC Approved by University of Minnesota

Professors James Van de Ven and William Durfee will be offering 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 will introduce students to the fundamental principles of fluid power systems, circuits, and components. Students will learn: 1) the benefits and limitations of fluid power compared with other power transmission technologies, 2) the function of common hydraulic components, 3) how to formulate and analyze models of hydraulic components and circuits, and 4) how to design hydraulic circuits for specific system requirements. The course will be delivered through short, focused video presentations that will 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 will be first offered during the fall of 2014.



Fundamentals of Fluid Power

Fluid power has the highest power density of all conventional power-transmission technologies. Learn the benefits and limitations of fluid power, how to analyze fluid power components and circuits, and how to design fluid power circuits for specific applications.

About the Course

In this course, you will be introduced to the fundamental principles and analytical modeling of fluid power components, circuits, and systems.

You will learn the benefits and limitations of fluid power compared with other power transmission technologies; the operation, use, and symbols of common hydraulic components; how to formulate and analyze models of hydraulic components and circuits; and how to design and predict the performance of fluid power circuits.

This course is supported by the National Science Foundation Engineering Research Center for Compact and Efficient Fluid Power, and is endorsed by the National Fluid Power Association, the leading industry trade group in fluid power.

Course Syllabus

UNIT 1: Fundamentals of Fluid Power

- Applications of fluid power
- Benefits and limitations of fluid power
- Hydraulics and pneumatics
- Fundamental laws applied to fluid power

No sessions available

Course at a Glance

- 5-7 hours of work / week
- English
- English subtitles

About the Instructors

James D. Van De Ven
University of Minnesota

Will Durfee
University of Minnesota

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UMN MOOC Home Page

CCEFP Supports Three Parker Chainless Challenge Teams, UIUC Takes First Place

The Parker Chainless Challenge is a national inter-university competition sponsored by Parker Hannifin, a corporate member of the CCEFP. The competition requires that a team of undergraduate students design and build a bicycle that uses fluid power as its main method power transmission. The competition includes three race events: a distance race, a 200 m sprint race, and an efficiency challenge during which only stored energy can be used to power the bicycle. Points are also awarded for design innovation, manufacturability, workmanship and marketability among other categories. In addition, the student teams are judged on a written report and presentation.

Three universities represented CCEFP in the 2013 Chainless Challenge competition that was held in Irvine, CA, in April 2013. The University of Illinois at Urbana-Champaign took first place overall in the competition and teams from Purdue University and the University of Minnesota also participated.

UIUC Team at the 2013 Parker-Hannifin Chainless Challenge

NSF Invites CCEFP to Exhibit at Change the World: Science and Engineering Careers Fair

Making students aware of the interesting research and broad range of career options associated with STEM education can be challenging. That's why on Sept. 27-28 at the Dulles Town Center in Loudoun County, Rep. Frank Wolf (R-VA) and the National Science Foundation (NSF) are hosting a free event entitled “*Change the World: Science & Engineering Careers Fair for Middle and High School Students and Their Families”.*

NSF invited CCEFP to exhibit at the event in the nation’s capital in September. Specifically, NSF was interested in displaying fluid power and CCEFP’s hands-on excavator demonstrator to be a hands-on tutorial at the event.

Through interactive exhibits, students and parents can get hands-on experience: moving FIRST Tech Robots around a competition field, negotiating obstacles and solving simple challenges; collecting data in real time from some of the ocean's unexplored and most challenging depths; meeting researchers who chase storms and researchers who discover new dinosaur species; creating an earthquake; building a rollercoaster and much more.

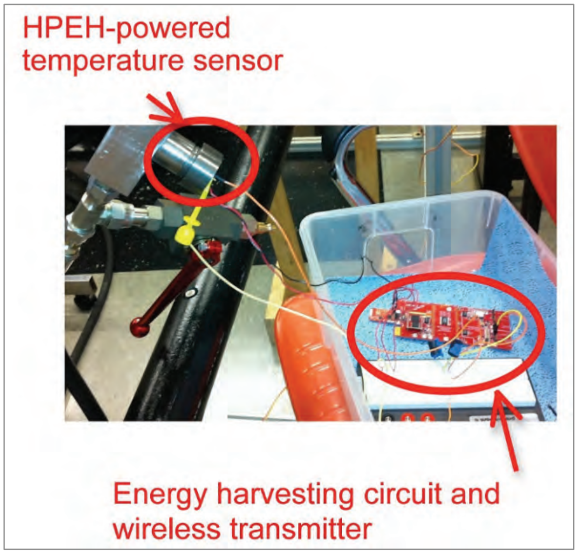
CCEFP Receives NSF REU Site Award

The Center received the competitive NSF Research Experiences for Undergraduates (REU) Site Award for Years 8 – 10. The goal 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 as well. To date, more than 145 REU students have participated in the CCEFP program -- more than in many REU site programs. Based on responses by 54 undergraduates to a 2012 longitudinal study, 55% of all former CCEFP REU students enter graduate school and 33% eventually become PhD candidates. Since revising the CCEFP REU program structure in 2008, the CCEFP REU Program has recruited, on average, over 35% women, and over 33% 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 Participants of the Purdue Fluid Power Bootcamp, May 2013

Energy harvesting for self-powered sensors – REU Highlights

The Hydraulic Pressure Energy Harvester (HPEH) project has had very strong participation from REU students since its inception. The project has had seven REU's engaged over its two year history, with several of these students working on the project for more than a year. There have been both paid REU's and volunteer REU's; but they have all shared in contributing to the overall success of the project. A key measure of the contribution of the REU students is that every single device prototype (six generations, with 9 distinct test articles) has been design, fabricated, and tested by the REU students. The REU students have adapted the underlying concept to develop prototypes applicable to high-pressure configurations, high-power configurations, low-power configurations, power-optimized configurations, and others. REU students developed and demonstrated the first HPEH-powered wireless sensor, as well.



High Pressure Energy Harvester Prototype

Caterpillar, Inc. Hosts CCEFP Student Retreat

CCEFP graduate and undergraduate students attended the annual student retreat graciously hosted by Caterpillar Inc., at the Hydraulic and Hydraulic Systems in Joliet, Illinois.

Caterpillar, Inc. Hosted CCEFP Students and Staff in Joliet, IL

Over 20 students from across the Center's institutions attended the 2½ day event. Students participated in two factory tours, an engineering lab tour, a trip to the Caterpillar Visitors Center, informal meetings with Caterpillar HR representatives, gave research and poster presentations, and attended a Joliet Slammers baseball game!

The CCEFP Student Leadership Council (SLC) aims, in part, to foster a positive social atmosphere between its student members. Given the physical separation of much of the student body, time spent together at conferences and meetings is particularly important to forming bonds that will enable greater overall moral and collaboration.

A CCEFP corporate member has the opportunity to learn more about the CCEFP; to have one-on-one interaction and professional relationship building with between 15-25 highly qualified and motivated graduate students who are conducting research in fluid power across the seven institutions of the CCEFP; has an opportunity to provide a direct recruitment link to CCEFP students; to provide exposure of the company, it's goals, it's accomplishments and it's direction.

The Center is grateful to Caterpillar Inc. for hosting the CCEFP, our students and staff.

CCEFP Hosts NFPA Fluid Power Challenge, An 8th Grade Engineering Competition

The Fluid Power Challenge, promoted by the National Fluid Power Association, hosted by the CCEFP, is a skills based competition for eighth grade students. The program challenges students to solve a real life engineering problems using fluid power (hydraulics and pneumatics).

CCEFP Fluid Power Challenge Competition

The event includes a Workshop Day where teams come together to learn about fluid power, build a pneumatic lifter and receive their challenge kits. Teams of four, then take their kits, including tools and supplies, back to school to work as a team on the challenge problem, develop a portfolio, and then build a prototype.

On the Challenge Day, teams return with their tools only (no prototypes) to build their fluid power mechanisms, and then compete in a timed competition. The FPC students teams work together, be creative, self-motivated, interested in problem-solving and committed to learning and applying engineering concepts. The competition is judged by engineers from the fluid power industry sponsors and supporters.

To date, the CCEFP has hosted three events, exposed over 300 students to fluid power technology. The CCEFP expects to expand efforts in the future.

Inaugural Year of the EngrTEAMS Program

2013 was the inaugural year of the EngrTEAMS Program, “Engineering to Transform the Education of Analysis, Measurement, and Science in a Team-Based Targeted Mathematics-Science Partnership” a large NSF/MSP program developing state-of-the-art science education pedagogy and spreading this work through professional development activities to reach 150 fourth to eighth grade science teachers.

EngrTEAMS is a multiyear program. In the first year, multiple faculty, researchers, and graduate students from the STEM Education Center developed curricular products that they piloted in a five-week professional development session for fourth to eighth grade science teachers. Subsequently, the teachers developed their own curricular products incorporating engineering content and concepts, which they are currently piloting in their own classrooms under the observation and evaluation of pedagogy research teams.

CCEFP is a major project partner providing content experts and advisement on the advisory board. Prof Paul Imbertson (CCEFP Education Director) is a Co-PI and Content Director for the program.

Recommitted Coalition with the White Earth Indian Reservation

The CCEFP performed a major reboot in its existing relationship with the Circle of Life School on the White Earth Indian Reservation in an economically depressed region of northern Minnesota. The reboot came about through the commitment of students and staff from the Innovative Engineers (IE), the National Society of Black Engineers (NSBE), and the American Indian Society for Engineering and Science (AISES). These changes will ensure the sustainability of their monthly engagements with the White Earth Indian Reservation for years to come.

The program is a major outreach effort designed to expose native students to the ways that science and technology can impact society. The program introduces the native high school students to native and non-native engineering students and them pathways to a future in STEM and related fields.

The students at the Circle of Life School are currently working with engineering students supported by the CCEFP on a variety of projects including wind analysis and the construction of a wind turbine for their school.

Circle of Life wind turbine

Bridges Program Formed to Enable Community Empowerment

The Bridges Program is a collaboration between the Universidad Nacional de Ingenieri, the Universidad Tecnologica LaSalle, Villanova University, and the University of Minnesota dedicated to building relationships and empowering people, communities, in the United States and Nicaragua. This is done through the initiation, support, and coordination of community-based projects.

The program was initiated in 2013 through the cooperative efforts of Prof. Paul Imbertson (CCEFP, Education Director), Prof. Pritpal Singh (Department Head, ECE, Villanova University) and Prof. Maria Virginia Moncada (Department Head, Electronic Engineering, National Engineering University of Nicaragua). Initial work is in the area of renewable energy projects in support of community and institutional empowerment, through implementation projects, shared research, co-creation, and professional development for instructors in Nicaragua.

An inaugural summit is planned for August 2014 in Jinotega, Nicaragua to bring together stakeholders from academia (pre-college, technical, and university), NGOs, communities, and governmental agencies.

The groundwork for this program was put in place by the efforts of the BRIDGE (Building Resources and Innovative Designs for Global Energy) Project and the University of Minnesota Innovative Engineers student group with the support of the CCEFP.

TECHNOLOGY TRANSFER HIGHLIGHTS

Vanderbilt's team EndoInSight participates in the NSF I-Corps 2013 fall cohort

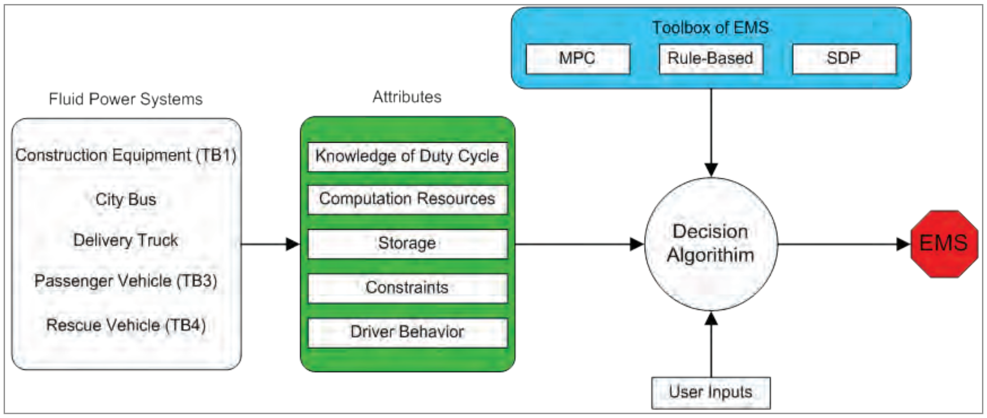
A team composed of Principal Investigator Pietro Valdastri, Business Mentor Rigved Joshi and Entrepreneurial Lead Byron Smith, spent 11 weeks meeting with clinicians, hospital administrator and industry experts to determine how a novel approach to generating fluid power for medical applications could be used to provide patients with a less-painful experience during their next colonoscopy. The team is excited about the market opportunity presented by disposable CO2 insufflation systems they have designed based on customer feedback and the team's entrepreneurial lead, Byron Smith, has found a new company, EndoInSight LLC, to pursue commercialization of their product concept.

Entrepreneurial Lead, Byron Smith, representing EndoInSight at the NSF I-Corps closing workshop.

For more information, go to: http://www.vanderbilt.edu/cttc/muse/endoinsight-wins-nsf-i-corps-grant

Control Optimization and Energy Management Software Piloted within CCEFP Member Companies

The goal of this project is to develop and implement a well-defined process for transferring energy management technology developed within the CCEFP to industrial partners. From previous Center-funded work in the study of energy management strategies (EMS), it is known that no single strategy is best for all applications. Multiple energy management strategy (EMS) tools have been created within the toolbox to be applied to different problems. At present, the tools are rule-based, model predictive and stochastic dynamic programming controllers. The choice of tool depends on the a priori level of knowledge about the duty cycle and the system characteristics, making it is possible to choose the most appropriate tool for the EMS. The goal is to make that algorithm 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.



Implementation of the EMS Toolbox

Licensing and affiliated projects for Hydraulic Pressure Energy Harvesters

CCEFP project 3E.1, the Pressure Ripple Energy Harvester, has focused on research and development into means to convert fluid-borne noise in hydraulic systems into electrical power at levels appropriate for self-powered wireless sensing. The project has met all of its performance goals for Hydraulic Pressure Energy Harvesters (HPEH) and has demonstrated prototype power generators with outputs ranging from 125 µW to 3.3 mW. These power outputs are sufficient for a broad range of sensing and communication applications, demonstrating that the underlying HPEH concept is flexible and viable. Two companies have elected to pursue licensing of the technology. In addition, there is a follow-on affiliated project funded through an NSF STTR to explore a commercial application for an HPEH-powered pipeline leak detection system. Finally, another affiliated project is in development with a company to develop HPEH-powered diagnostic sensors for fluid power systems. This project includes a prototype with a flexible design enabling the use of combinations of commercially available piezoelectric elements, permitting ease of configuration of the device for different target power demands.

CCEFP Research Project Drives Novel Magnetic Based Position Measurement System

Ferromagnetic objects have inherent magnetic fields around them. Researchers have shown that the magnetic field variation around a ferromagnetic object can be modeled using purely the geometry of the object under consideration. Exploiting this model of the inherent magnetic field, the position of the object can be measured quite accurately using a small inexpensive magnetic sensor. Further, the use one additional redundant magnetic sensor can eliminate the need to calibrate the position measurement system. The technology has been demonstrated through a series of experimental results that the developed measurement system is applicable to accurate position measurement of small and large ferromagnetic objects, including cars on highways, oscillating pistons in IC engines, pneumatic cylinders, hydraulic cylinders, as well as moving parts in many machines.

A primary motivation behind this discovery was the CCEFP Free Piston Engine Pump (FPEP) project shown in Figure 1. One of the critical barriers to overcome was the need to quickly and accurately measure the position of the outer piston in a potentially harsh operating environment. The non-contacting magnetic sensor solved this difficult problem. Note that the FPEP was equipped with a linear variable differential transformer (LVDT) which was used only as a reference sensor.

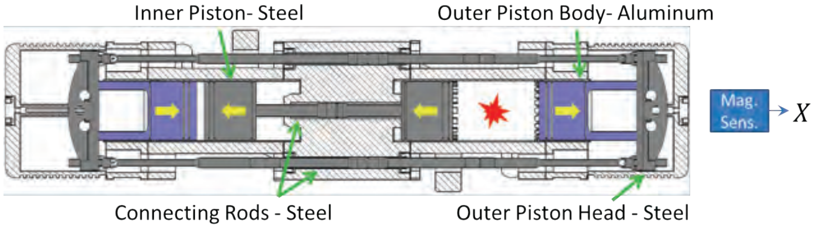


Figure 1. Use of the inherent magnetic field in a Free Piston Engine Pump for piston position estimation.

By modeling the inherent magnetic field of the outer piston and measuring the field using magnetic sensors, piston position can be estimated. Figure 2 shows the result from an experiment with the FPEP. It can be seen that the developed technology is capable of accurately estimating piston position even under fast transients.

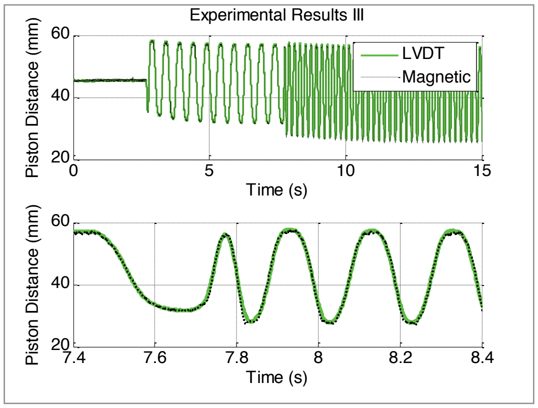


Figure 2. Results from applying the technology to measure piston position in the FPEP.

In cases that the piston does not have an inherent magnetic field (for example pistons made of aluminum), the same technology can be applied by adding a magnet to the piston head. This has been shown through experiments with a pneumatic actuator made of aluminum shown in Figure 3. In these experiments a LVDT was again used as a reference.

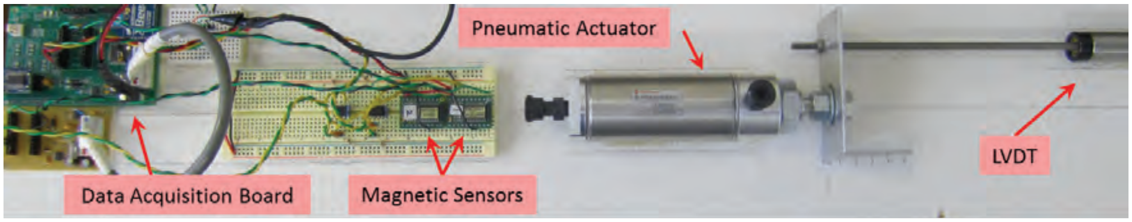


Figure 3. Test setup for piston position measurement in nonmagnetic pneumatic cylinder.

Using the developed technology, along with a small embedded magnet on the internal piston head, it can be shown that piston position can once again be accurately measured. Figure 4 shows a sample result from the experiments with the pneumatic actuator.

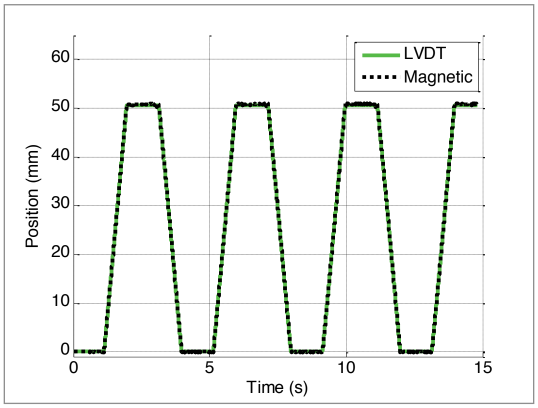


Figure 4. Piston position measurement in a pneumatic actuator.

Members of the UMN research team are actively pursuing an internal university grant to establish a start-up enterprise under a new initiative funded by the State of Minnesota called MnDRIVE (Minnesota Discovery, Research and InnoVation Economy) focused on advancing Minnesota's economy and positioning the state as a leader in key industries.

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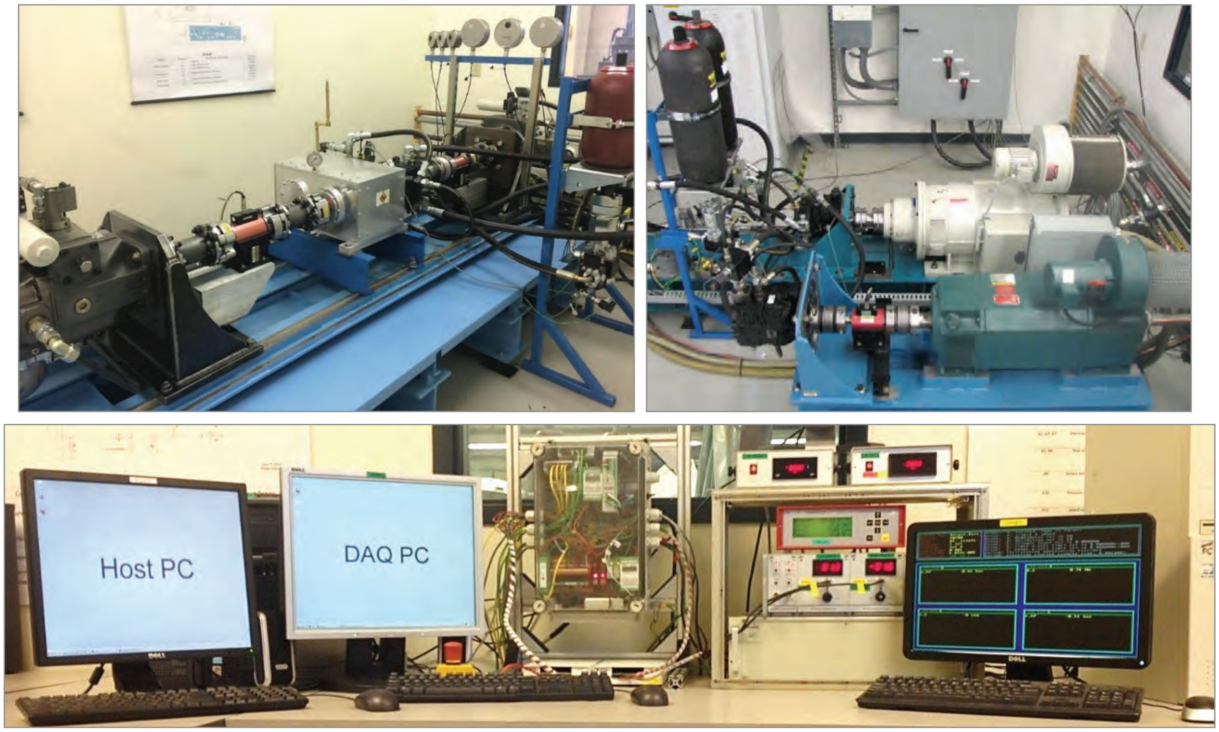
INFRASTRUCTURE HIGHLIGHTS

Hydraulic Hybrid Powertrain Test Rig used for High Performance Fluid Testing at Purdue

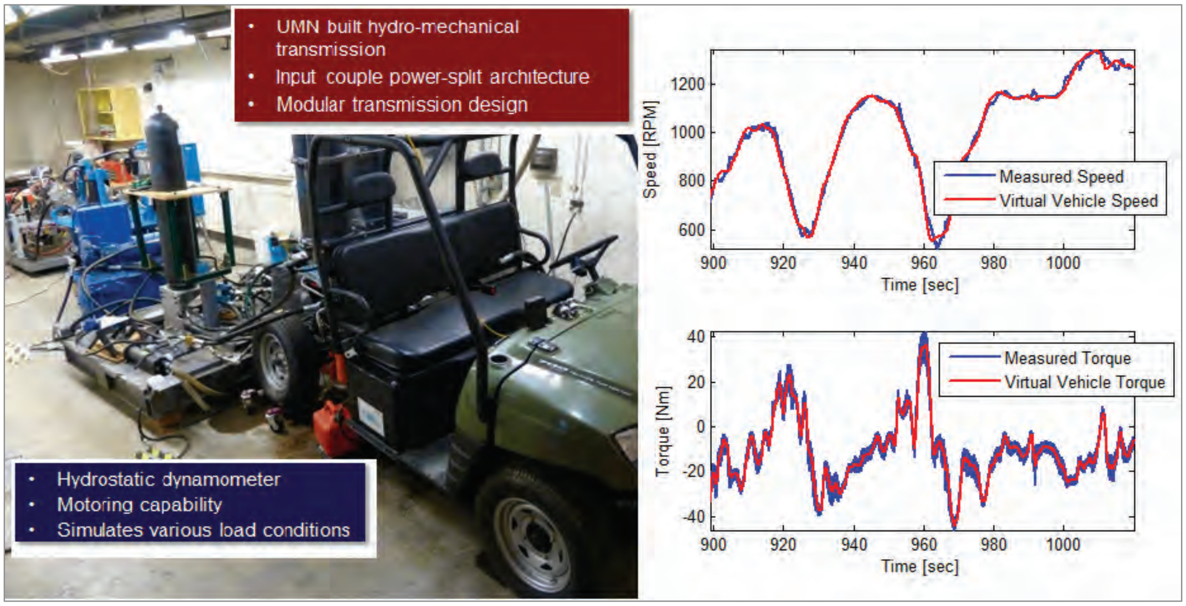
Researchers at Purdue’s Maha lab focus on investigating the design and performance of alternative drive train configurations for both on-road and off-road highway applications. The aim of which is to develop system configurations which are capable of significantly reducing fuel consumption while maintaining the original systems performance. Throughout the years various drivetrain configurations have been developed and explored at the Maha lab including power split transmissions, multi-motor concepts, and a new blended hybrid transmission among others. Two Hardware-In-The-Loop (HIL) transmission test rigs aid the researchers in bringing these drivetrain configurations closer to production. In 2013, researchers assisted an industrial partner with investigating high performance oils in one of the HIL transmission test rigs. The fluids tested were purpose blended for optimizing the performance of hydraulic hybrid transmissions. Purdue’s HIL test rig was especially well suited for the industrial partner’s requirement that the transmission operate repeatedly in a realistic manner with full data acquisition capabilities. This research project is another example of how the Center is assisting industry with bringing hydraulic hybrid technologies to market.



Hydraulic hybrid test rig

Hydraulic Hybrid Vehicle Tested on Purpose-Built Dynamometer at Minnesota

The Hydraulic Hybrid Passenger Vehicle (HHPV) “Generation I” test bed features a modular hydraulic hybrid drive train designed to achieve both high fuel economy and high performance. A hydrostatic dynamometer was completed in Year 8 to enable evaluating the fuel efficiency and to enable tuning the vehicle controllers. The dynamometer provides a controlled environment for testing, thus eliminating the need for a test track. It can also be programmed to emulate different vehicle load characteristics. Unlike most chassis dynamometers, it is capable of motoring, allowing testing with brake regeneration. The Generation I vehicle successfully navigated drive cycles simulated using the in-house dynamometer with repeatable and consistent performance in Year 8. Calculated and measured speeds and torques are shown in in the figure below. The hybrid powertrain was tested as a continuously variable transmission (CVT). A Rule-Based hybrid algorithm from Project 1A.1 was then implemented. The fuel efficiency for a highway drive cycle improved by 3% using the hybrid algorithm. Substantially more improvement is expected for urban drive cycles. Efficiency for the urban cycles will be evaluated immediately following a modification to the vehicle's clutch, which is required to enable tracking portions of the urban cycle.



Generation I Hydraulic Hybrid Passenger Vehicle (HHPV) attached to purpose-built dynamometer. The graphs on the right illustrate the calculated and measured speed and torque of the HHPV drive train.

Enhanced Display of the Excavator Simulator at Georgia Tech

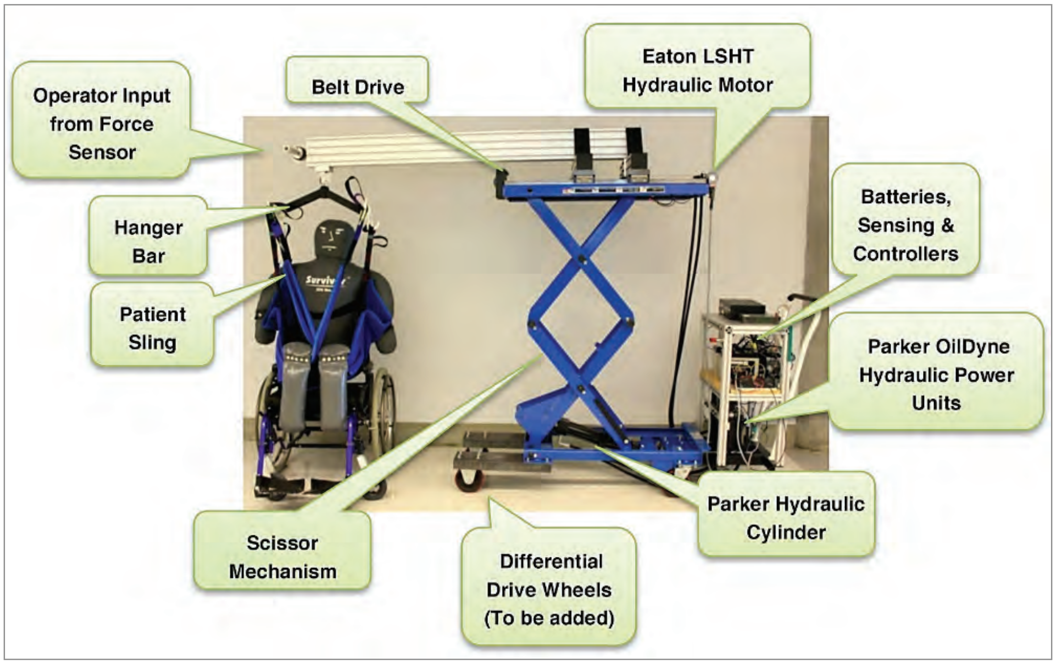
While ultimate verification of operator interfaces requires implementation on the actual equipment, studies of alternative designs are more reliably performed on simulations if they faithfully represent reality. This is because each subject operator can be provided with identical work conditions. Simulations have been used extensively in project 3A.1 and 3A.3 to study interfaces for excavators but they lacked realistic depth display. The Bobcat excavator simulator at Georgia Tech has now been retrofitted with a stereoscopic 3D representation of the accurately drawn arm, bucket and the simulated workspace. While high end simulators in 3D have been beyond the reach of the CCEFP, software in the public domain (Open-GL) and clever programming has enabled stereo viewing on a consumer grade 3D TV screen mounted on the front of the actual excavator cab of the same model used in TB1. The dynamics of the excavator and its interactions with soil are incorporated in a Simulink model which drives the display as well as physical cab rotation. With this new improvement, researchers can confirm and extend previous results in interface design. The extensions will include new hand controller configurations, displays relevant to in-the-cab and remote operation and generic principles of manual control design. The figure shows a view of the screen as it appears to someone without 3D polarizing glasses. Hence, we see the view of the left and right eye overlapping, whereas the operator wearing glasses will see them separately with the appropriate eye.

3D excavator simulator display

Patient Transfer Device at Georgia Tech

Test Bed 4, fluid power at the human scale, has been designed and is in the first phase of operation. Its purpose is to assist with the transfer of patients with little or no mobility, ranging from normal to very heavy patient weights. Untethered, valveless, electro-hydraulic pump control is attained for multiple degrees of freedom by using a reversible DC electric motor driving a bidirectional hydraulic gear pump for each degree of freedom. Each hydraulic pump drives either a hydraulic motor or cylinder. While the current prototype is bulkier than desired, this is only for providing modularity in the test bed and simplicity in the prototype design; it could easily be optimized to fit in a much more compact package. Electric power, sensing and control are onboard, obtained from batteries, servo drives, and a National Instruments Compact Rio controller. The control input is from a force sensing handle mounted near the patient, and a basic real time rate control is implemented. Current experimentation is on operator interfaces and control of extension and lift degrees of freedom.

In addition, progress has also been made in the operator interface development, control design, and simulation development. A detailed task analysis and subsequent pilot benchmarking operator study were performed using a current market lift device, through collaboration between NCAT and Georgia Tech. In terms of the operator interface and control research, an advanced passivity-based human power amplifier control technique for collaborative manipulation was implemented on a pre-prototype hydraulic lift device; this algorithm is an extension of a control system developed in the graduated CCEFP project 3A.2. Also in progress is development of a dynamic simulation to aid in the control design, including the dynamics of the mechanical, hydraulic, and electrical subsystems. Other near term next steps include addition of powered differential drive wheels and further development of control techniques.



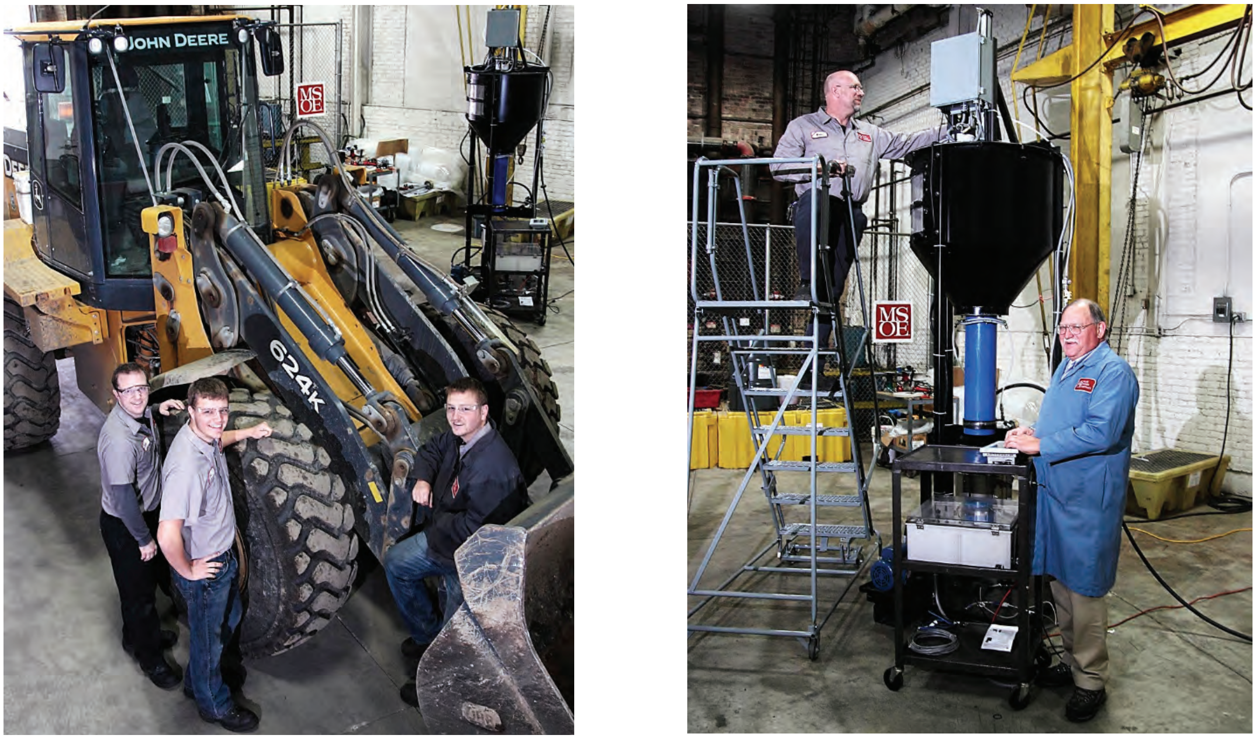
First prototype hydraulically actuated patient transfer device with two degrees of freedom controlled by operator force input

Fluid Power Institute Off-Campus Laboratory at MSOE

The MSOE Fluid Power Institute has added a new off-campus laboratory facility to support the R&D needs of the global fluid power industry. This laboratory, located in the Chase Commerce Center on Milwaukee's near south side, is designed to evaluate large components, systems, and vehicles. At the new high-power lab, FPI staff and students design, build, instrument, and evaluate large-scale fluid power equipment; providing a practical, applications-oriented, educational experience for MSOE students.

The new lab features:

- 12,000 square-feet
- High-bay ceiling
- Drive-in access
- Reconfigurable workspaces
- Major hydraulic power capability



MSOE Fluid Power Institute Off-Campus Laboratory

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.

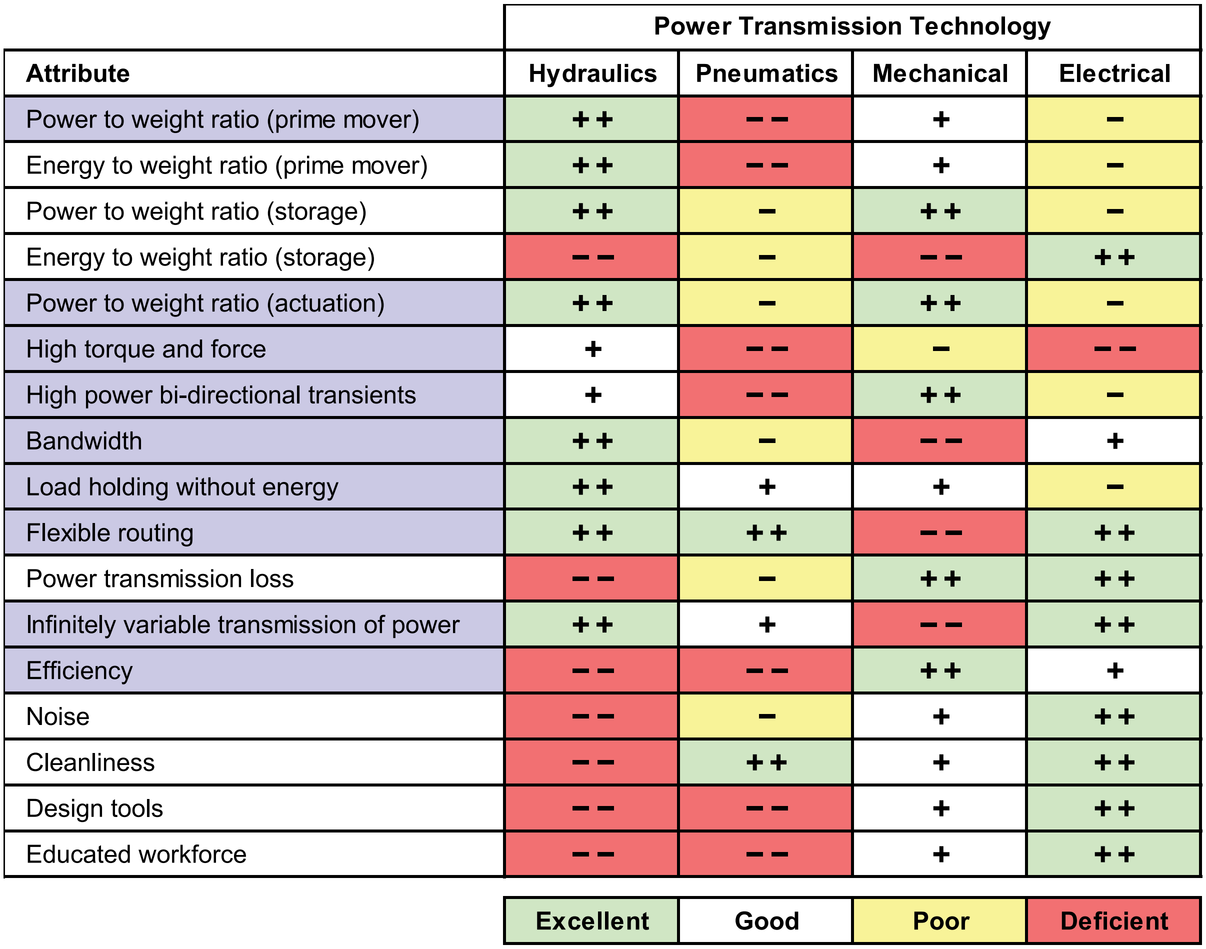
Although fluid power offers advantages over competing technologies, it has been confined to applications where the required power density precludes other solutions. Fluid power has a number of shortcomings that are barriers to more widespread use. These barriers are 1) inefficient components and systems; 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.

Mobile Off-Road Equipment

Hydraulics has been the dominant power transmission choice for mobile off-road equipment 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 low efficiency of hydraulics has not deterred its use in mobile off-road equipment because its inherent advantages outweighed the poor efficiency. Large increases 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 by 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 high 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 ratios become less important. 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	– –	– –	+	+ +

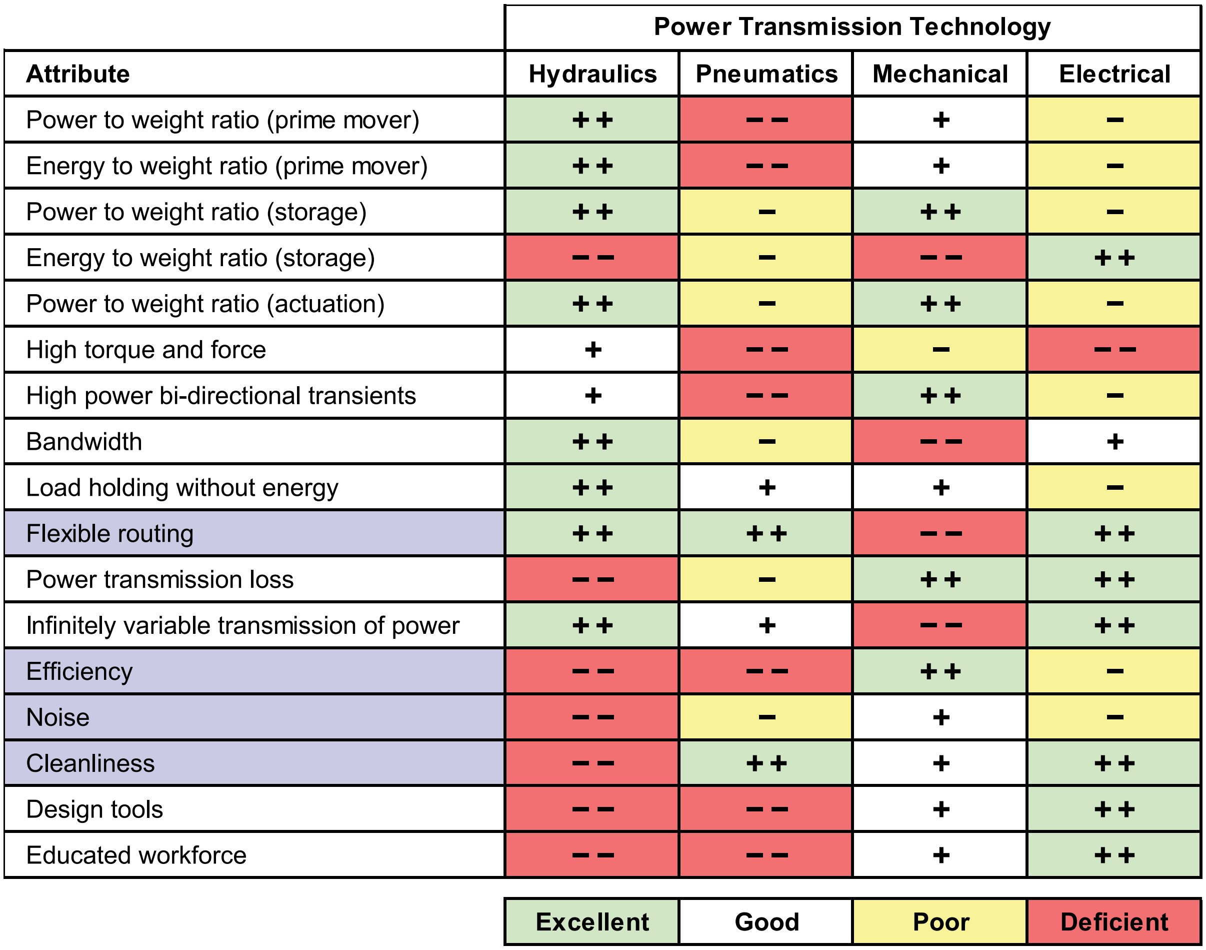
Excellent	**Good**	**Poor**	**Deficient**

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. Requirements 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 and cleanliness 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 specific 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” site would also not have shop air to use for cleaning and other non-power transmission needs. Neither hydraulic nor mechanical power transmission technologies offer the flexibility that pneumatics provides, so they are less often chosen.

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, 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	− −	− −	+	+ +

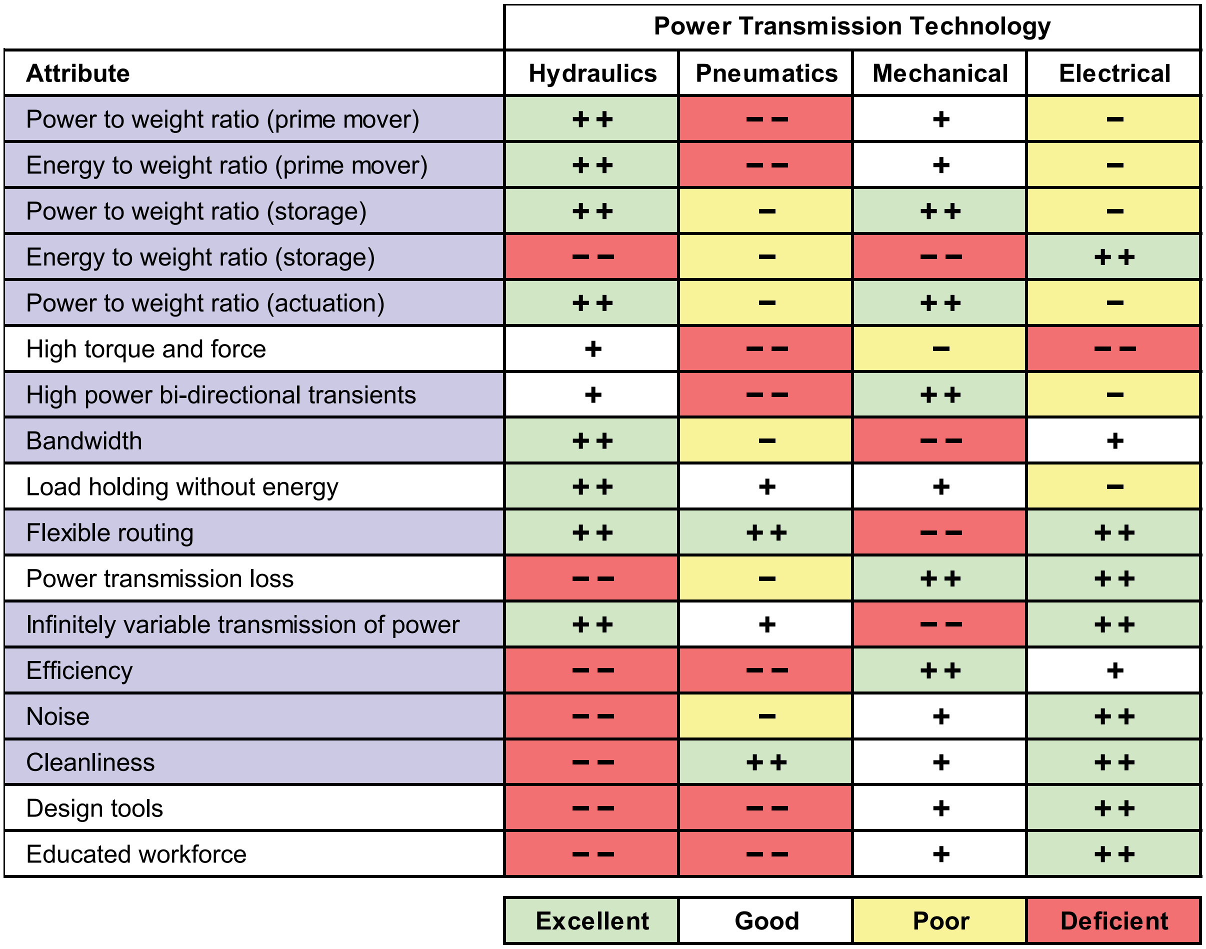
Excellent	**Good**	**Poor**	**Deficient**

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 supply smaller, developing more compact energy storage, increasing system efficiency, reducing noise and, in the case of hydraulics, making the system leak-free.

Hybrid Passenger Vehicles

The attributes that are critical to the use of hybrids in the passenger car 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.

Strategic Research Plan

The CCEFP has identified the following major goals necessary to realize our vision:

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.

These goals address the aspiration shared by CCEFP and its industry members to leverage fluid power's inherent strengths and overcome critical weaknesses in order to maintain and grow the current markets and to expand the field of play for fluid power to new, high growth markets.

The technical barriers that the CCEFP strategic research plan address were identified in the state of the art analysis in the previous pages. The research plan also addresses the major goals of the Center. 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

These nine attributes naturally group into the three thrusts of the 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.

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

- Test Bed 1, the excavator (mobile heavy equipment), 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 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 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 making the use of fluid power ubiquitous.

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- and utility scale wind turbine drivetrains, 100 kW - 10 MW)
- Test Bed β - Precision Pneumatics MRI-Guided Surgery (MRI-compatible surgical devices, 5W - 50W)

The Center's 3-plane strategic planning chart illustrates how the Center's systems-level goals, and barriers in the way of achieving those goals, motivate and drive the research plan and how these goals integrate fundamental, enabling technology, and systems-level research, as well as proof-of-concept test beds, to address barriers and to deliver discoveries, advances in knowledge, and new technology.

The nine barriers exist within all three levels of the 3-plane chart. As previously discussed these barriers naturally group into the Efficiency, Compactness and Effectiveness thrusts. The projects at the enabling technologies and fundamental knowledge levels are color coded by thrust. Each thrust is led by a senior faculty member from a different core university of CCEFP. The thrust leaders are members of both the CCEFP Management Committee and the CCEFP Executive Committee where they participate in determining the strategic direction of the Center and the allocation of its resources.

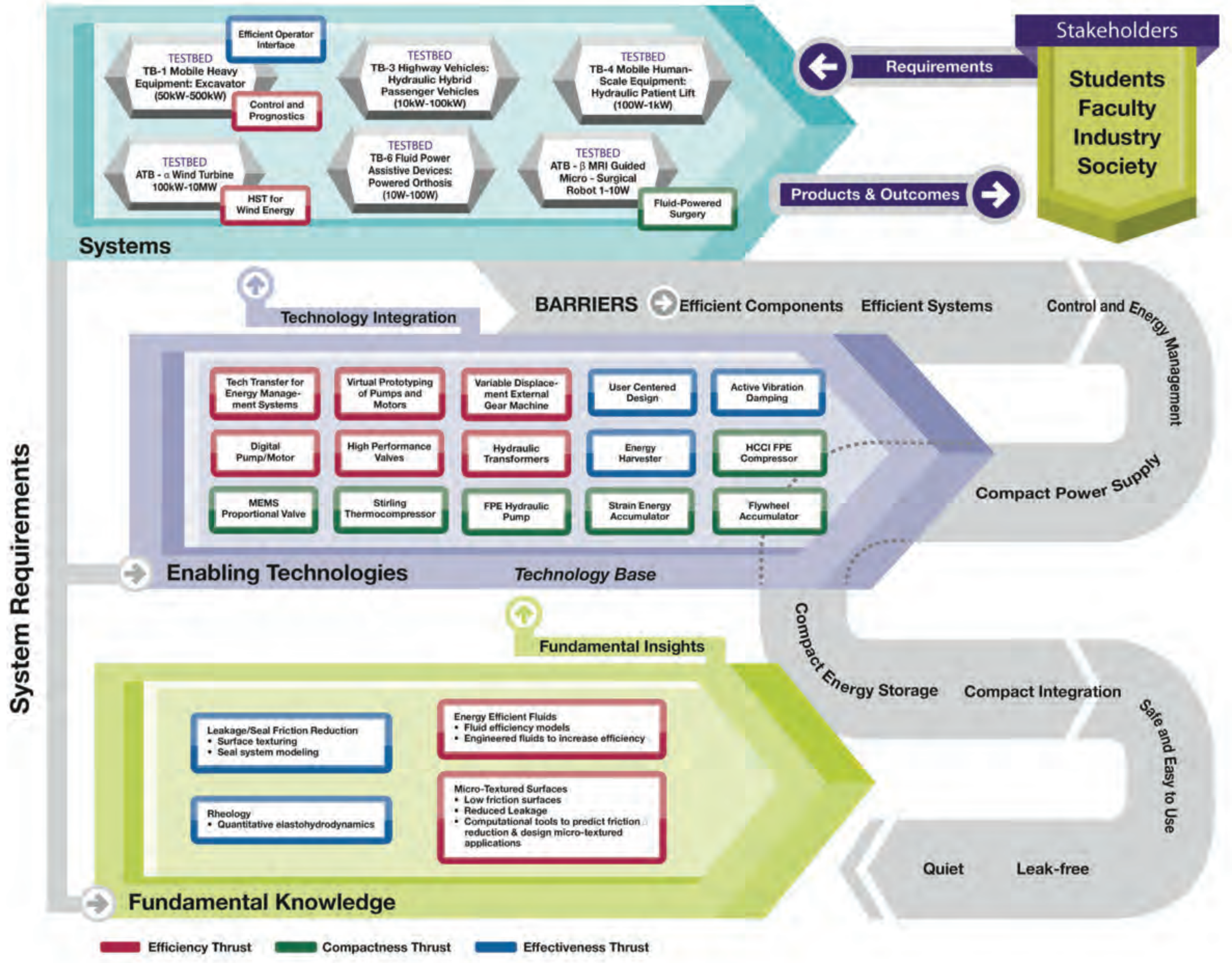
The CCEFP strategic research plan is designed to overcome the technical barriers to achieving the Center's vision. To overcome the barrier of inefficiency, the Center is developing new components and systems and novel control methods to improve system performance and reduce energy consumption. The approaches 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.

In December 2012, a groundbreaking report titled "Estimating the Impact (Energy, Emissions and Economics) of the U.S. Fluid Power Industry" was published by the Oak Ridge National Laboratory (ORNL) [5]. The report provides the findings a Department of Energy-funded study to estimate the energy-specific footprint (consumption, emissions, efficiency) of currently deployed fluid power systems in the US. The report authors are Dr. Lonnie Love of ORNL and Eric Lanke and Pete Alles of the National Fluid Power Association. Thirty-one industrial partners provided input to the study. The report provides information that will have an impact on fluid power research in years to come. Some of the key findings include:

- Fluid power systems consume between 2.0 and 2.9 Quadrillion Btus (Quads) per year and produce 310-380 million metric tons of CO_2. The energy to operate fluid power systems is 2-3% of all of the energy consumed in the US.
    - Mobile hydraulics consumes 0.4-1.3 Quads/year
    - Industrial hydraulic equipment consumes approximately 1.1 Quads/year
    - Pneumatic equipment consumes approximately 0.5 Quads/year
- Across all industries, fluid power efficiencies range from 9% to 60% with an average of 22%. The specific application of the fluid power system impacts its efficiency.
- The study provides an overview of the aggregate, sector and market energy usage for fluid power systems. It also offers suggestions for some potential areas of improvement.

The DOE study provides insights on the impact of fluid power on energy consumption in the US. For the first time, fluid power practitioners have an understanding of energy use and efficiency in aggregate and by sector. The report will have a significant impact on the direction of research in fluid power. It is a cornerstone of the Center's strategic research plan and post-NSF sustainability plan.

The 3-plane chart appears on the following page.


Stakeholders
Students
Faculty
Industry
Society
Requirements
Products & Outcomes
TESTBED
TB-1 Mobile Heavy Equipment: Excavator (50kW-500kW)
Efficient Operator Interface
Control and Prognostics
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
Systems
Technology Integration
BARRIERS
Efficient Components
Efficient Systems
Control and Energy Management
Compact Power Supply
Compact Energy Storage
Compact Integration
Safe and Easy to Use
Quiet
Leak-free
Tech Transfer for Energy Management Systems
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
MEMS Proportional Valve
Stirling Thermocompressor
FPE Hydraulic Pump
Strain Energy Accumulator
Flywheel Accumulator
Enabling Technologies
Technology Base
Fundamental Insights
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
Fundamental Knowledge
System Requirements
Efficiency Thrust
Compactness Thrust
Effectiveness Thrust

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)

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.

Micro- and Nano-Texturing for Low-Friction Fluid Power Systems (Project 1D)

This project creates nano-textures for friction and leakage reduction using a cost-effective manufacturing technique. There is one patent pending for the technology that was submitted by UIUC without participation by CCEFP industry members. The technology has been demonstrated in a research lab environment and is estimated to be at TRL 4. One company that became a member after the patent application was filed has expressed an interest in licensing the technology.

Free Piston Engine Compressor (Project 2B.1)

This project developed a unique high inertance free piston engine air compressor with efficiencies up to 6.6% and energy density up to 3750kJ/kg. The unit would enable the test bed 4 compact rescue robot to operate for several hours without additional weight (thus outperforming all battery-based electromechanical solutions). The technology was demonstrated in a research lab environment and is estimated to be at TRL 4.

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.

Improved Seal Design Based on Adaptive Materials (Project 3D.3)

The goal of this project was to identify new materials and seal designs that can effectively increase the operating lifetime of sealing systems. The research identified strain energy as a main factor in seal degradation, developed seal design rules that provide desirable material behavior and material variation over the seal and created a useful design procedure for improving seal lifetime performance by minimizing strain energy. The technology has been demonstrated in a research lab environment and is estimated to be at TRL 4-5. The lead researcher worked collaboratively with one CCEFP industry member to transfer the research findings and has recently been in communication with another to do so.

In addition to these Center-funded research projects, Center researchers have motivated other associated projects that are a TRL 4 or above. Some of the more promising projects are described below.

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 received a $50k MnDRIVE Entrepreneurship Award from the University of Minnesota for help in 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. A utility patent on this pump architecture is pending.

2.1 ERC RESEARCH PROGRAM (BY THRUST AND TESTBED)

Research projects at CCEFP are categorized by which of the three thrusts of Center research - efficiency, compactness and effectiveness - they are most closely aligned with. The first digit in the project number identifies the thrust. 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 control and for "1B" projects the focus is material surfaces/interfaces.

In actuality, nearly all of the research projects have substantial elements of more than one thrust so the project numbering system does not capture all of the aspects of a given project. For example, Project 1D (microtexturing), is targeting friction reduction which will improve efficiency during operation. In addition, the friction reduction is also likely to lower starting friction. High starting friction in hydraulic motors often requires that motors be larger than is needed for normal operation in order to have the torque required to start the motor. Reducing starting friction would allow the use of smaller displacement motors in a given application and a more compact system. Another 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. There are also both 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 to fluid power. These areas are: creating more efficient components and systems, improving efficiency through control optimization and energy management. Creating efficient components and systems is a transformational barrier 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 table below shows the efficiency thrust projects funded during the reporting period 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	
1A.1: Technology Transfer Process for Energy Management Systems	•	•	•							TB3
1A.2: Multi-Actuator Hydraulic Hybrid Machine Systems	•	•	•			•				TB1
1B.1: Next Steps towards Digital Prototyping of Pumps and Motors	•									TB1
1D: Microtextured Surfaces for Low Friction and Leakage	•					•		•		1G.1
1E.1: Helical Ring On/Off Valve Based 4-Quadrant Virtually Variable Displacement Pump/Motor	•	•	•			•			•	TB3
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
1J.1: Hydraulic Transmissions for Wind Energy	•	•	•			•				TB-α

Efficiency Thrust Technical Barriers

Efficiency Projects

Project 1A.1: Technology Transfer Process for Energy Management Systems

The goal of this project is to develop and implement a well-defined process for transferring energy management technology developed within the Center to industrial partners supporting the CCEFP. From previous Center-funded work in the study of energy management strategies (EMS), it was concluded that there is no single strategy that is optimal for all applications [1-6]. We have developed a formal process for transitioning the algorithms developed to practitioners and a software framework for interfacing to the available tools.

The project the efficiency barrier by providing a way for efficient operation algorithms developed within the Center to be readily implemented up by industrial partners. This project provides a set of "best practices" for transitioning the tools from the academic setting to the industrial setting. This will be a good approach to attracting industry support and supporting Center sustainability.

Project 1A.2: Multi-Actuator Hydraulic Hybrid Machine Systems

In the past, project 1A.2 has focused on the development of system architectures and control methods for optimal power management in multi-actuator mobile hydraulic machines using displacement-controlled linear and rotary actuators. Through this project, a 50% reduction of energy consumption for typical working cycles of multi-actuator machines has been demonstrated. In addition, a reduction in cooling capacity of up to 50% is feasible while maintaining typical working temperatures and performance. The investigation of hydraulic hybrid architectures for multi-actuator machines and the potential for further fuel savings from these systems has also been a subject of research. Simulations have shown that implementing hydraulic hybrid architectures can allow the combustion engine to be downsized to 50% of its current rated power.

Since August 2012, the project has been focused on reducing production costs, further improving system efficiency and productivity and introducing machine prognostics of highly efficient displacement controlled hydraulic machines. To achieve lower production costs and higher system efficiencies, pump switching between actuators during machine operation will be analyzed, thus reducing the number of and size of the pumps installed in the hydraulic system and ultimately leading to lower parasitic losses. Such concepts are especially important for large machines where the current design approach requires the installation of large pumps. Preliminary simulations of a single pump, two actuator displacement controlled system have shown that pump switching is a viable solution to reduce production costs of multi-actuator displacement controlled machines and increase system efficiencies. Another goal of the project is the development of effective machine prognostics concepts. These will allow for the prediction of impending failures thereby avoiding expensive machine breakdowns making displacement control a more competitive technology.

The project primarily addresses the efficiency barrier by developing new system concepts and control strategies for multi-actuator mobile machines. It also addresses the compactness barrier since displacement-controlled systems allow higher operating pressures and a reduction of interfaces and components. Displacement controlled systems with pump switching will further address the efficiency and compactness barriers by reducing the number of pumps required thereby minimizing parasitic losses. The project will provide architectures including required system control concepts for multi-actuator machines utilizing displacement control and hybrid concepts in combination with pump switching. This will support the implementation of this new energy saving technology in larger and more complex machines. The investigation of methods to predict impending failures by utilizing existing sensors will further strengthen this new technology and hopefully contribute to faster technology acceptance.

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. The latest virtual prototyping and optimization techniques will be used 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 1D: Microtextured Surfaces for Low Friction and Leakage

The goal of the project is to enhance the performance of fluid power components using microtextured surfaces that have significantly reduced friction and leakage relative to state of the art. These performance enhancements will be enabled by a fundamental understanding of lubricant behavior on microtextured surfaces, application of microtextured surfaces to fluid power components and design of viscoelastic properties of lubricants. Target applications include reciprocating rods, as well as seals and rotating components. We will fabricate and test microtextured plates, rods, and shafts. We will then integrate these components in the excavator and the orthosis test beds, and also test them in industry.

The ultimate goal is to enable leak-free components with friction lower than state of the art. Such a technology would overcome current barriers to fluid power systems (efficient components, leak-free), and provide a transformational capability for future fluid power systems (efficient components). The technology will be validated through collaboration with industry and on the excavator and orthosis test beds. The work will also improve fundamental understanding critical to fluid power components.

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 into virtually variable displacement pump/motors (VVDPM). The prototype VVDPM will then be performance mapped, with operating speed/torque ranges that coincide with CCEFP test bed 3. Prototype targets include 21-35MPa operating pressure, VVDPM system bandwidth in excess of 10Hz, and hydraulic valve efficiency greater than 85% at 50% VVDPM displacement.

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 [1]. By pairing on/off valves with a fixed displacement pump or motor of any type, variable displacement functionality can be achieved with designs that are inherently efficient or compact but traditionally fixed. This project addresses the Center's goal of increasing efficiency by developing efficient pulse width modulated alternatives to inefficient throttling valves. It 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 the test bench experimental results of a three piston digital pump/motor to implementation on a test bed (hydraulic vehicle or excavator) for demonstration and eventual 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. During the previous cycle, full four quadrant operation was 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 from the previous grant cycle 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 pump/motor 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. The focus is on creating a variable displacement pump/motor that can meet or exceed existing designs in peak efficiency, and demonstrate less of a drop-off in efficiency as the displacement is decreased. By us a two degree of freedom rotary valve, the expected benefits of piston-by-piston control will be achieved with a simpler and more cost effective control mechanism than competing research approaches.

The need for efficient hydraulic components is 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 will also facilitate the realization of practical hydraulic hybrid powertrains in both on-highway and off-highway vehicles. The key element to the new design 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 are 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 (TB4).

Hydraulic 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 goal of the project is to develop high performance actuation mechanisms to enable high bandwidth valves and improve the performance and efficiency of existing systems. The concept is based on coupling energy storage mechanisms with translational movement to increase the speed and controllability of linear actuators. The high speed linear actuation method is being applied to hydraulic proportional valves. The stored actuation energy (such as a rotating mass) is intermittently coupled and decoupled to produce linear or rotary motion in the primary actuator. The project will develop the bidirectional proportional control algorithms for the Energy Coupler Actuated Valve (ECAV), integrate the ECAV with both a poppet and a spool valve body and experimentally investigate the pressure-flow-time performance, and 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 a variable displacement external gear machine (VD-EGM). 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 are to (1) formulate a new design principle for VD-EGM, and (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 components. This will be accomplished by characterizing fluids in benchtop instruments, analyzing fluid efficiency effects in a hydraulic dynamometer, and modeling fluid-component interactions in Matlab Simulink. Improvements in bulk modulus, boundary friction, and shear stability properties are expected to yield a 10% increase in overall system efficiency. Non-Newtonian fluids will be formulated and characterized throughout 2014. Dynamometer studies of bulk modulus, boundary friction, and shear stability effects will be conducted Q3 2014 through Q2 2016. These results will be used to develop and validate a system efficiency model that incorporates the properties of advanced 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 viscosity research of Professor Bair (3D.2), improved the low-speed mechanical efficiency properties of the test fluid for Professor Chase (TB3) by at least 10%.

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, these facilities require expensive power transmission lines and typically incur significant construction and maintenance costs. A small wind facility is a cost-effective method of power generation for areas with limited power needs, such as farms or factories. Most 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.

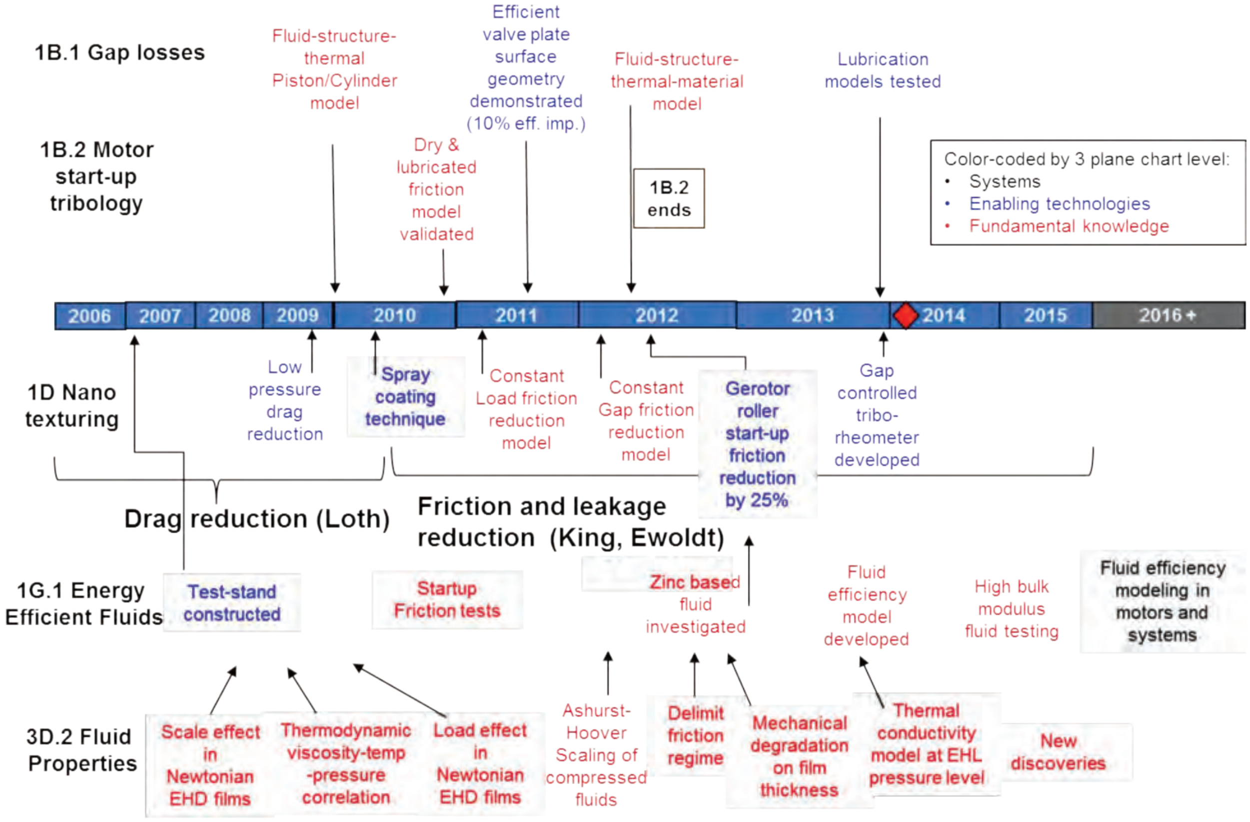
A hydrostatic transmission (HST) functions as a continuously variable transmission and eliminates the need for the gearbox. Gearbox reliability is a major issue and gearbox replacement is quite expensive. In a recent study by Reliawind, it was reported that the major components contributing to low reliability 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 applying an 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. Finally, this project focuses on creating a new market for fluid power and, thus, strongly supports the Center’s goal of making the use of fluid ubiquitous.

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).

Gaps 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 based on these improved understanding and models will be developed and tested in TB1 in 2016.

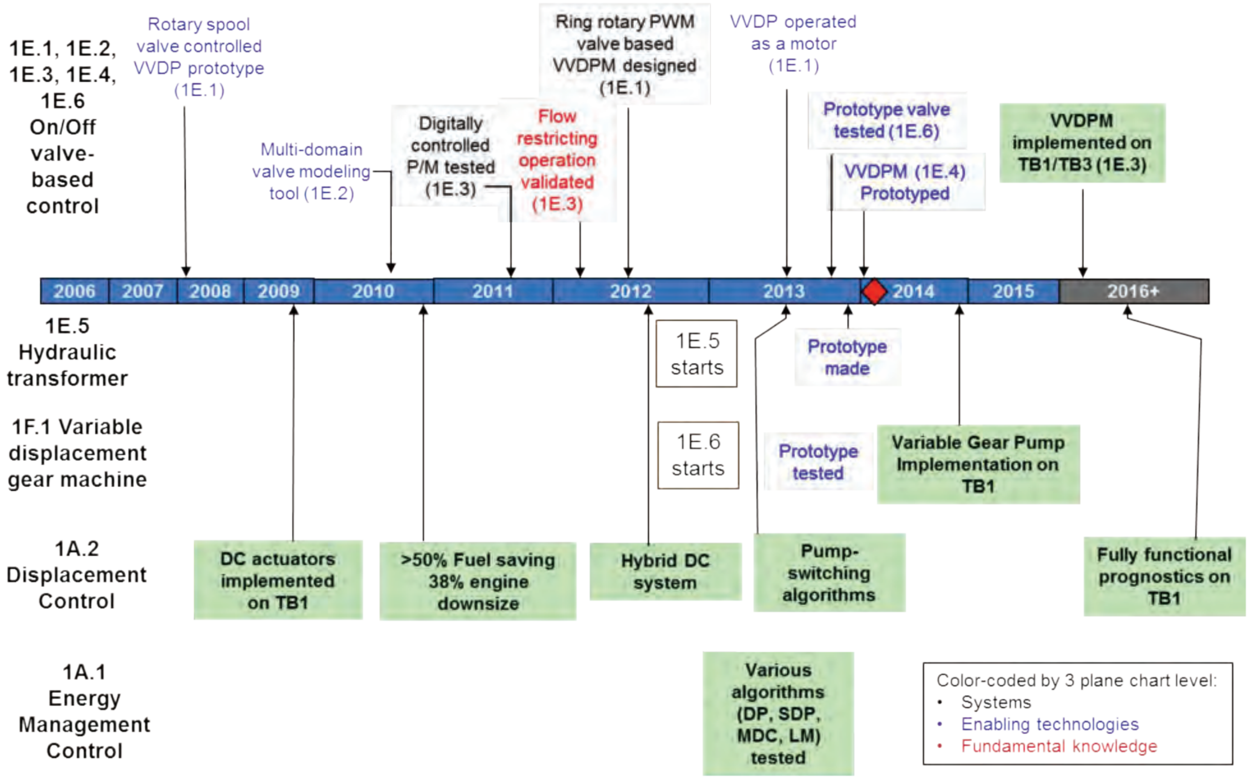
Nano-texturing

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 gerotor roller surfaces to reduce start-up friction by 25% in 2011. A gap controlled tribo-rheometer was designed and utilized to validate the previously developed models.

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 unanticipated 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 were investigated in 2013. Next year, the focus is to build a thermal conductivity cell at 700MPa.

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 being 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 initiated research into 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 (2014, 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). 1E.4's VVDPM's design is finished and the prototype device is expected to complete soon (2014). Both projects predict significant efficiency improvement over conventional VDP's 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). 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. 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. Algorithms from project 1A.1 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 third major goal: creating portable, human-scale fluid power applications.

The table below shows the compactness thrust projects funded during the reporting period 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
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 20W 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, electric motor, and air pump.

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 addresses two transformational barriers as outlined in the CCEFP strategic research plan: compact power supply and compact energy storage. This is achieved by proposing a hydraulic free-piston engine, 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 pneumatic compressors, particularly with respect to enhancing heat transfer within the compressor to enhance efficiency. 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. Enhanced compactness is particularly needed at the scale of TB6 (10-100W). This project will contribute to the Center's goal of breaking the barrier of low energy density power sources for untethered devices. The efficiency thrust is addressed as a by-product of requiring high heat transfer within the device. The novel in-cylinder heat exchangers already developed in this project have been shown to be very effective, and their inclusion on larger scales will be investigated through model-scaling. 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 – specifically utilizing pneumatics.

Project 2C.2: Advanced Strain Energy Accumulator

The objective of this research is to extend the current state of knowledge in the use of strain energy elastomeric materials in the design of compact energy storage devices. Specifically, this project seeks a low cost, low maintenance, high energy density accumulator targeted toward a fluid powered automotive regenerative braking system (hydraulic hybrid) or a pneumatic ankle foot orthosis medical assist device. This project will focus on improving the energy storage capabilities of accumulators for the specific purpose of storing large amounts of hydraulic or pneumatic energy with an energy density appropriate for applications such as regenerative braking in passenger vehicles or medical assist devices and will be appropriate for either series or parallel configurations.

The metric for success of the hybrid version will be an experimental prototype capable of storing up to 200 kJ of energy (3500 lbs at 35 mph) at a peak power of 90 kW (35 mph to zero in 4.5 second) in a package of acceptable weight and volume for a compact to midsized passenger vehicle (accumulator system energy density >10 kJ/liter). This metric will enable implementation in a passenger vehicle for city driving. In the pneumatic version of the accumulator an efficiency increase of 25% over existing configurations is the threshold for success. Additional potential benefits of this research include solutions to more traditional accumulator problems including cost, pre-charge issues, fluid contamination from gas diffusion through the bladder and in the pneumatic case a reduction in exhaust gas noise.

This project contributes to the Center's strategic goals of compact and efficient energy storage. The tasks of designing new compact and efficient energy storage devices is central to the Center's vision of "significantly reducing energy consumption" by "enabling the migration of fluid power to passenger cars". Compact energy-dense storage solutions are critical to the success of this migration. This project addresses the knowledge level of this goal (explore new energy density concepts) by seeking a design to provide the enabler (improve energy density of storage mechanisms) and ultimately the needed system capability (reduce size and weight of FP systems to work in passenger vehicles) for this important goal.1 The hydraulic version of the accumulator will aim to demonstrate on the SUV test bed (TB3).

In this past year, 2013, the pneumatic version of the accumulator was realized in pneumatic systems. There exists a great potential for energy savings, and hence increased efficiency, in pneumatic systems, particularly industrial pneumatics. A pneumatic prototype was designed for the Ankle-Foot Orthosis (AFO) test bed (TB6). The prototype was then constructed and tested at Vanderbilt, and subsequently implemented at UIUC. In preliminary experiments on TB6 the pneumatic version of the accumulator was demonstrated to have an energy savings of 17.5% relative to operating with no accumulator. Subsequent experiments showed energy savings as high as 27% percent thus meeting the defined success criteria.

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

The goal of this project is to develop a 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 project's goal is to significantly increase hydraulic storage energy density while maintaining good round-trip (storage-regeneration) efficiency. Overcoming the energy density barrier is one of CCEFP's transformational barriers and is a key enabler for implementing a commercially successful hydraulic hybrid powertrain in a passenger vehicle

Project 2F: MEMS Proportional Pneumatic Valve

The goal of this project is to create extremely efficient proportional valves for pneumatic systems by exploiting Micro-Electrical Mechanical Systems (MEMS) technology. The valves are expected to require under 5 mW 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 4 cc. Supporting goals include leveraging the potential of piezoelectric materials such as "PZT", developing MEMS-scale sealing technologies and developing position sensing strategies for the MEMS scale devices.

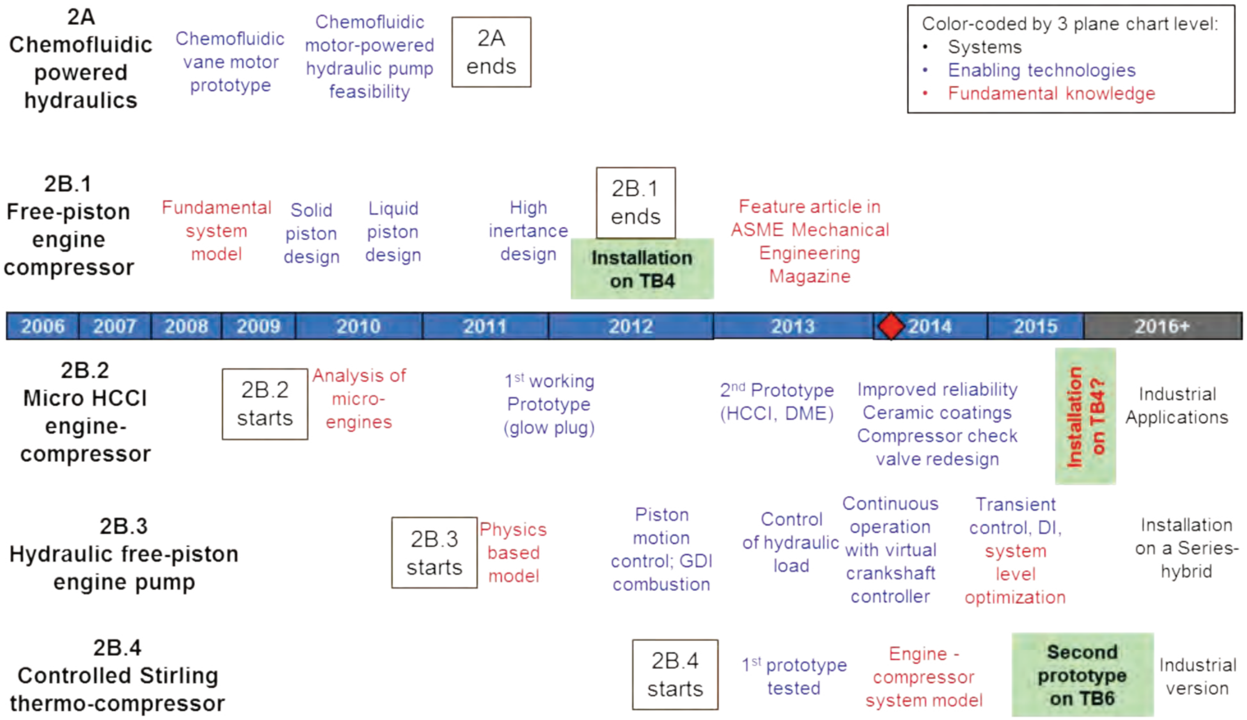
This project has breakthrough potential toward the Center's transformational strategic goal of developing efficient fluid power components. While we are developing generic proportional valves, the extremely low power requirements and compactness of these valves make them especially attractive for portable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

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 cylinders, valves, and sensors are no longer independent entities assembled together, but are a single integrated system that can be manufactured simultaneously. 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.

The project addresses the major technical barriers relating to 1) compact integrated systems (by designing systems where valves, cylinders, 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, the project addresses a key transformational goal of the Center - making fluid power ubiquitous - by applying fluid power in medicine.

Compact Power Supplies Technology Integration



Compact Power Supplies Milestone Chart

The goal of the compact power supplies projects is 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 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 does not reflect the advantage of using lightweight, high-power (high power-density) fluid power actuators over other power supply and actuation systems. The analysis can also be performed on a volume-specific, as opposed to a mass-specific basis.

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.

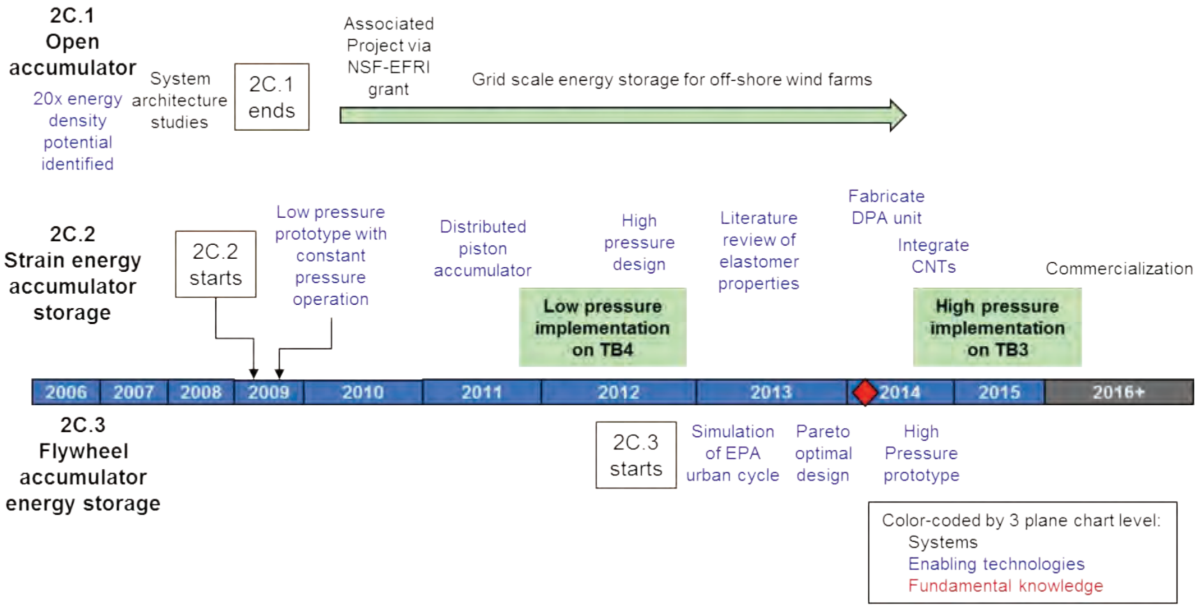
The free-piston engine compressor (2B.1) targeted for TB4 ended in 2012. Researchers developed a fundamental dynamic model of the engine compressor in 2009. This model allowed the model-based design iteration of several prototypes (solid piston in 2007, liquid piston in 2007, and high inertance liquid 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 no being considered 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 most recent reporting year include improving reliability and performance by addressing the fundamental interaction between the piston and the cylinder liner. New materials are being investigated and improved sealing is expected. Better sealing will result in a higher compression ratio and in turn, pure HCCI and greatly improved efficiency. Ways to address noise level, vibration and heat output are also being considered. The following year will also see the investigation of the compressor check valves for better fatigue properties.

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). The previous year has focused on a transient control method involving the design of a combustion detection mechanism and modification of the existing active control algorithm. Within the last year, this transient controller has been implemented and experimental results have demonstrated its effectiveness. Other accomplishments include experimental measurement of the losses of the engine that show a 64% reduction in engine losses over those of a conventional ICE. Implementation on a series hydraulic hybrid vehicle is anticipated in the long term (2016).

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 hydrocarbon fuel, but only as an external heat source and as such is fuel agnostic and could operate with any source of high flux heat. The Stirling thermocompressor is expected to run cool and quiet. It also escapes many of the challenges of the internal combustion (or decomposition in the case of 2A) based 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, the system model of the first prototype was validated. Current tasks include formulating a system model of the entire engine-compressor (the first prototype was a sealed pressurizer), fabricating and testing the second prototype. Installation of a prototype into TB6 is expected in late 2015. Since the pursuit of an efficient compressor stage is emphasized in this project via novel means (dynamic heat exchangers), the results from this project are expected to be adapted for industrial scale compressors (2017).

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 transformational goal of the Center is to increase the energy density by an order of magnitude 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:

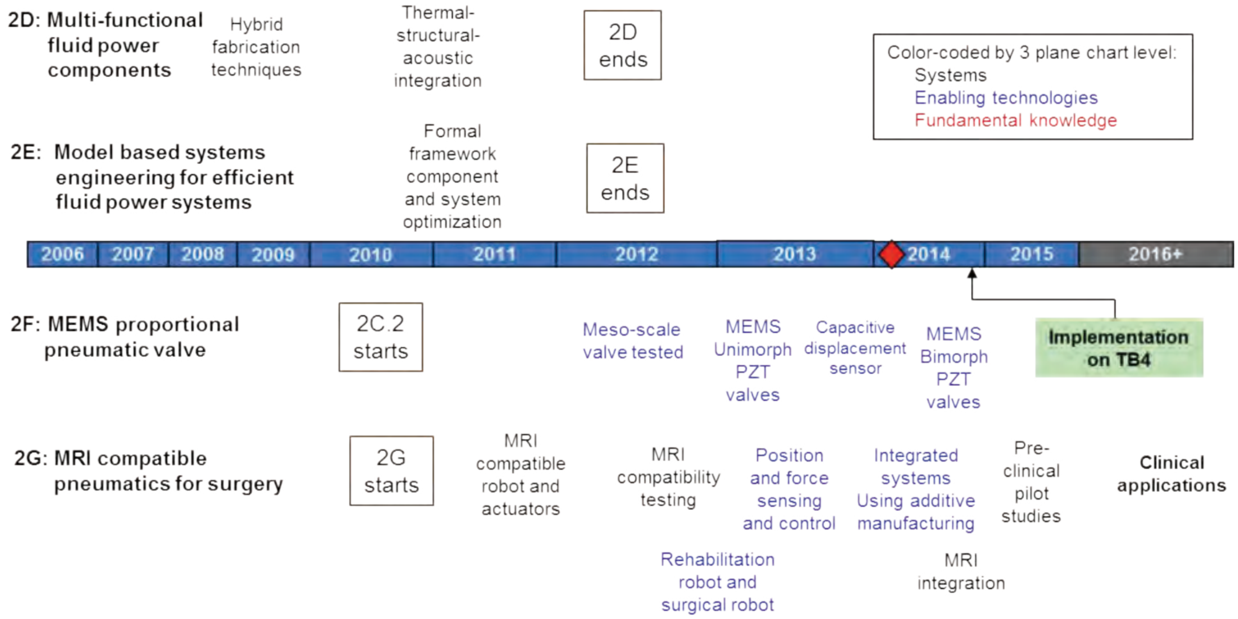
- Open accumulator (2C.1)
- Strain energy accumulator (2C.2)
- Flywheel accumulator (2C.3)

The open accumulator project (2C.1) proposes to store energy by compressing air from the atmosphere to high pressure. The 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 graduated 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.

The strain energy accumulator project (2C.2) 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 low cost and less frequent 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. A broader investigation of energy savings in pneumatic system is currently underway. Current work on the hydraulic version includes a more fundamental study and investigation of material properties. The inclusion of carbon nanotubes into the elastomer will be investigated over the next two years. 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. Installation and testing of a high pressure prototype on TB3 is expected in (2015).

The flywheel accumulator project (2C.3) 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 the last year include a design optimization for a simulated hydraulic hybrid powertrain performing the EPA Urban Dynamometer Driving Schedule. A simulation of an un-optimized design indicates an energy density of 26 kJ/kg and an efficiency of 84%. Future steps include optimization of the design parameters for operation of the system on a standard drive cycle, and design, fabrication and testing of an optimally designed prototype.

Compact Integration Technology Integration



Compact Integration Milestone Chart

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 to now being pursued through two Center-funded projects: Fluid Powered Surgery and Rehabilitation via Compact Integrated Systems (2G), and MEMS Proportional Pneumatic Valve (2F).

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 treatment of the hippocampus area of the brain for the treatment of epilepsy. Both projects take advantage of the fact the 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, (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. Plans for next year include integrating the surgical robot with the MRI scanner at Vanderbilt and transitioning of the rehabilitation robot into a clinical setting.

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 within the last year 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. Milestones for the upcoming year include demonstration of a bimorph actuation array, demonstration of the a complete MEMS device and demonstration on the Ankle-Foot Orthosis testbed (TB6).

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 fourth major goal: ubiquity, capable of being used anywhere.

The table below shows the effectiveness thrust projects funded during the reporting period 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. The excavator simulations were potentially compromised by lack of depth perception and will be verified with the recently completed stereo 3D display and with limited field tests by experienced operators. The intuitiveness of hand controllers, position versus velocity control, and the effectiveness of selected data presentation modes will be evaluated. Double digit percentage improvement in efficiency and economy are expected as have been illustrated in some instances.

Interface designs that reduce fatigue while maintaining intuitiveness are proposed as improvements over previously tested designs.

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, 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 (FP) 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 FP 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 FP 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 fluid power 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 general goal of this project is the development of realistic numerical models of the seals and seal systems used in fluid power systems, which would be capable of predicting the key seal performance characteristics, especially seal leakage and friction, and serve as design tools. A further aim is to develop a fundamental understanding of the physics of sealing through the model development.

The project attacks the effectiveness barrier 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.

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:

- Rheology of degraded oil
- Accurate prediction of minimum film thickness in EHL
- Solution of Navier-Stokes for piezoviscous liquids
- Thermal conductivity measurements at elevated pressure
- Targets of opportunity

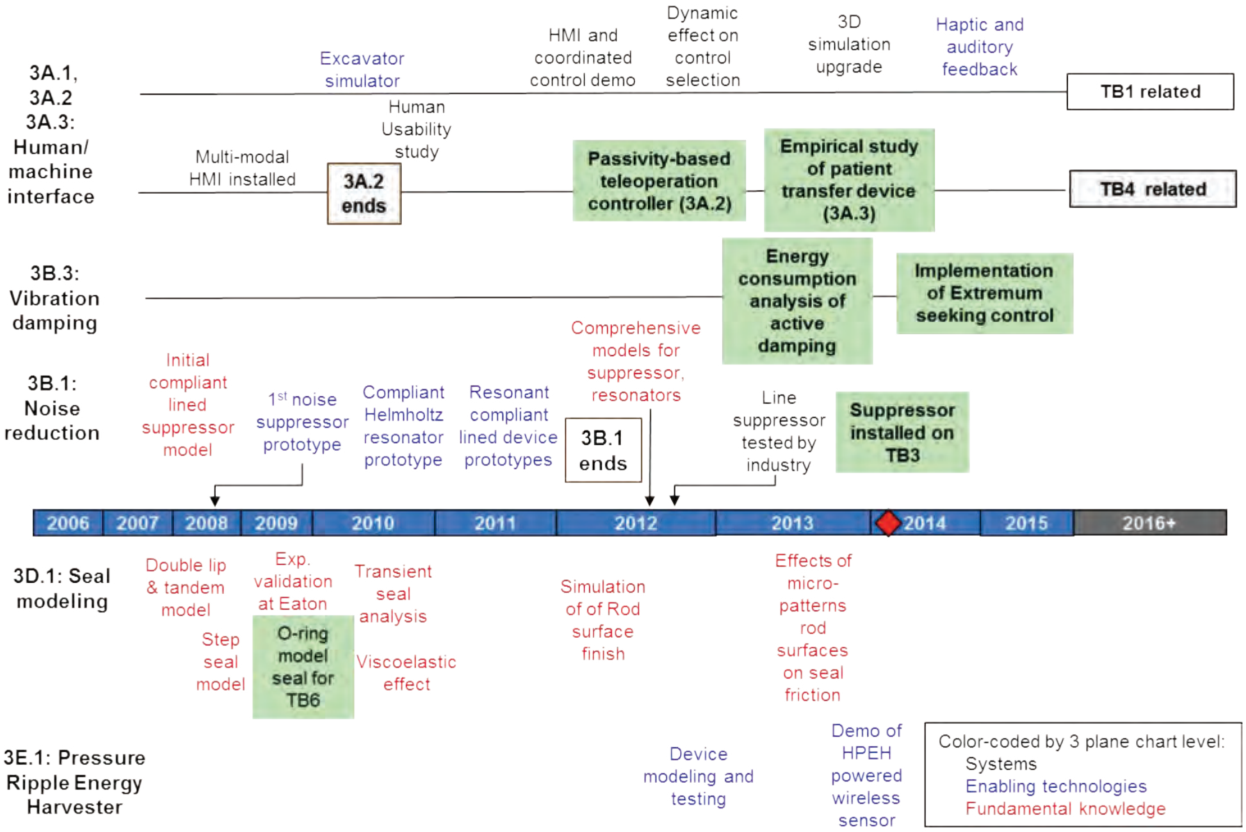
The project addresses the Center’s compactness and efficiency thrusts. More compact components must necessarily have smaller radius of curvature of the contacting elements. A clear strategy for making more compact components is also to increase the operating pressure. The resulting increase in load and 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. Initial prototype devices sized for sensor-node power requirements will be available by Spring 2014. An initial power response model was available by Summer 2013; a refined model will be a major final deliverable in Summer 2014.

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

Safe and Easy to Use

Safe and intuitive operation in human-machine interactive devices was addressed Project 3A.1. Project 3A.2, which graduated in 2010, investigated passive 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. A new project for active vibration damping (3B.3) 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 TB1, TB4 (old and new) and TB6.

TB1 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.

TB4 - rescue robot related: 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 the TB4-rescue robot in 2011-2012 by the student researcher in 3A.2.

New TB4 - patient mover related: Energy consumption analysis of active vibration damping has been finished. Empirical study of patient transfer device (3A.3) has also been conducted in 2013.

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 were developed in 2013.

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 is being evaluated by industry. Project 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.

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:	Wayne Book, Georgia Institute of Technology Paul Michael, Milwaukee School of Engineering Andrea Vacca, Purdue University John Lumkes, Purdue University Ken Cunefare, Georgia Institute of Technology
Test bed manager/staff:	Anthony Franklin
Industrial Partners:	Hydac, Bosch Rexroth, Danfoss, Sun Hydraulics, Parker Hannifin

1. Statement of Project Goals

Since the inception of the Center, the goal of this test bed has been to study new system concepts based on throttle-less actuator technology to demonstrate fuel savings and improved performance for the large sector of construction, agricultural and forestry machinery. The test bed also served to study and demonstrate effective control strategies for complex multi-actuator systems and new human-machine interfaces, such as those which provide haptic feedback.

Dramatic improvements on fuel economy have been predicted and demonstrated on the test bed, through use of displacement-controlled (DC) actuation. Lower waste heat was also predicted after transition to DC actuation, thus maintaining acceptable oil temperatures throughout the excavator hydraulic system. Also, a study for the feasibility utilizing a novel hydraulic hybrid architecture proved that a significant reduction in engine size is possible while equaling or exceeding the performance capability of a machine. Additional fuel savings were predicted for the DC hybrid architecture over the non-hybrid DC architecture.

In this reporting period, the primary question to be answered is what are the technological barriers, solutions and potential for DC actuation and hydraulic hybrid technologies to be successful in improving fuel consumption in multi-actuator mobile machines? Task definition and functional requirements:

- Reduce engine size by 50% of standard excavator
- Maintain standard machine performance
- Improve energy savings over non-hybrid DC excavator

2. Test Bed Role in Support of Strategic Plan

This test bed supports the Center's goal to achieve a drastic improvement in efficiency of existing fluid power applications and to reduce petroleum consumption and pollution. The test bed is used to demonstrate fuel saving technologies and effective machine power management, especially for large and high power equipment. The demonstrated new actuator technology will open new applications in both large scale heavy duty machinery and robots and in human scaled applications like surgery robots or other portable devices where efficient and compact actuator technology is necessary.

3. Project Description

A. Description and explanation of research approach

Test bed 1, the excavator, has been used primarily to demonstrate potential energy savings of multi-actuator mobile machines through innovative system designs and advanced control strategies. However, the system is also very suitable for demonstrating the capabilities and performance of individual components and systems developed by projects throughout CCEFP.

The core of the test bed will be based upon the theoretical results from project 1A.2 although technologies developed as part of other CCEFP projects will be integrated onto the test bed for demonstration. The contributions are as follows:

- Project 1A.2 (Ivantysynova, Purdue):
  - Controls for optimal power management of multi-actuator DC hydraulic system

  - Design and installation of novel hybrid hydraulic system and downsizing of excavator engine
  - Reduction of hydraulic cooling power due to improved system efficiency
  - Design and installation of smart pump with integrated electronic pump controls
  - Design and implementation of energy management strategies on hybrid hydraulic excavators
  - Design of pump-switching architectures that enhance the capability of multi-actuator machines using DC actuation
  - Investigation of advanced control strategies enabling pump-switching functionality in DC multi-actuator machines
  - Investigation of system prognostic schemes for DC hybrid multi-actuator machine systems

- Project 1B.1 (Ivantysynova, Purdue): Development of next generation of highly efficient and smart variable displacement pumps
- Project 1G.1 (Michael, Milwaukee School of Engineering): Testing of energy efficient hydraulic fluids
- Project 3A.1 (Book, Georgia Tech): Tele-operation of the test bed using haptic controls and the Phantom controller
- Project 1E.2 (Cunefare, Georgia Tech): Novel energy-harvesting concept to provide power for pressure sensors
- Project 1E.2 (Lumkes, Purdue): Development of virtual variable displacement pump for the excavator low pressure hydraulic system using high speed on-off valves
- Project 1E.3 (Lumkes, Purdue): Development of a high efficiency, high bandwidth, actively controlled variable displacement pump/motor
- Project 1E.7 (Vacca, Purdue): New generation of variable displacement external gear pumps
- Project 3B.3 (Vacca, Purdue): Novel, adaptive control strategy based on extremum-seeking control for active vibration damping.

B. Achievements

Achievements prior to reporting period

- Four variable displacement pumps were installed on TB1 (mini-excavator) along with associated sensors and electronic control hardware. All eight functions were displacement controlled, and the test-bed was instrumented with required electronics (sensors and control hardware) for data acquisition and control. Working actuator and pump controls were implemented by Spring, 2010.
- Following system simulations, performance measurements made on the test bed demonstrated 50% energy savings, 40% fuel savings, 17% reduced cycle time and 69% productivity improvements over the standard, load sensing hydraulic system for an aggressive, digging cycle (August 2010) during independent, side-by-side testing done by Caterpillar.
- A simulation model predicted that installed cooling power in the system could be reduced by 50%, due to removal of control valves and subsequent elimination of heat generated due to throttling.
- A power management algorithm was evaluated for the non-hybrid DC excavator prototype, and fuel efficiency results showed a 56.4% improvement for a lighter duty cycle such as a pipe-laying cycle for an excavator.
- As part of 1A.2, a feasibility study in simulation predicted that a novel hybrid hydraulic architecture (called the DC series-parallel (S-P) hybrid excavator, Figure 1) allows meeting aggressive digging cycles with a 50% downsized engine. In this study, a conservative, rule-based power management approach was used (called ‘single-point’ strategy) and this showed 20.4% savings in fuel over the DC non-hybrid (51% over the standard) excavator.
- Another rule-based strategy (called the ‘minimum-speed strategy’) that attempted to exploit all available system degrees of freedom, showed higher fuel savings over the DC hybrid (25.4% fuel savings over the DC non-hybrid), and was closer to optimal power management results (26.8% more efficient than DC non-hybrid) from dynamic programming.

Achievements during the reporting period:

Integration of Series-Hybrid Swing Drive to Test-Bed 1

Figure 1 shows the novel DC S-P hybrid excavator architecture. Braking energy from the excavator's cabin rotation can be recovered and stored in a hydraulic accumulator through use of a variable displacement, over-center swing motor, and such a configuration does not need additional pumps on the engine shaft. The primary unit of the series-hybrid swing drive can charge or discharge accumulator and when appropriately controlled, is responsible for enabling up 50% engine downsizing in this architecture.

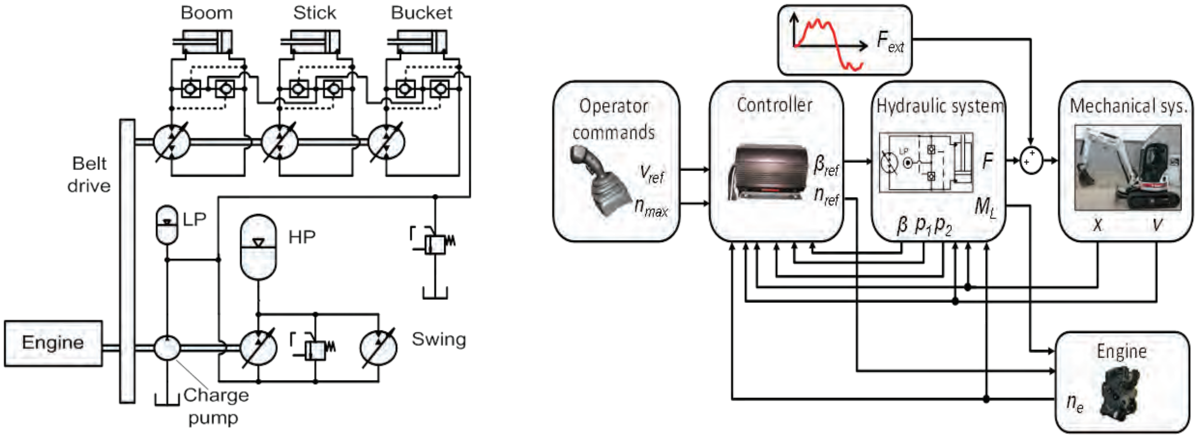


Figure 1: Series-Parallel Hybrid DC Excavator System (L) and Detailed System Model (R) used in Simulation

A detailed co-simulation model used to capture system dynamics (including all hydraulics, mechanics and engine dynamics), as well as evaluate power management strategies by predicting energy and fuel consumption. In Figure 2, are shown the key components integrated into the excavator to integrate the series-hybrid swing drive. Note that the engine was not actually downsized on the prototype excavator.

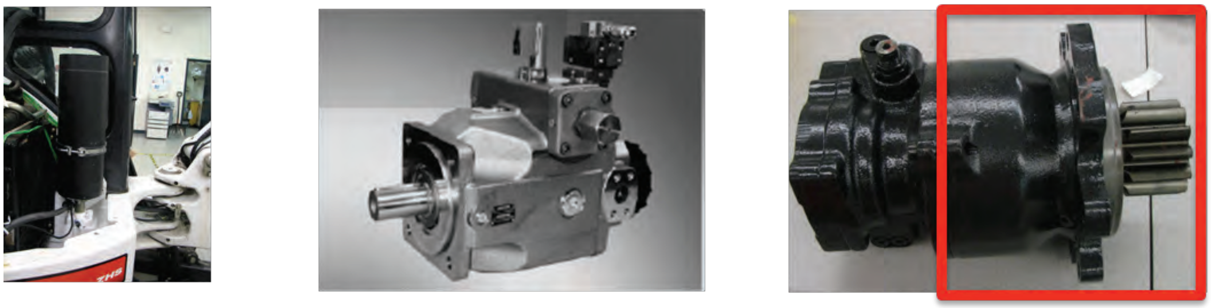


Figure 2 : Hybrid System Integration (L to R : accumulator, variable swing motor and new gearbox)

Closed-Loop Speed Control for Secondary-Controlled Swing Motor

In the left-half of Fig. 3, the control scheme is shown for the motion control of the swing motor. In essence, the swing drive is closed-loop speed controlled when the operator commands motion from the swing drive, whereas it is closed-loop position controlled when no motion is commanded. When motion is commanded, the speed-control strategy must account for varying accumulator pressures (needed for efficient system operation), and it does so through a feed-forward term. It also accounts for varying inertia of rotation, by using information from linear position sensors on the boom, stick and bucket.

Good tracking of speed commands was shown in measurements (top-right) in Figure 3, together with tracking of displacement commands for the swing motor (bottom-right).

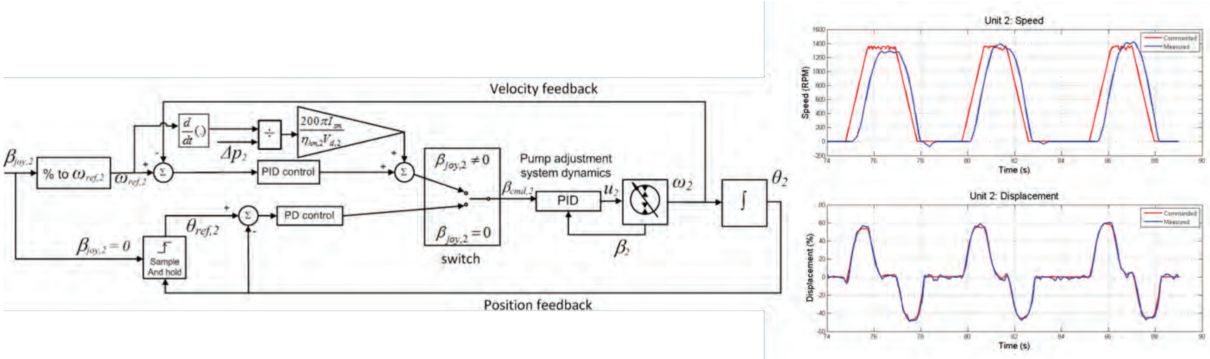


Figure 3 : Closed-Loop Speed Control for Secondary-Controlled Swing Drive

Single-Point Strategy for Power Management: Measurements

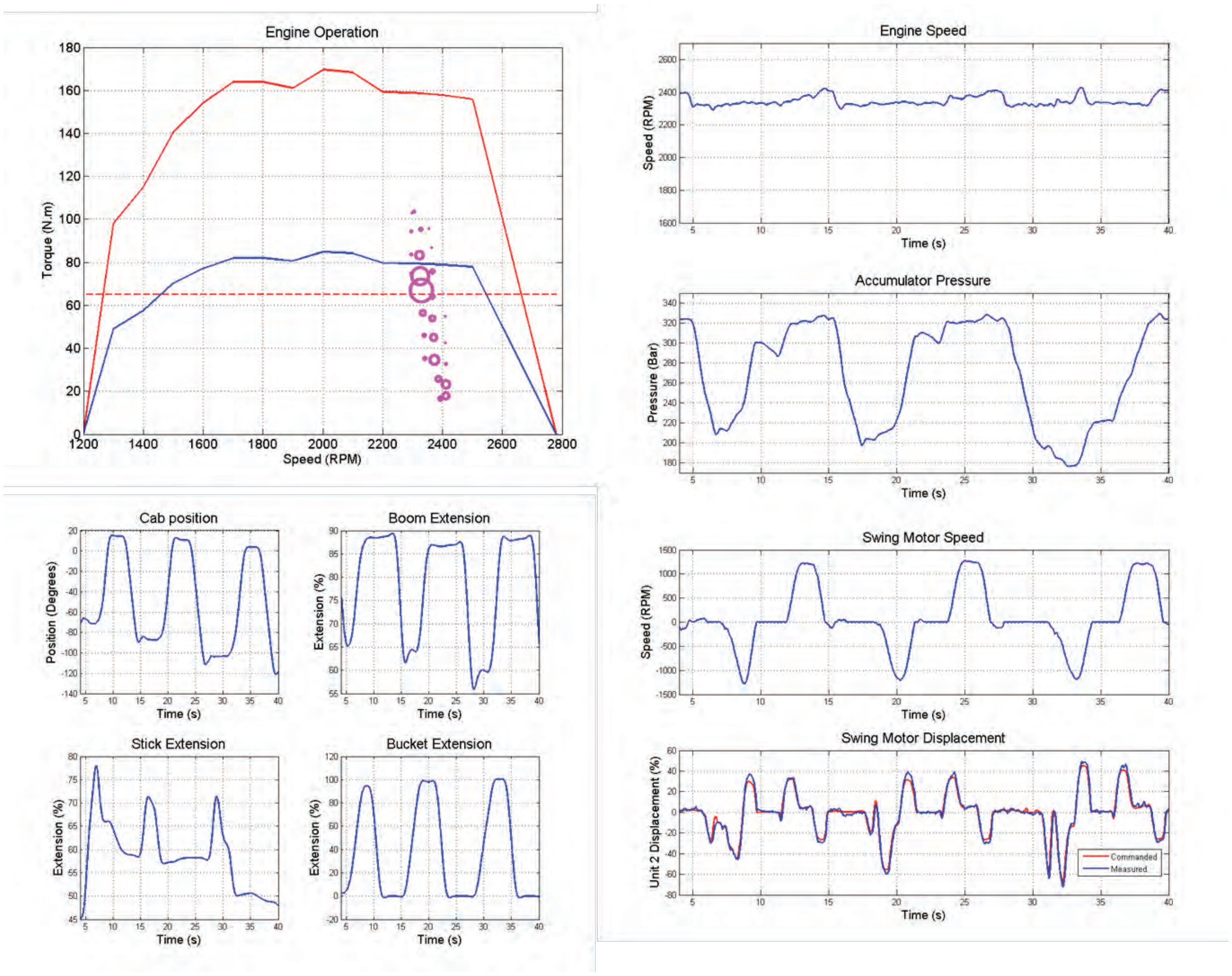


Figure 4 : Measurement Results – Single-Point Strategy

Figure 4 shows measurement results using the single-point strategy, from October, 2013. The full-sized engine is operated close to the sweet-spot of the downsized engine (by control of the primary unit through appropriate rules), and close to the maximum rated engine speed. The excavator was put through a 90-degree, novice digging cycle. The accumulator pressure is high for more than 50% of the time, because of the conservative nature of this strategy.

Minimum-Speed Strategy for Power Management: Measurements

Figure 5 shows measurements made with the minimum-speed strategy as the excavator was put through a 90-degree digging cycle. This strategy led to consistently lower accumulator pressures (bottom-right) than the single-point strategy. Good tracking of engine speed commands is also shown (top-right). For these experiments, it was desired to keep the engine below 25 kW (maximum power is 40 kW) the constant-power contour (due to the high inertia of the full-sized engine on the prototype, as compared to the inertia of a 50% down-sized engine (20-kW rated power)).

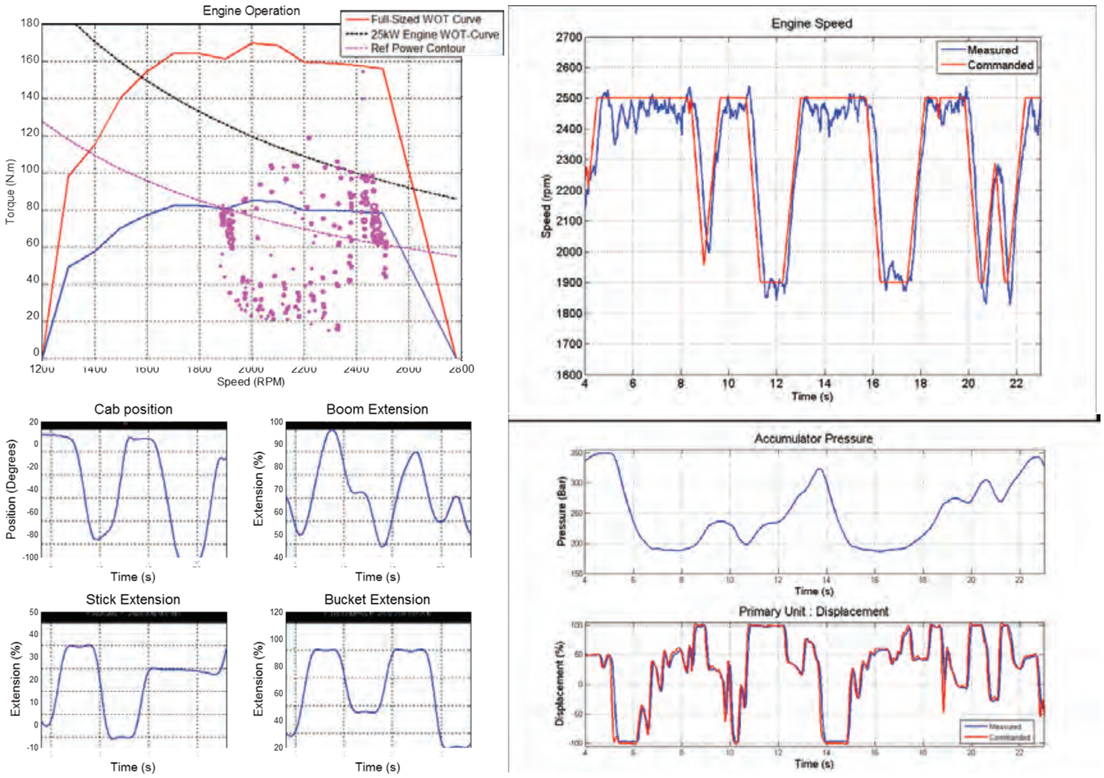


Figure 5: Measurement Results – Minimum-Speed Strategy

Planned Achievements following the reporting period:

- Conduct on-vehicle experiments. Deliverables include:
  - Demonstration of pump-switching technology on TB1 [Fall, 2014]
  - Implementation of enabling control strategies for pump-switching architectures [Spring, 2015]
  - Incorporation of system prognostics schemes [Fall, 2015]

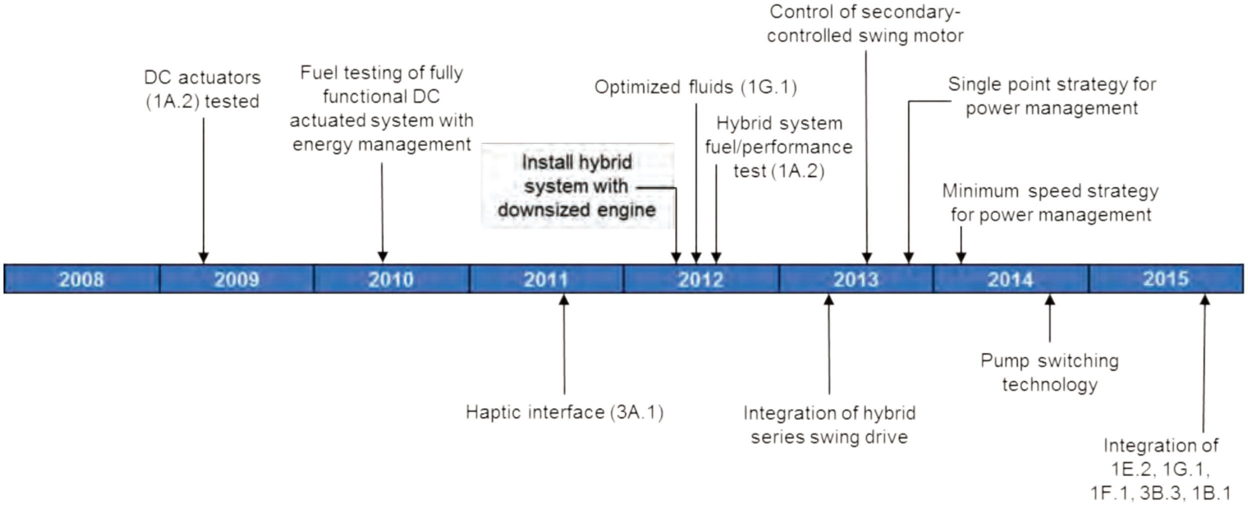
- Demonstration of technologies from other CCEFP projects. Deliverables include:
  - Integration of high speed valves to create a virtual variable displacement pump for low pressure system and measurements of energy savings (1E.2) [Summer, 2015]
  - Comparison of energy consumption of TB1 using standard hydraulic oil and energy efficient fluids developed (1G.1) [Summer, 2015]
  - Implementation of adaptive control strategies for active vibration control (3B.3) [Fall, 2015]
  - Integration of variable-displacement external gear pump (1F.1) [Fall, 2015]
  - Integration of next generation of efficient pumps for control of a single actuator (1B.1) [Spring, 2016]

C. Member company benefits

The results gained from TB1 are directly transferable to industry and have already offered benefits to member companies. Some of these benefits include:

- Test bed 1 provides a usable displacement controlled actuator prototype that can be evaluated and tested by industry members. This saves them much time and money compared to if they were to build prototypes themselves in order evaluate the potential of displacement controlled actuation hydraulic systems
- 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 technologies being developed in this project will help OEMs meet upcoming US emission regulations.
- With future work that is intended to implemented on TB1, the capabilities of DC hybrid multi-actuator machines will be enhanced through realization of novel pump-switching architectures.

Test Bed 1 Technology Integration



Test Bed 1 Milestone Chart

The excavator test bed has served 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 (1A.2). Investigation of hybrid series swing drive was finished in 2013. Various power management strategies have been investigated. The pump switching technology will be tested in 2014 and the prognostic system will be tested in 2015 (1A.2).

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 Li, Mechanical Engineering, University of Minnesota
Other Faculty:	Thomas R. Chase, Mechanical Engineering, University of Minnesota
Graduate Students:	Tan Cheng, Kai-Loon Cheong, Zhekang Du
Undergrad Student:	Andrew Harm
Industrial Partners:	Bosch-Rexroth, Eaton, Parker Hannifin, Danfoss and others

1. Statement of Test Bed Goals

The overall goal of this project is to realize hydraulic hybrid powertrains 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) 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 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, especially since the 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 are not as well studied as other hydraulic hybrid architectures. Power-splits combine the positive aspects of a series and parallel drive train. This test bed is currently developing two hydraulic hybrid passenger vehicles, 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 an F-150 pickup truck, which has refined vehicle dynamics capable of highway speeds. Its power-train utilizes a custom-built continuously variable power split hydraulic transmission developed by FTI which will be complemented with hydraulic accumulators to enable 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. Also, the transmission is not optimally sized for hybrid operation and presents some control restrictions when operated in hybrid modes. Therefore, the “Generation 1” vehicle is being continued despite the pending availability of the roadworthy “Generation 2” vehicle.

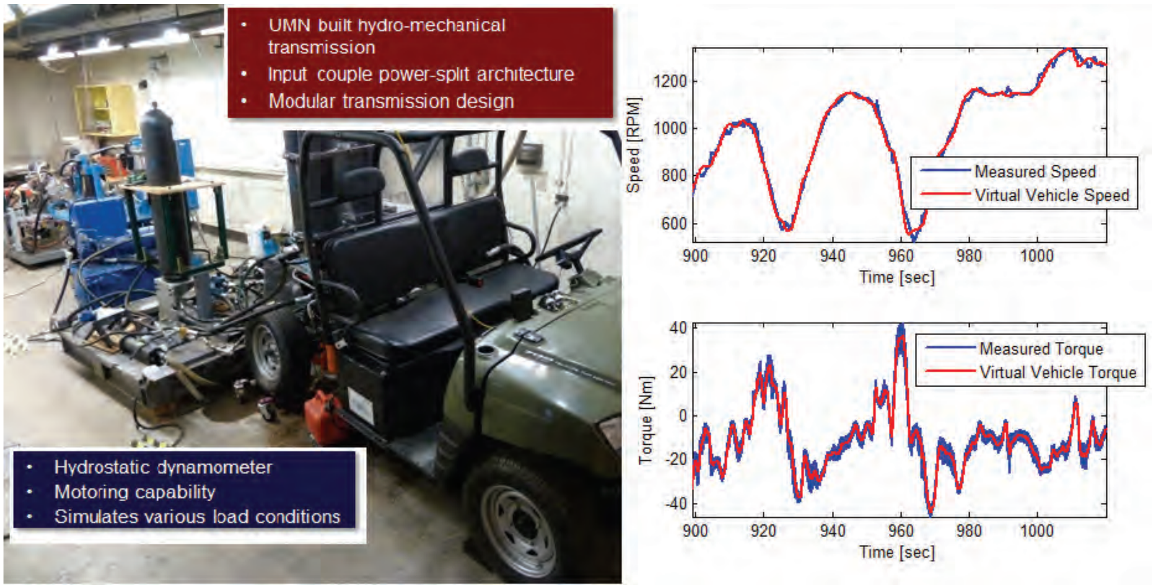


Figure 1: Overview of Test Bed 3 HHPV Generation 1 with hydro-static dynamometer. The graphs on the right illustrate the effectiveness of the dynamometer in fuel economy evaluation.

B. Achievements

Achievements Applicable to the Generation 1

Recent years' major achievements:

(i) *Drive train rebuild:* The first hydraulic hybrid transmission was completely rebuilt to use only gears to transmit power to and from the hydraulic pump/motors to improve its efficiency and reliability.

(ii) *Hydrostatic dynamometer system design and implementation:* An in-house hydrostatic dynamometer was designed and constructed in 2011-2012. The dynamometer enables repeatable fuel efficiency evaluation and eliminates the need to drive the vehicle on a test track. It also enables fine-tuning controllers rapidly. A novel controller was implemented to enable the dynamometer to exert the desired torque on the vehicle output shaft. It utilizes a "virtual vehicle" concept to account for the vehicle's inertia torque.

(iii) *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. The new engine was characterized using the in-house hydrostatic dynamometer.

(iv) *General chassis improvements:* The charge flow system was rebuilt to substantially improve the system efficiency. A hydraulic circuit to facilitate start-up of the vehicle was developed. The vehicle chassis was entirely re-wired, resulting in better robustness and data acquisition quality.

Major achievements in year 2013:

Transmission CVT mode tests: With the hydrostatic dynamometer operational, the vehicle has undergone a series of performance and fuel economy evaluations. Two types of experimental efficiency evaluations were conducted: steady-state condition and drive cycle schedules. In this section, the hydraulic hybrid powertrain operated in Continuous Variable Transmission (CVT) mode, which will be used to set baseline performance. In CVT operating mode, the accumulator is maintained at a constant pressure, so it is essentially not utilized. Figure 2 depicts the steady-state efficiency of the power-split transmission operated in CVT mode as a function of output power. The highest overall powertrain efficiency recorded is approximately 23% at 10kW output load. The transmission was operating at 80% efficiency at this point. The

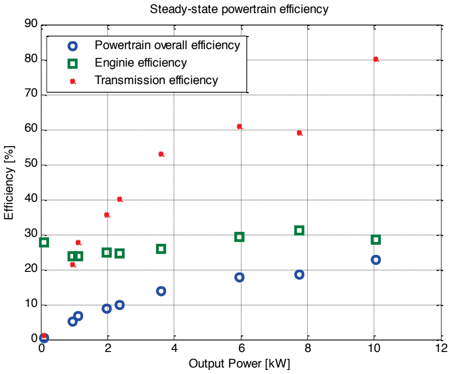


Figure 2: UMN-built power-split transmission steady-state efficiency in CVT mode.

general trend shows increasing efficiency with increasing output power. While the engine was operated at relatively steady efficiency, the transmission efficiency is reduced drastically at low load (below 4kW) due to power recirculation.

The powertrain is driven through EPA UDDS and highway drive cycles, using the hydrostatic dynamometer, to evaluate the fuel economy. Figure 3 shows the tracking performance and repeatability of the vehicle-dynamometer system, with approximately 1mph standard deviation tracking error. The tests yield 50 mpg for the UDDS cycle and 62 mpg for the highway cycle.

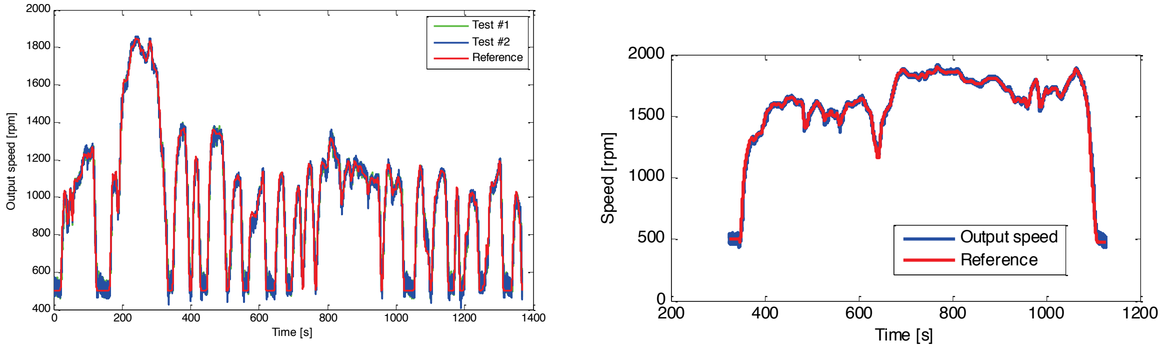


Figure 3: UDDS (left) and highway (right) drive cycle tracking

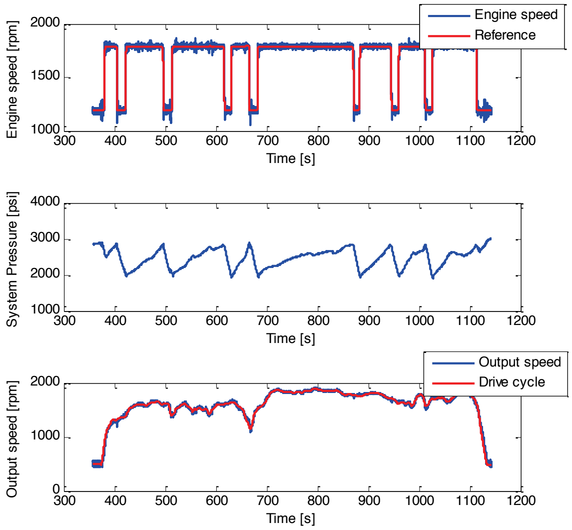


Figure 4: Hybrid powertrain operated with rule-based strategy in highway drive cycle

Energy management strategy implementation: Various algorithms developed in Project 1A.1 are being incorporated into the high level control for the hydraulic hybrid vehicle and evaluated with dynamometer testing. The first strategy, rule-based, has been successfully implemented for the highway drive cycle, with fuel efficiency of 3% improvement compared to CVT strategy. The hybrid powertrain behaved as predicted in simulation as shown in Figure 4. Testing of other algorithms are in progress.

Powertrain and dynamometer control systems: Three core controllers have been designed and successfully implemented on the vehicle-dynamometer system to obtain consistent and reliable drive cycle test results. Firstly, the hybrid powertrain controller utilizes the three-level hierarchical strategy developed in previous years. Secondly, the dynamometer controller, completed this year, applies a novel “virtual vehicle” concept to exert correct load on the vehicle based upon the torque applied by the power-train. Lastly, the “virtual driver” controller is designed to eliminate the need of an actual driver during drive cycle tests.

Improving efficiency: During early test runs, output torque was found to be lower than anticipated. The cause was identified to be lubrication oil being pumped within the gearbox. By lowering the oil level, the gearbox viscous friction has been reduced by 44%. Several internal hydraulic leakages have also been identified and corrected. Pressure and temperature sensors were added while the transmission was torn down to enable improved testing of energy efficient fluids.

Dynamometer Hardware and Electrical Upgrades: A flywheel has been installed to modestly increase the inertia. This reduces the sensitivity of the system to high frequency disturbances and as a result, leads to significant improvement in the vehicle load tracking performance. High dynamic bandwidth can still be achieved. A portion of the electrical system has also been re-wired to improve the actuation of the pump/motors and reliability.

Achievements Applicable to the Generation 2

Recent years' achievements

Transmission Characterization: A method has been developed to determine the FTI transmission efficiency map under various hybrid operating conditions given limited data. This map is necessary for proper design of the vehicle operating strategy. Preliminary transmission characterization tests revealed significant leakage which was attributed to broken seals. The seals were subsequently replaced.

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.

Current year achievements

The FTI transmission has recently been re-installed on the F-150 at Folsom. With help from Ford, a signal conditioning and data acquisition system for interfacing with the vehicle and transmission has been constructed. Hardware-in-the-loop testing is near completion at UMN and will soon be installed on the vehicle.

C. Plans

Plans for Generation 1 Vehicle

Plans for the Generation 1 vehicle will focus on core project integration and are described in order below. Hybrid operation will be tested with various energy management strategies. Both the modified Lagrange multiplier strategy and Project 1A.1's Rule-based control strategy are currently in progress. The more complex Stochastic Dynamic Programming (SPD) and Model Predictive Control (MPC) algorithms developed in Project 1A.1 will be implemented and tested in Summer 2014

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. The new oil will be compared with a baseline shear stable high viscosity index hydraulic fluid on the vehicle in Fall 2014.

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. 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 (Fall 2014)

Strain energy accumulators are designed to provide the advantage of constant pressure operation, thereby improving its energy density. 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 (Spring/Summer 2015)

Plans for Generation 2 Vehicle

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 architecture. After the Generation 2 vehicle is fully functional, a continuous variable transmission (CVT) strategy and hybrid strategy will be tested. The current plan is to house it at FTI in New York where they will take the role of maintaining, housing the vehicle and for providing hardware support. The TB3 team will then visit FTI five times and Ford once, each time for several days for implementations. As schedule for the visits is as follows:

- Visit #1: Implement computer interface with vehicle, gain access to engine and transmission control inputs, gain access to vehicle and transmission measurements. [3/14]
- Visit #2: Perform system identification (for vehicle control). [4/14]
- Visit #3: Low level vehicle control implementation and tuning. [8/14]

- Visit #4: Implementation of two high level control strategies: CVT and mild hybrid (regenerative braking, launch assist, CVT). [10/14]
- Visit #5: Implementation of full hybrid operation and prepare vehicle for dynamometer testing. [12/14]
- Visit #6 (Ford, Dearborn): Dynamometer testing of CVT, mild hybrid and full hybrid operations. [5/15]

Plans for Generation 3 Vehicle

Generation 3 powertrain will target a mid-sized sedan (Toyota Corolla or Honda Civic). The goal is to apply the knowledge gained from Gen 1 and Gen 2 development and design a power train that fits the need for a passenger vehicle. In addition to efficiency, there will be focus on driving performance and compactness. Designing a new platform, however, requires substantial amount of resources and support from industry. Hence collaboration with OEMs plays a vital role to the success of Generation 3. By the end of Y9/Y10, partnership with a transmission manufacturer, a hydraulic company, a fluid specialty manufacturer and a kit-car manufacturer is expected. Before the hardware development stage, the conceptualization and design stage can be separated into three stages:

- Phase 1: In search of partnership with industrial OEMs. [6/1/15]
- Phase 2: Identify and determine the powertrain requirements and components. [12/1/15]
- Phase 3: Simulation and design of transmission and components integration to achieve all thrusts. [5/31/16]

Milestones and Deliverables

Generation I:

- Task 1: Compare the effectiveness of various energy management strategies. Candidates include algorithms developed in Project 1A.1 (Model Predictive Control, and Stochastic Dynamic Programming), and the modified Lagrange multiplier method developed by the TB3 team. [11/14]
- Task 2: Baseline Generation I vehicle performance by running it through the EPA urban drive cycle in continuously variable transmission (CVT) mode using mineral oil based hydraulic fluid. Evaluate performance of biodegradable synthetic hydraulic oil using identical drive cycle and mode. [8/14]
- Task 2a: Design and install a fluid conditioning system to improve transmission efficiency. Necessity of this stage will be determined by fluid condition measured during Task 2, and initiated if deemed essential. [9/14]
- Task 3: Performance evaluation of the 4 quadrant Virtually Variable Displacement Pump/Motor (VVDPM) under HIL test (1E.1) [3/15]
- Task 4: Testing of strain energy accumulator (2C.2) [6/15]
- Task 5: Passive noise control implementation [6/15]

Generation II:

- CVT and Mild Hybrid Control strategy demonstrated in Generation 2 vehicle [10/14]
- Hybrid Control strategy demonstrated in Generation 2 vehicle [12/14]
- EPA cycle fuel economy evaluated [5/15]

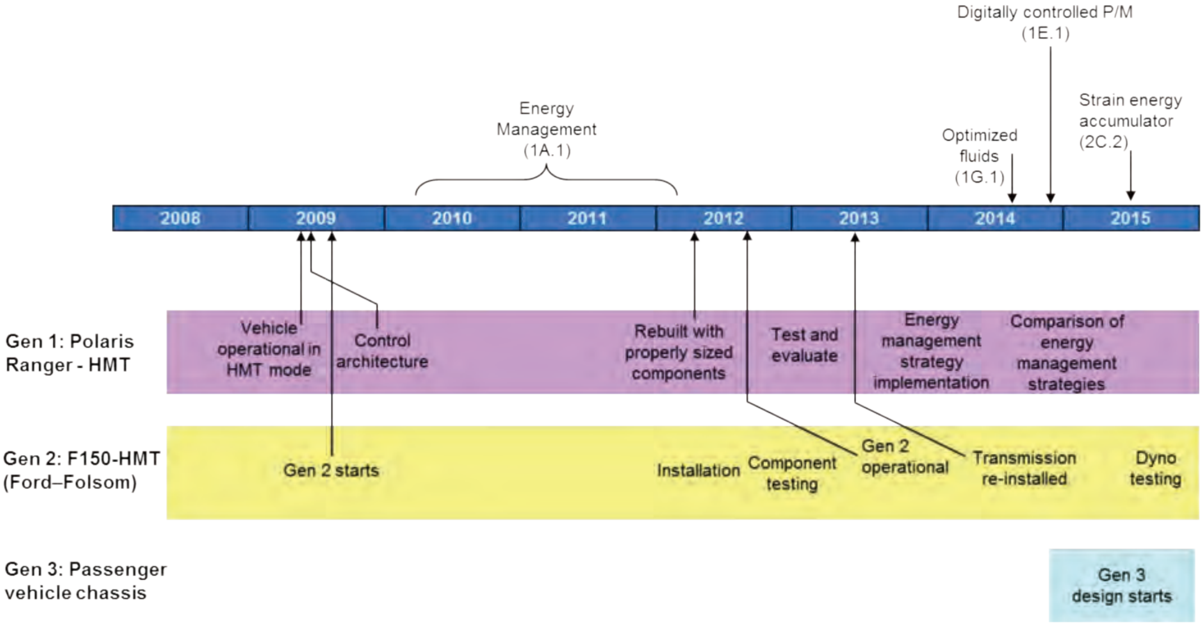
Generation III:

- Initiation of Generation 3 powertrain conceptualization and design [6/15]

D. 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.

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 Polaris ranger 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 commercially available, but over-sized 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, components were redesigned and optimally sized. A redesigned drivetrain 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. Continuously variable transmission (CVT) operation was tested on the hydraulic dynamometer in 2013. Various energy management strategies have been implemented.

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

- The effect of two hydraulic fluids on fuel economy will be tested in 2014. (1G.1)
- Various energy management control algorithms that have been designed will be tested in 2014. (1A.1)
- The rotary spool-valve based virtually variable displacement pump/motor will replace the bent-axis “speeder” P/M and undergo testing in 2014. (1E.1)
- A strain-energy storage prototype will be installed and tested in 2015. (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. A control approach similar to Gen 1 will be implemented and tested in the future.

A Gen 3 passenger vehicle chassis is desirable to demonstrate the potential of the hydraulic hybrid technologies, but its development 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
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 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/swing (3B.3), multi-modal human machine interfaces (3A.1), user-centered design (3A.3), the hydraulic transformer (1E.5), and potentially others.

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.

3. Project/Test Bed Description

E. Description and explanation of research

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, (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.

F. Achievements

Achievements in previous years

In previous years, much of the needs assessment was conducted, including interviews with a range of stakeholders, including mobility limited patients, clinicians in various settings, and industry representatives. From this information, a first set of design requirements was developed, and a subsequent high level device design concept was developed. A hydraulically actuated exploratory pre-prototype device was used to obtain additional design requirements, to gain experience with transfer operations, and to test control strategies using a force sensing handle.

Achievements in the past year

Needs Assessment

A substantial needs assessment and involvement of collaborators with expertise in a range of areas was performed. In the area of assistive device research, our advisors include Dr. Stephen Sprigle, of Georgia Tech’s Center for Assistive Technology and Environmental Access, Dr. Rory Cooper, of the Quality of Life Technology Engineering Research Center (QoLT ERC). We obtained two IRB approvals, one for a focus group and individual interviews, and one for benchmark operator testing using current market lift devices. Our focus group and individual interviews included a range of outside stakeholders, including (1) engineers and salespeople with current market lift manufacturers, (2) clinicians and physical therapists in nursing homes and the Shepherd Center, (3) home caregivers of spinal cord injury patients including one bariatric, and (4) spinal cord injury patients. We have also worked with our collaborators in the human factors area Dr. Park, Dr. Jiang and Brittney Jimerson, with North Carolina A&T (NCAT) on the evaluation of current market lifts, task analysis, and operator experiment design. Brittney from NCAT provided a very detailed task analysis, helped to develop a subsequent benchmark operator testing protocol, and helped run those operator experiments with current market lifts, which involved performing a variety of mannequin transfers within a simulated home environment. The results of this needs assessment were combined and transformed into functional design requirements, such as necessary motions, lifting capabilities, and battery life.

Machine Design and Design Review Meeting

Based on the functional requirements and experiments with an exploratory pre-prototype lift device, we developed a set of lower level design requirements, and we analyzed a variety of options for mechanisms, actuation, hydraulic and electric power. We computed the necessary power, force/torque and speed for each mechanism option, then determined associated flow and pressure needs. We opted for a form of electro-hydraulic pump control, using a separate hydraulic power unit for each DOF. We also investigated options for onboard electric power, controllers, sensing, as well as other analyses such as weight, stowable size, and battery life.

A design review meeting was held at Georgia Tech in May 2013, in which we discussed the design options, analyses, and proposed device. A range of interests and expertise were represented in the meeting, including assistive device design experts Dr. Stephen Sprigle from Georgia Tech and Dr. Rory Cooper from the QoLT ERC, systems design specialist Dr. James Van de Ven from UMN, design engineer for a leading lift manufacturer Mr. Scott Gregory, NCAT human factors PhD student Brittney Jimerson, and research engineer and hydraulics and fabrication specialist James Huggins from Georgia Tech.

The current design has two DOF currently functional, a main lifting mechanism and a boom extension (Figure 1). The lifting utilizes a scissor lift actuated by a hydraulic cylinder and the boom uses a timing belt and sprockets actuated by a hydraulic motor. Each DOF is powered by a Parker OilDyne hydraulic power unit, which includes a reversible DC motor, a bidirectional gear pump, and a reservoir. Onboard power is from two 12V deep cycle batteries in series. Sensor data acquisition, processing and control algorithms are implemented using a National Instruments Compact Rio (cRio). The cRio provides a control signal to an Advanced Motion Control servo drive for the electric motor, operated in current control mode.

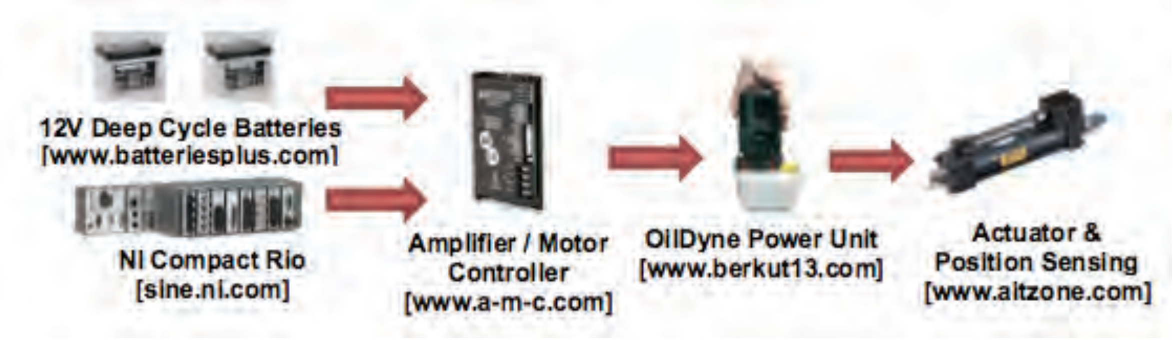


Figure 1: Power and Actuation for Each Degree of Freedom Using Electro-Hydraulic Pump Control

Fabrication and Testing of First Prototoype

Two primary DOFs of the prototype patient transfer assist device have been fabricated and are fully functional and untethered, the main lifting and boom extension; the device is currently on an unpowered mobile base with casters, and a pair of differential drive wheels are being added. The patient rests in a sling suspended from a hanger bar, similar to the patient interface of a current market lift. Operator control from a force sensing handle mounted near the patient has been implemented, as well as software control. All electrical and hydraulic power components, controllers, sensors, and signal processing are onboard. The current prototype is shown in Figure 2. While the current prototype is bulkier than desired, this is only for providing modularity and simplicity in the prototype design; it can easily be optimized to fit in a much more compact package.

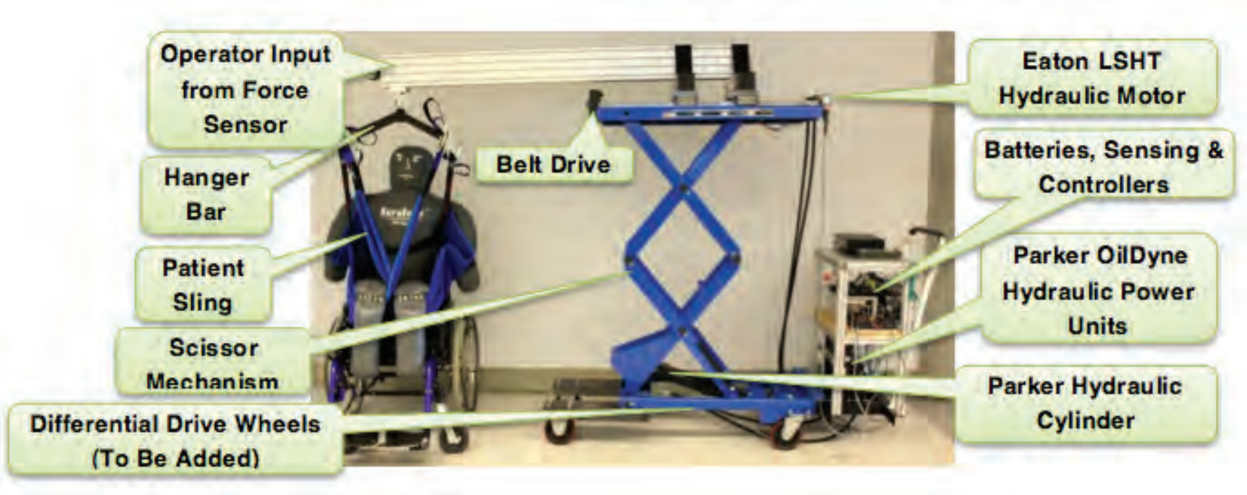


Figure 2: Current Prototype Patient Transfer Device

Control and Caretaker Interface Design
A first step toward an advanced operator interface strategy was implemented on one DOF of a valve-controlled exploratory pre-prototype device, a passivity based human power amplifier control algorithm, an extension of the algorithm developed in graduated CCEFP project 3A.2. Advantages of this strategy are that it provides a balance of tradeoffs between rate control and force control, way to manage environmental interaction forces, and provides safety and stability. It utilizes a virtual mass and the compressibility of the fluid to provide some compliance and achieve force- and velocity- coordination with the operator input, and it provides a form of haptic information on external and load forces. This form of control was implemented on one DOF of the exploratory pre-prototype device.

As a first step on the new prototype device, basic rate control using the NI Compact Rio, servo drives, and position sensor feedback was implemented in two degrees of freedom. The device can be controlled from a force sensing operator input handle mounted at the end of the arm, near the patient, which includes a multi-axis force/torque sensor. As for the low level control, the electric motor and hydraulic pump lead to a highly nonlinear plant; one challenge is to obtain desired dynamic response while managing overall slow plant dynamics, nonlinearities such as pump “stiction”, and switching required for the series wound motor.

G. Plans

Plans for the next year
Control and Caretaker Interface Design
Control algorithms to be tested include collaborative manipulation strategies that allow for management of interaction forces, low level electro-hydraulic pump control, and other features to make the operation more intuitive. Approaches to achieve force/rate control, add compliance and manage interaction forces include further development of the passivity-based human power amplifier control to work with the electro-hydraulic pump control system, as well as impedance/admittance control. The intuitiveness features include methods to mitigate undesirable effects and allow the caretaker to focus more on the patient, such as preventing tipping, managing base/arm kinematic redundancy, managing environment interaction forces, compensating for patient swing/oscillation, and mitigating any effects of the machine dynamics interacting with the operator biodynamics. Further testing will be required to determine which features are most needed. For preventing tipping, several approaches have been investigated, including a model predictive control method implemented on the previous version of Test Bed 4, the Compact Rescue Crawler, as well as an online moment computation method used on mobile cranes. A wide array of approaches have also been used to manage swinging/oscillation, including the vibration control approach used by Dr. Vacca in project 3B.3. Versions of passivity based control, tip-over stability control, and oscillation compensation are all graduated or current CCEFP projects to be implemented on Test Bed 4. Additionally, a new, more accessible and ergonomic force sensing operator input device will be designed and implemented.

Machine Design and Modeling

Several features will be added to this prototype. First, a dynamic simulation including the mechanical system with patient payload, hydraulic and electrical systems will be completed. Also, a set of differential drive wheels will be added to the base, utilizing the same electro-hydraulic pump controlled system as the other degrees of freedom, actuated by hydraulic wheel motors. Additional sensors such as pressure and force are needed for various control strategies. Also, an improved, more ergonomic and easily accessible force sensing operator input device will be designed and implemented. We are making the machine and software designs as modular as possible, to enable integration of CCEFP subsystem projects. An actuated variable base width or shape modification may also prove to be a useful additional degree of freedom.

Human Operator Studies

Once the first control system design is complete, a set of human operator experiments with a mannequin will be performed, along with statistical analyses of the results. Experiments will include full transfer operations, using a protocol similar to the benchmark testing that NCAT helped to develop, as well as subtask experiments aimed at testing individual controller and device features.

Longer Term Vision

In future years, this test bed can provide a system in which to test additional subsystem and component technologies, as they further develop. Alternative operator interface designs developed by collaborators at NCAT can be tested. Alternative hydraulic system architectures may also be tested. The needs assessment indicated that several additional actuated degrees of freedom would be helpful, but they are beyond the scope in the next year. These include a patient sling rotation, swing/rotation with respect to the mobile base, and base geometry adjustments.

Expected milestones and deliverables.

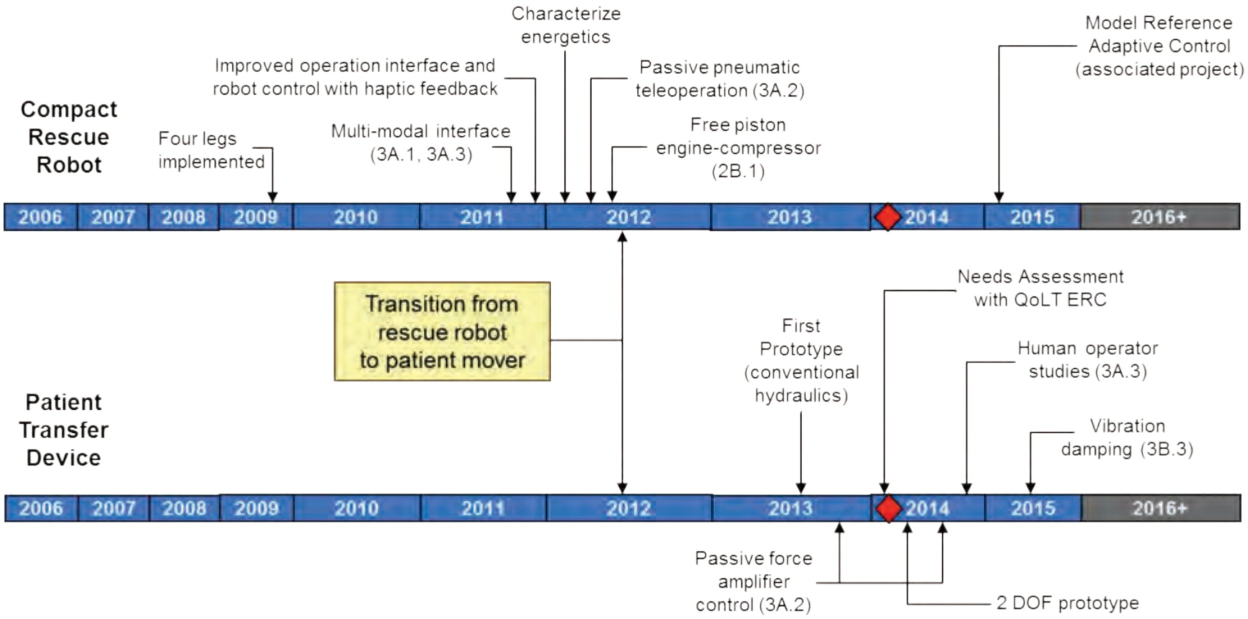
Milestones:

- Differential drive wheels tested [Month 3]
- Dynamic simulation model validated [Month 4]
- Preliminary testing with control strategies implemented in simulation and hardware completed [Month 10]
- First round of human operator studies [Month 12]

H. Member company benefits

This project provides several potential benefits to member companies. It responds to a significant market need where fluid power technology can be utilized, thus providing an opportunity 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 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:

- Passive force amplifier control (2013) for inherently safe human-machine interaction (3A.2)
- Human centered design and operator studies (2013) for intuitive operation of multiple degrees of freedom (3A.3)
- Active vibration damping (2014) for smooth control that limits exposure of forces to the patient (3B.3)
- Hydraulic transformers (2014) for efficient operation (1E.5)

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. The test bed also presents a unique opportunity for two ERC's to work collaboratively.

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

Research Team

Project Leader:	Elizabeth Hsiao-Wecksler, MechSE, UIUC
Other Faculty:	Will Durfee, ME, Minnesota Geza Kogler, Applied Physiology, Georgia Tech
Graduate Students:	David Li, Morgan Boes, Mazharul Islam, Matt Petrucci, UIUC Jicheng Xia,, Brett Neubauer, UMN
Undergraduate Students:	Katie Neville, Chenzhang Xiao, Jay Sung, Zack Block, Lela DiMonte, UIUC; Souransu Nandi, National Institute of Technology in Durgapu, India ; Kathleen Fitzsimmons, Jon Nath
Industrial Partner:	Parker Hannifin

1. Statement of Test Bed Goals

The goal of test bed 6 (TB6) is to drive the development of enabling fluid power technologies to:

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

(2) 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 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 testbed 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 testbed goals.

2. Test Bed Role in Support of Strategic Plan

The test bed addresses the Center's compactness goal through the creation of miniature fluid power systems that push the practical limits of weight, power and duration for compact, untethered, wearable fluid power systems. The test bed also addresses the goal of making fluid power ubiquitous by creating human-scaled fluid power devices to assist people with daily activities and creating new market opportunities for fluid power, including medical devices.

3. Test Bed Description

A. Description and explanation of research approach

Problem Statement: 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.

Challenges: 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 <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.

B. Achievements

Portable Pneumatic AFO (PPAFO) UIUC

In 2010, the first generation portable powered ankle-foot orthosis (PPAFO) was constructed to demonstrate device feasibility. The Gen1.0 PPAFO is an improvement over state-of-the-art passive and active systems because it provides subject-specific motion control and torque assistance without tethered power supply or electronics. The device can provide modest dorsiflexion (toes-up) and plantarflexion (toes-down) torque actuation at the ankle. Two U.S. patents on the technology embodied by the PPAFO have been filed; co-inventors are CCEFP students and faculty from the U Illinois, U Minnesota, Georgia Tech, and MSOE.

Figure 1 Pneumatic elastomeric accumulator

We have improved the efficiency, compactness, control, usability, and possible applications of the PPAFO. Using a commercial pneumatic rotary actuator located lateral to the ankle joint (originally from SMC, currently from Parker Hannifin) and a canister of compressed CO_2 at the waist to serve as a placeholder for a more compact actuation systems and power source, the Gen 1.0 PPAFO can generate up to 12 Nm at 100 psig with run times less than 30 minutes with a 20 oz. bottle. Theoretical and experimental component and system efficiencies of the PPAFO system suggested an overall efficiency of 19% based on calculations from the product of component (50%) and system (39%) efficiencies. That analysis also suggested that the exhaust gas from the higher pressure plantarflexion actuation (100 psig) could be captured into an accumulator and then recycled to power the lower pressure dorsiflexion actuation (30 psig). Working with students at Vanderbilt on Project 2C.2 (strain energy accumulator), a pneumatic elastomeric accumulator was constructed for use with the regenerative pneumatic circuit that was tested during walking tests (Figure 1). In 2013, the effect of two control algorithms on fuel efficiency was investigated. It was found that, by increasing the net work output, a more intelligent, state estimation controller improved the fuel efficiency by 72% as compared to a basic, direct event controller with the regenerative circuit. With the use of the state estimation controller and the regenerative pneumatic circuit, the run time of a 9 oz bottle was expanded to 19 minutes from an original 15 minutes.

To address compactness, we have focused on the development of pneumatic ankle actuation systems with higher torque output (target: 50Nm @ 120 psig) than commercially available. It was realized that the compact integrated rotary actuator developed by MSOE in 2010 would not be a viable design (max capable 50psig for 6 Nm). In 2011, work began with CCEFP industry partner Parker Hannifin to utilize their expertise in pneumatic rotary actuators to design a custom product. This work stopped in fall of 2012 due to Parker work priorities. We have sponsored ME capstone design teams at Bradley University. The current team is optimizing a new pneumatic linear actuator and gear train design. In 2012, a lighter and less complex structural shell design for the Gen 2.0 PPAFO was developed, which will allow for swapping of modular system components (Figure 2). The weight of the PPAFO went from 1.86 kg to 1.60 kg. In 2013, multiple sized (S, M, L) foot and shank bilateral shells to support testing on a variety of sized test subjects were received. These designs allowed us to start testing on a variety of test subject sizes and begin clinical trials on various patient populations.

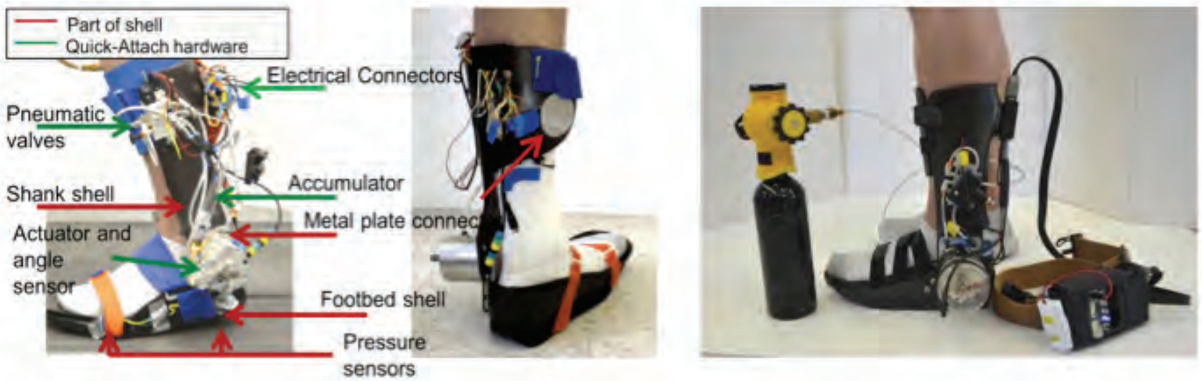


***Figure 2** Gen 2.0 PPAFO. Left, Middle: Includes elastomeric accumulator, revised valving, and new shell without metal struts or medial side. Modular hardware can be swapped between different sized shells. Right: PPAFO with belt-worn controller box and CO2 power supply.*

To address control of the PPAFO across a variety of walking environments (level ground, stairs, ramps), different actuation-timing control strategies, solenoid vs. proportional control, and recognition and control for different gait modes were examined. The initial controller for level ground walking was a simple direct event threshold-based control using just the heel and toe sensors. To better accommodate impaired gait, a model-based state estimator controller was developed that also added the angle sensor. We examined how work and fuel use were affected by these two 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 performance compared to solenoid valves; however due to the large size of commercially available proportional valving systems, inclusion of proportional control on the PPAFO has not yet been implemented. These results highlight technological barriers to compact fluid-powered orthoses due to low torque actuation and large valves. In 2011, work began 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% on average. It was determined that only stair or ramp descent require a different control scheme than level ground or stair/ramp ascent, and differential gait mode control has been implemented. Although having a high identification success rate, the use of a single IMU still resulted in a one-step delay in control actuation of the PPAFO. Further work is ongoing to eliminate this delay.

In 2011, CCEFP faculty and students at NCAT began development of two user interfaces: (1) a clinician user interface for tracking patient medical history and therapy progression, and (2) an interactive game interface (using a serious gaming approach) to be used by the patient while using the PPAFO as a joy stick as part of a seated rehab therapy. In collaboration with researchers at the Rehabilitation Institute of Chicago, we have begun testing the advantages of the PPAFO compared to a range of other assistive devices (tibial stimulators, and commercially-available passive AFOs) in post-stroke and multiple sclerosis subject populations. In an associated project with collaborators at the Parkinson’s disease and 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. A pilot study on healthy young adults provided insight into the feasibility of this application, and preliminary data collection with people with Parkinson's began in 2013.

Hydraulic AFO (HAFO) UMN

The research objective of the HAFO project within TB6 has been to understand the capabilities and limits of small-scale hydraulics. The research motivation of the project has been the need for small, light, untethered, wearable robots. The development objective of the project was to create an untethered HAFO that meets demanding specifications. The results of the project have been a better understanding of hydraulic systems at small scale from a theoretical perspective and the creation of a physical prototype that is the highest power, untethered AFO.

A key part of our work has been system and component level modeling to predict the efficiency and weight of hydraulic systems. Simple physics was used to model components and the models were validated with experimental data when needed. For example, a simple model was used to determine the leakage and friction of an o-ring seal, important because o-rings are the most logical choice to seal pistons and rods at tiny scales. The models showed conclusively that the practical limit on component size is efficiency. For example, the efficiency of a cylinder with bore of the cylinder. Below about 4 mm bore, practical systems become highly inefficient. Additional models showed that at small sizes, it can be more efficient to use gap rather than o-ring seals. Modeling the efficiency and weight of components for a motor plus transmission compared to a conduit plus cylinder system led to a useful result about system design. For a 100 W system, if the hydaulic solution is to be lighter than the electromechanical solution, the hydraulics must be run at high pressure so all of our prototypes are designed to run at 2000 psi.

With the computational models informing the design, we determined that the best system architecture is a power transmission chain that is battery > motor controller > DC electric motor > tiny hydraulic pump > hose > cylinder > linear-to-rotary transmission > ankle torque. We also determined that the best configuration is to place the power supply at the waist and the cylinder at the ankle with thin hoses as the interconnect (Figure 3). The power supply is complete while the powered ankle component is being fabricated. 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. The University of Minnesota will file a provisional patent application for the HAFO in February, 2014 and an NIH R21 application has been submitted to use the HAFO as an AFO emulator in a project to optimize fitting of AFOs to children with cerebral palsy.

Figure 3: HAFO prototype with waist-worn power supply (left) and ankle component (right).

Simulation of the complete system showed that position control is possible while providing joint torques that mimic walking. The system simulation also showed the importance of the oil as mineral oil, our preferred choice for this application, can trigger control instabilities at transition points of the gait cycle because of its viscosity and bulk modulus properties.

Plans, Milestones and Deliverables for Next Year

PPAFO: Complete longevity assessment of PPAFO with additional healthy test subjects to verify robust operation. Continue to work with Bradley University to develop new actuation system. Perform clinical trials on use of PPAFO on post-stroke, multiple sclerosis, and Parkinson's populations. Investigate new control schemes. (Spring 2014). Implement new higher torque output pneumatic actuation system on PPAFO. Demonstration of HCCI engine with PPAFO (Summer 2014). Initial evaluation of MEMS proportional valve on PPAFO (Fall 2014)

HAFO: Complete version 0 of prototype AFO, validating operation to 2,000 psi (Spring 2014). Complete first controller for HAFO: position-based walking controller (Summer 2014). Evaluate alternative fluid power circuits. Preliminary design of custom pump (Fall 2014).

Plans, Milestones and Deliverables for Next Two-Five Years

PPAFO: We will demonstrate the PPAFO on two different applications and will seek external funding to support extended clinical research. To achieve these goals, we will conduct the following tasks:

- Task 1: Technology improvements: Increase the efficiency of power consumption, improve torque to weight and torque to size performance, and integrate a compact power source and a proportional MEMS valve. Integrate MEMS valve and Stirling engine. Milestones: Integrate custom actuator into PPAFO [May 2014]; Integrate HCCI engine into PPAFO [Summer 2014]; Integrate MEMS proportional valve into PPAFO [October 2014]; Integrate Stirling engine [January 2015].
- Task 2: For a walking assistance application, design and implement control, including neural network state estimation and gait mode recognition. We will also explore energy harvesting from the biomechanics of walking to aid with improving system efficiency. Milestones: ANN integration (computer driven) completed [May 2014]; Gait mode recognition and actuation without one-step delay completed [May 2015]; Concepts for energy harvesting completed [December 2014].
- 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 2014]; Initial integration of clinician and patient user interfaces with PPAFO [September 2014]; Torque and rotational velocity control completed [March 2015]; Demonstration of post-stroke therapy [May 2015]

HAFO:

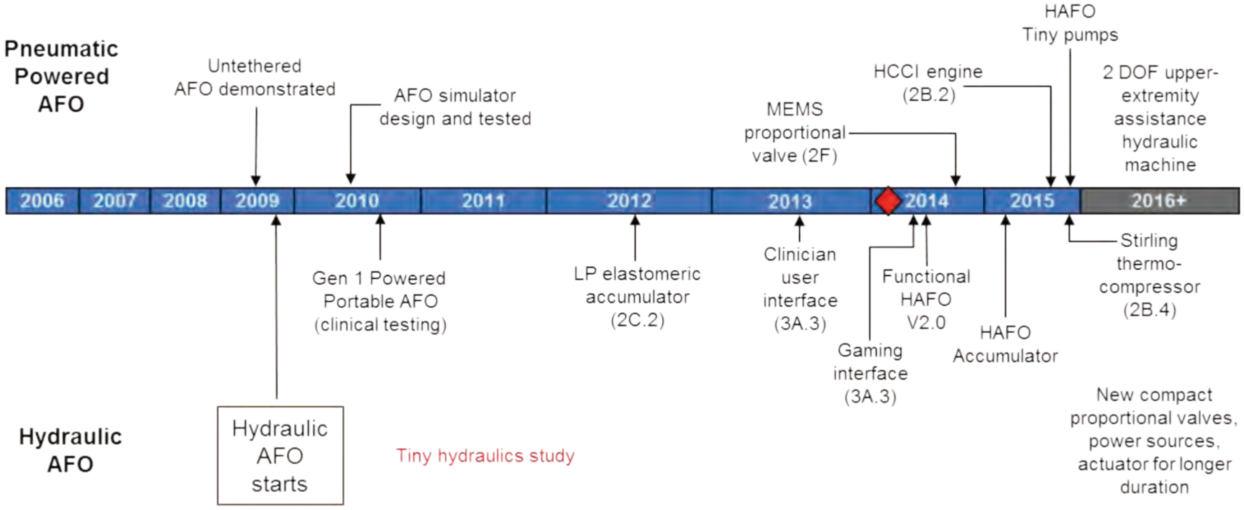
- Task 1 --Fluid Power Circuits, Control Algorithms and Fluids: Examine alternative circuits in simulation and experiments and will assess for size, weight and efficiency. Deliverables: Simulations and experimental data from several circuit, control algorithm and fluid realizations. Publication reporting findings. (Sept 2014 – May 2015).
- Task 2 --Tiny Pumps: Fully understand the pump requirements for the HAFO, and then examine system level trade-offs using simulation. Design and fabricate a custom pump that matches the application.. Designing our own pump means we can explore component integration in the power supply to further reduce size and weight. Deliverables: Multiple prototype pumps. Simulation and experiment testing for performance. Publication reporting findings. (January 2015 – December 2015).
- Task 3 -- Using an Accumulator to Handle Power Burst: Determine through simulation and experimentation how to optimize energy storage in an accumulator to handle the power burst that occurs at toe-off. Adapt the strain energy accumulator developed in CCEFP project 2C.2 for use in our application. Consider super-capacitors to store energy on the electrical side instead of the fluid side. Deliverables: HAFO with energy storage. Simulations and experimental data with results. Publication reporting findings. (January 2015 – December 2015).
- Task 4 --Two DOF Upper-Extremity Assistance Machine: Extend our findings to a system of greater complexity. A two degree of freedom upper extremity wearable assist machine is an appropriate configuration for beginning to examine issues where fluid power actuation needs to be coordinated. The machine will be targeted for repetitive tasks where human judgment is required, for example package handling or fruit harvesting. This extension to the test bed will also enable pilot data to be collected that can be used for submitting research proposals to NSF and NIH. Deliverables:

Simulations of configurations. Working prototype that has been evaluated for task use by a human operator. Publication reporting findings. (June 2015 – May 2016).

C. Member company benefits

New technologies that miniaturize current components such as power sources, actuators, and valves will be developed. 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 was targeted to be a pneumatic device. In 2009, a version using tiny hydraulics was added because of its ability to achieve the required compactness.

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

- A clinician-centered user interface was implemented in 2013, a rehabilitation game interface for patients will be implemented next. (3A.3)
- The compact MEMS proportional pneumatic valve will be tested in 2014. (2F)
- The micro HCCI free-piston engine-compressor will be tested as a power source in 2015. (2B.2)
- The controlled Stirling thermal-compressor will be tested as a power source in 2015. (2B.4)

A hydraulic version of the AFO is also 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 2014, tiny pumps in 2015, tiny accumulator by the end of 2015, and a full two DOF upper-extremity assistance machine 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 educators and program leaders for new audiences; and to leverage and coordinate the accomplishments of individual Education and Outreach projects to facilitate the progress and successes of other Education and Outreach 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.

Organization: The EO program is divided into thrusts, each containing several projects, which address these four objectives. Some projects are focused on STEM education with examples drawn from fluid power when appropriate, while other projects are specific to fluid power technology and its application.

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 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. Some of these efforts are conducted through the offices and programs at each of its seven universities, while others are realized through the work of the Center's affiliated organizations, including NSBE, LSAMP, and AGEP institutions. The CCEFP staff coordinates other efforts.

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 current state of the Center's diversity portfolio is promising and encouraging. Efforts in this area are paying dividends, although there is still work to be done. The vast majority of center affiliates are US Citizens or Permanent Residents, so we will focus on those.

Women – Representation is near or above national averages in all categories. It is notable that 35.3% of Undergrad Non-REU and 41.2% of Undergrad REU students are women as compared to 18.9% nationally. 11% of Center faculty are women, while 27% of the Center's Leadership Team is female.

Racial Minorities – The CCEFP greatly exceeded national averages in nearly all categories. We are particularly pleased with the percentage of Undergrad Non-REU and REU students who are racial minorities, 47.1% and 29.4%, 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 (9.1%), and graduate students at the doctoral level (12.5% domestic students, 11.5% foreign students).

Hispanic/Latinos – Numbers of Hispanic/Latinos and persons with disabilities remain small, although represented at the graduate and undergraduate level. The Center is eager to continue to support the students who have been recruited, while taking steps to address the recruitment of Hispanic and Latino/a personnel.

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 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. While most projects are specific to fluid power education, there are some that focus on STEM education, with examples drawn from fluid power when appropriate. 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 Curriculum	Culture of Research and Ed Integration
Thrust A: Public Outreach **Bringing the message of fluid power to the general public**				
A.1 Interactive Exhibits Fluid Power	x	x		x
Thrust B: Pre-College 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.3 Hands-on Fluid Power Workshops	x	x		
B.4 gidaa STEM Programs	x	x		
B.5 BRIDGE Program	x	x		
B.7 NFPA Fluid Power Challenge Competition	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
C.2 Fluid Power College Level Curriculum	x	x	x	x
C.3 Fluid Power Projects in Capstone Design Courses	x	x	x	x
C.4 Fluid Power in Engineering Courses	x	x	x	x
C.5 giiwed'anang North Star Alliance	x	x		x
C.6 Fluid Power Simulator	x	x	x	
C.8 Student Leadership Council (SLC)	x	x		x
C.9/10 Research Diversity Supplement (RDS)	x	x		x
C.11 Innovative Engineers (IE)	x	x		x
Thrust D: Industry Engagement **Making connections between CCEFP and industry**				
D.1 Fluid Power Scholars/Interns	x	x		x
D.2 Industry Student Networking	x	x		x
D.5 CCEFP Webcasts Series	x	x		x
Thrust E: Evaluation **Measuring CCEFP program effectiveness**	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. (Project D.2)
- **Curriculum and Courses** - The CCEFP is leading the effort to develop new, and to modify existing courses with fluid power content based on CCEFP research and is making substantial modification to curriculum in CCEFP universities, which will help to create a cadre of highly skilled students who will become future fluid power industry professionals and future engineering faculty, by integrating fluid power into existing curriculum, including mini-books and creating curriculum modules. The University of Minnesota was recently awarded the first Massive-Open-Online-Course 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.3 and 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 goal 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 as well. To date, more than 145 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 revising the CCEFP REU program structure in 2008, the CCEFP REU Program has recruited, on average, over 35% women, and over 33% 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** - Eighteen enthusiastic REU students conducted research in CCEFP labs at the Center's six of the seven universities during the summer of 2013. REU students participated in the Center's third Fluid Power Boot Camp for REUs at Purdue University, June 2013. To date, 148 REU students have participated in Center research. (Project C.1)
- **Student Retreat** - The 2013 Student Retreat was held in Joliet, IL at Caterpillar, Inc., a corporate member of the Center. The two-day event featured an orientation to the company, a tour of the manufacturing facility, a tour of the assembly facility, a trip to the Caterpillar, Inc. museum and a Joliet Slammers baseball game with Cat engineers. The event was a huge success and offered a blend of social activities, insight into a fluid power company, and a face-to-face meeting of SLC members and industry members. Plans for the 2014 Student Retreat are underway. (Project C.8)
- **CCEFP-GEM Partnership** - The ERC-GEM-Industry partnership model has been developed and implemented. The specialized membership model includes cooperation between the ERC and the Industry member, who are both academic and corporate members of the National GEM Consortium, and who jointly sponsor the ERC GEM Fellow. The GEM Fellow receives over $150,000 in financial support in the form of an academic student stipend, tuition remission, and summer intern salary. This rich collaboration offers nothing but benefits to the GEM Fellow, the ERC, the Industry member, and the GEM Consortium. The first GEM-ERC Fellow, Mr. Oscar Pena, was named for Fall 2013 under Professor Michael Leamy at Georgia Institute of Technology. The CCEFP submitted an informal proposal to NSF and was invited to discuss the program, in person, November 2013. NSF ERC leaders were strongly supportive and agreed to provide supplemental funding to extend the CCEFP's pilot program into another year. The formal proposal to NSF will be submitted by end of month, March 2014. (Project C.10)
- **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. (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 17 travel grants to CCEFP graduate students in the first year of its launch. This program has proven to be very popular among students and faculty. (Project C.8)
- **Webcast Special Topics by Industry Experts** - A proposed expansion of the Center's popular webcast series includes special topics discussions led by industry experts. (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 hosted the event in the fall of 2013, recruiting six schools, sponsoring 19 student teams, and exposing over 80 students to fluid power technology. Several industry corporate sponsors served as judges of the event. It was a highly successful collaboration between CCEFP and NFPA. (Project B.7)
- **gidaa Robotics** - The gidaa Robotics Program, with activities near the Fond du Lac Indian Reservation, continues to emerge as a stellar after-school outreach program of the CCEFP. Over 60 elementary, middle, and high school students participate each year and has expanded into two additional neighboring schools. The new South Ridge School infrastructure was designed to accommodate the robotics program and now the school day course is part of the school's regular core curriculum. The Robotics Teacher Training lead by CCEFP teachers helped to launch a new sister program at a second middle school in the local area. (Project B.4b)
- **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)
- **Parker Hannifin Chainless Challenge** - Since 2011, four of the seven CCEFP institutions have participated in the Parker Hannifin Chainless Challenge - an engineering design competition for undergraduates to design and build the most efficient and effective human-assisted green energy vehicle. Over 15 undergraduate students participate in Chainless Challenge competitions each year, one of which was selected as a Fluid Power Scholar in 2013. The CCEFP, in partnership with Parker Hannifin, is increasing the number of fluid power educated individuals entering the industry.
- **Research Diversity Supplement** - The CCEFP is committed to promoting the increased participation, recruitment, and retention of diverse undergraduate and undergraduate students in engineering. To do so, the Center has launched a Research Diversity Supplement Program to support undergraduate and graduate students in fluid power. To date the CCEFP has supported nine undergraduate and five graduate students. (Project C.9 and C.10)
- **Fluid Power Scholars** - The Fluid Power Scholars Program is in its fifth year. To date, 30 high-performing undergraduate engineering students completed a fluid power boot camp followed by a full-time summer internships at CCEFP member companies. Since 2010, 67% of Scholars have been hired into the fluid power industry, and their host company has hired 47%. The FPScholars program is experiencing a re-vamp, which includes a more efficient intern-selection process. The results of this work will be evident after June 2014. (Project D.1)
- **RET** - Four RET participants conducted research in CCEFP labs. 46 RETs have participated since the Center's launch. The CCEFP is the only ERC to have RET-designed curricula published to the NSF website, TeachEngineering.com, a repository of STEM curriculum. Three fluid power lesson modules are available. (Project B.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, and 2) Create a culture that integrates research and education for undergraduate and graduate students across all partner institutions.

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 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:

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 positive outcome from industry's point of view as well. The CCEFP is pleased to announce it being the recipient of an NSF REU Site Award for three years, a $390,000 grant! More than 145 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 revising the CCEFP REU program structure in 2008, the CCEFP REU Program has recruited, on average, over 35% women, and over 33% 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.

Fluid Power Scholars Program:

The Fluid Power Scholars program compliments the REU program. Despite the challenged economy, the program was successfully launched in 2010 with continued support in 2011, 2012, 2013 and is underway for 2013. Thirty scholar/interns were named during the program's first three years and plans call for naming ten more in 2014. All scholars/interns participate in an intensive fluid power orientation followed by an exceptional summer internship experience within a fluid power company. To date, 63% 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. Successes 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.

A change is underway with the Fluid Power Scholars Program. Over the years, several companies asked if they could name their "Fluid Power Scholar" from existing leadership intern programs within their company, or otherwise utilize their own hiring infrastructure and systems to recruit and employ the intern they would name as the "Fluid Power Scholar". It has become clear the procedures the Center had established (posting a position electronically, recruitment, application process, etc.) were laborious for all parties involved (Center staff, company staff, company human resources, student applicants). It was also clear the original procedures were not the element of the program that industry needed the Center to provide. What the Center could offer, in which companies could not, was a short fluid power training program. In fact, the "rigmarole" was actually a deterrent for some companies, as they had to create a "special" process to hire a fluid power scholar. Thus, the Center has eliminated the efforts of providing the recruitment of students and asked companies to utilize their own infrastructure to recruit, identify and hire their intern, which will be named the CCEFP Fluid Power Scholar. Instead, the CCEFP recruits the companies to commit to hiring one or two interns to be named Fluid Power Scholars and provide the sponsorship to the MSOE fluid power training workshop.

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 highlighted as one the CCEFP intends to expand post-NSF years.

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. To date, 17 travel grants of up to $1000 each have been issued to CCEFP graduate students to work collaboratively with other research teams or companies. Five project grants have been issued to perform outreach or internal collaboration of CCEFP students. The SLC issues calls for proposals quarterly and the CCEFP expects to continue meeting these needs of the students.

Capstone Design Projects: In Y7, the CCEFP Education and Outreach program initiated a supplemental funding program for faculty across the CCEFP who wish to advise and mentor a capstone project in fluid power. In this reporting year, two projects have been granted supplemental awards resulting in more than 25 undergraduate engineering students gaining direct experience in fluid power. Additionally, the EO Program provided a $6,000 grant (3rd year of funding, EO Project C.3a) to Elizabeth Hsiao-Wecksler at UIUC to host a joint fluid power capstone project with Bradley University. The CCEFP will now formally support the Parker Hannifin Chainless Challenge Competition - an engineering competition for university students utilizing fluid power to propel a bicycle. Four teams have been advised at CCEFP institutions - Purdue University, Milwaukee School of Engineering, University of Illinois, Urbana-Champaign, and the University of Minnesota. In the future, the CCEFP expects to work with NFPA to promote capstone design projects in fluid power to its member companies. In recent years, NFPA board members committed to sponsoring fluid power capstone projects; likely CCEFP industry members may be interested in the same. A process will be developed whereby CCEFP faculty or staff would facilitate matching CCEFP and NFPA companies with interests in sponsoring a project to the appropriate engineering program, either within or outside the CCEFP network. The Parker Chainless Challenge is a national inter-university competition sponsored by Parker Hannifin, a corporate member of the CCEFP. The competition requires that a team of undergraduate students design and build a bicycle that uses fluid power as its main method power transmission. The competition includes three race events: a distance race, a 200 m sprint race, and an efficiency challenge during which only stored energy can be used to power the bicycle. Points are also awarded for design innovation, manufacturability, workmanship and marketability among other categories. In addition, the student teams are judged on a written report and presentation. Three universities represented CCEFP in the 2013 Chainless Challenge competition that was held in Irvine, CA, in April 2013. The University of Illinois at Urbana-Champaign took first place overall in the competition and teams from Purdue University and the University of Minnesota also participated.

Integration of Fluid Power into Core Curriculum: The Fluid Power College Level Curriculum (Project C.2) 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. In Year 8, 2 new courses were offered, seven courses modified with content resulting from the work within the CCEFP. To date, 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 Y8 highlight of significant achievement: Professors James Van de Ven and William Durfee will be offering 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 will introduce students to the fundamental principles of fluid power systems, circuits, and components. Students will learn: 1) the benefits and limitations of fluid power compared with other power transmission technologies, 2) the function of common hydraulic components, 3) how to formulate and analyze models of hydraulic components and circuits, and 4) how to design hydraulic circuits for specific system requirements. The course will be delivered through short, focused video presentations that will 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 will be first offered during the fall of 2014.

Professor Jim Van de Ven, University of Minnesota, continues to lead efforts to develop undergraduate and graduate fluid power curriculum. Preliminary plans and actions for fluid power curriculum design and dissemination include:

- Continue to encourage the incorporation of fluid power content into existing courses throughout the Center.
    - The Fluid Power College Level Curriculum project makes it easier for instructors within and outside of the CCEFP network to include college-level fluid power material in their course.
    - Encourage competition throughout the Center to develop additional mini-books. Those in development are a Fluid Mechanics module, a Hydraulic Fluids module, and a module on Systems Engineering in Fluid Power Applications. Plans are underway to update and revise the Fluid Power System Dynamics mini-book.
    - Utilize multiple modes to increase the digital repository content of the OpenCourseWare site; various online access points to the products of the Center’s research and education impacts.
    - Funding has been set aside for new curriculum module initiatives in Y9.
- Encourage CCEFP faculty who are teaching core undergraduate classes to write and present papers on infusing fluid power modules into existing mechanical engineering classes (system dynamics, fluid mechanics, and thermodynamics) in the education sections of technical conferences. Encourage participation by providing travel support to authors.
- Publicize presentations among technical conference colleagues to increase exposure.
- Increase awareness of digital repository among industry members through distribution of a brochure at meetings.
- Encourage CCEFP member schools to include fluid power in list of ABET outcomes for related core mechanical engineering courses (system dynamics, fluid mechanics, and thermodynamics).

The Center is very pleased that the ratio of Graduate to Undergraduate students who are involved with the CCEFP has reached a low value of 0.8 during the current reporting period (table 3b). This welcome result is due to the increasing number of undergraduate students involved with CCEFP programs. This ratio is well below ERC averages. The large number of undergraduate students who are 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.

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**	**An Outstanding Achievement**	**Current Employment and Contributions to the Field**
Tim Deppen University of Illinois at Urbana-Champaign PhD, May 2013	Won the 2013 Cozad New Venture Award Finalist for Entrepreneurial Excellence - Student Startup in the Champaign County Innovation Celebration Semi-finalist for the 2013-2014 Student Startup Madness	**Servabo Inc. and John Deere** *Co-Founder and Dynamic Systems Simulation Engineer.* As a co-founder of Servabo, roles range from product design and development to business strategy creation, marketing, and contract negation. The goal of the company is make people safer by leveraging innovations in technology. Directly apply knowledge of vehicle modeling and controls to advance John Deere simulation and system analysis capabilities.
Venkat Durbha University of Minnesota PhD, December 2013		**Eaton Corporation** *Hydraulic Design Engineer.* Designing and modeling of hydraulic subsystems in developing projects. Developing control strategies for the hydraulic subsystem to meet the target specifications.
Kyle Merrill Purdue University PhD, August 2012		**Parker Hannifin** *Engineer.* The CCEFP increased my capability to work across different disciplines and across different countries. I am working in research and new product development of hydraulic piston pumps and motors.
Meghan Miller Milwaukee School of Engineering M.S., February 2013	Co-author on manuscript published in Tribology Transactions with Paul Michael	**ExxonMobil** *Test Engineer.* Developing and testing industrial lubricants and greases.
Roxanne Moore Georgia Institute of Technology PhD, August 2012	Engineering really cool cakes.	**Georgia Tech** *Postdoctoral Fellow.* Write engineering curriculum for Georgia middle and high school classrooms, observing the classes, and training teachers to teach the courses. Quantitatively model K-12 education settings to better understand why different school interventions succeed or fail. Partnering with a local high school teacher to bring an invention competition to several Georgia high schools, modeled after Georgia Tech's InVenture

		Prize. Teach a sophomore-level design class in Mechanical Engineering.
Jonathan Meyer University of Minnesota PhD, 2014		**Bosch-Rexroth** *Control Systems Engineer.* Developing software and controls for off-highway mobile systems such as construction and agricultural machinery. On a team developing new model-based design tools that will be used for the design and development of software and controls for new projects. Lead person responsible for hardware-in-the-loop testing of the controls before implementation on the physical system.
John Tucker Vanderbilt University M.S., December 2012		**Laird Technologies** *Technical Support Engineer.* Assist customers and coworkers with any technical questions or issues. Working with a wide range of products centered around improving electronic performance though EMI reduction. Provide cost estimation of modified and custom items in order to provide up to date pricing to our sales force.

Priorities for the Future

The college education program continues to focus on two priorities: 1) to infuse fluid power into the core curriculum and 2) to provide high quality research and internship experiences for undergraduates and graduate students. 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, the Research Diversity Supplement Program (C.9/10), 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.

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.

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 Y9, 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 isolate and leverage organizational strengths to achieve the greatest gains in workforce development in the fluid power industry. The organization of the Workforce Development Program would include a joint directorship by the CCEFP and NFPA, with oversight by a governing Workforce Development Program Advisory Committee, consisting of invested academic and industry representatives. A WDP team will exist in each geographic location of CCEFP (Minneapolis, MN) and NFPA (Milwaukee, WI). A CCEFP Workforce Development Program Director and team and NFPA Workforce Development Program Director and team will be responsible for program coordination and implementation in consultation with each other. Each WDP team will divide responsibilities of program coordination and implementation based on its respective roles in the various aspects of the program. 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. As an example, NFPA has proven success in marketing and communications, whereas CCEFP has proven success in student program support and development. By leveraging each organization’s strengths, the WDP 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 independent CCEFP and NFPA programs.

3.2 PRE-COLLEGE PROGRAM

The Pre-College 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. These outcomes are also served by the CCEFP outreach programs that are STEM-oriented but without a core fluid power focus. The Center is of the opinion that increasing interest in STEM fields among young students is an important first step to increase the number of students later pursuing engineering studies, some of them in fluid power.

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

Fluid Power Challenge
The Fluid Power Challenge is a design competition for eighth grade students to learn how to solve an engineering problem using fluid power. The Fluid Power Challenge Competition enables students to use concrete learning experiences with hydraulics and pneumatics to better understand concepts of design and physics, to develop mathematical thinking and problem solving skills, and to participate in team building through hands-on engineering construction. Offered at the University of Minnesota in 2009, 2012 and 2013, the Fluid Power Challenge has reach more than 300 8th grade students in metropolitan and out-state Minnesota communities. More than 18 unique schools have participated, many with Project Lead The Way curricula, and many who are technology magnet schools. The CCEFP expects to continue to host the Fluid Power Challenge, as it is a sponsored program through the National Fluid Power Association and expand its offerings to other CCEFP site locations.

gidaa robotics Program: Year 8 saw yet another expansion in the suite of education programs targeting Native American students of all ages. With support from the CCEFP, both Cloquet High School and South Ridge School offered its 10th to 12th grade students a year-long robotics course that is integrated into the school day, as well as an after-school program, tailored to grades 7-12, that meets two nights a week over the course of three months. Students in the robotics after-school program build a robot to compete in the annual RoboFest Robotics Challenge, a competition designed to promote and support STEM activities. Over 100 students participate in these two programs each year; 65% of these students represent racial or ethnic minorities, and approximately half are female. With the support of the CCEFP, South Ridge School will host its fifth annual RoboFest Competition in the Spring 2014. South Ridge School is currently the only site in the state of Minnesota to allow students to qualify for the International RoboFest Competition, held at Lawrence Technical University. Due to the successful Robotics Teacher Training held in the spring of 2012, the CCEFP now supports a sister robotics program at a neighboring high school in Cloquet, Minnesota. The program continues to expand. CCEFP has determined, however, that the program is in a sustainable phase and the support from the CCEFP will begin to decline as the new Workforce Development Program begins to take focus and CCEFP headquarters will focus on fluid power curriculum, courses and student support.

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 40 RET projects to date, and many teachers have been repeat participants. 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. Additionally, two 2013 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). Note that Professor Lumkes, along with two teachers and a number of high school students, visited Bangang in Cameroon, Africa in May 2012. Additionally, a team of RETs, faculty, graduate, undergraduate and high school students from Purdue University, participated in the outreach event "CHANGE THE WORLD Science and Engineering Fair" in Washington DC. NSF specifically invited the CCEFP to participate and demonstrate fluid power to thousands of engaged students. Lastly, Professor Lumkes is integrating the work of the RETs on curriculum with the work of the REUs on a new and more compact version of the Fluid Power Demonstrator Kit while continuing to conduct outreach to Cameroon. The RET effort at Purdue is one of a kind. In future years, Y9 and Y10, the RET program will begin to ramp down, proportionally to NSF funding.

Priorities for the Future

With the CCEFP now in its eighth year, planning for 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 the National Fluid Power Association (NFPA) to partner on public and pre-college fluid power outreach and engagement. To do this, the CCEFP and NFPA will leverage existing national partnerships, which have been established together and independently within each organization, to expose the general public, teachers, and students to fluid power and its importance in our lives. The CCEFP will strategize with the NFPA on the best modes to create such awareness, however the CCEFP will serve as a supporter role rather than a lead role in public and 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. Approximately fifty fluid power manufacturers and distributors are Center members, and time and again they have stated that the education outcomes (i.e. intellectual capital) of the Center are as important to them as are the research outcomes. These Center partners share in a common goal: that the Center will foster deep understanding of fluid power technology and its applications among its students. Toward that end, the Center is striving to provide students with specialized, research-driven education while striving to connect students with 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 full time 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 Y8, 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 undergraduate internship program to be modified and expanded in Y9.
- CCEFP Webcast Series
  - Popular on-line research seminar series on CCEFP progress, presented by students. Y8 allowed us to expand the seminar series to include guest presenters from industry.
- 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.
- Industry Advisory Board (IAB) Summits
  - The IAB meetings quarterly at each geographic hub of CCEFP institutions. Students present research updates to the IAB audience.
- CCEFP Annual Meeting
  - In the fall of 2012, the NFPA and CCEFP held their first joint meeting at UIUC. The successful event offered industry-sponsored kiosks where over 17 companies participated. The event provided opportunities for speed-meetings and resume exchanges for student attendees, which included more than 20 students from outside CCEFP schools who received travel grants from NFPA and CCEFP.
  - In the fall of 2013, CCEFP continued the trend, offered the speed-meeting/resume-exchange for industry and students. It was a grand success.
- CCEFP-Industry GEM Fellow
  - A fellowship sponsorship program found its way to fruition, leveraging the National GEM Consortium and the mutual industrial members of CCEFP, NFPA and GEM. The National GEM Consortium provides fellowships to highly qualified diverse engineering graduate students. In the program, the CCEFP and an industry member would co-sponsor the fellowship for a graduate student candidate, creating a fluid power researcher for the CCEFP and an experienced employee for the company.
  - CCEFP and GEM proposed the pilot program, in person, to NSF. A warm reception indicated NSF is eager to support this successful program, alluded to sponsorship of another pilot year within 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. In addition, the CCEFP and NFPA will hold Workforce Development Summits where students, educators, researchers, and industry experts will gather for the premier fluid power workforce development meeting in the United States.

Education Activities Matrix

	REU / Undergraduate	**RET / Teacher**	**Pre-College**	**College Education**	**Industry**	**General Community**
University of Minnesota	✓		✓	✓	✓	✓
GeorgiaTech	✓		✓	✓	✓	✓
MSOE	✓		✓	✓	✓	★
NCAT	✓	✓	✓	✓	✓	★
Purdue	✓	✓	✓	✓	✓	✓
UIUC	✓		✓	✓	✓	✓
Vanderbilt	✓		✓	✓	✓	★

✓ = In Place ★ = Future Year

As mentioned in section 3.1, the center is very pleased that the ratio of Graduate to Undergraduate students who are involved with the CCEFP has reached a low value of 0.8 during the current reporting period (table 3b). This welcome result is due to the increasing number of undergraduate students involved with CCEFP programs. This ratio is well below ERC averages. The large number of undergraduate students who are 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.

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

Industry interest in the CCEFP continues to remain high with seven new member companies joining in the past year. Perhaps more importantly, however, was the dramatic improvement in relations with the National Fluid Power Association (NFPA.org) 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 significantly more invested in helping the Center achieve sustainability. As an outcome our two organizations have reached a verbal agreement to collaborate much more closely going forward with a formal written agreement anticipated by the end of this fiscal year. As part of this agreement the two organizations will jointly share administrative, E & O and fund raising activities where it makes most sense by leveraging each organization's strengths. This collaboration is described in greater detail in the sustainability update of section 5.3.

4.1 VISION, GOALS, AND STRATEGY

The industrial collaboration vision for the CCEFP remains unchanged which is 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 communication, frequent interaction and strong relationships. It is crucial that the CCEFP continue to develop and maintain these close relationships with industry as it implements the new cooperative partnership with the NFPA. Because the CCEFP enjoys such broad industry representation it can be challenging to achieve the necessary level of engagement to ensure each member's long term commitment. To improve this engagement we plan to leverage the already well-established industry communications network and numerous media outlets of the NFPA.

Members have differing reasons for affiliating with the CCEFP. Besides the obvious pre-competitive research benefits some members are simply 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.

Our modified sustainability strategy calls for replacing our existing membership dues structure with an annual "gift" from the 501c3 NFPA Foundation to support pre-competitive research, workforce development and Center administration. The NFPA will assume the role of fund raising with support from key CCEFP member staff. With NSF approval, the revised sustainability plan calls for guaranteed annual gifts from the NFPA Foundation for the next two years that are slightly greater than the projected combined industry annual membership dues of ~$750,000. 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 and maintain critical mass. This gift amount is projected to grow each year until a minimum industry funding level for Center viability of $1.5 million is achieved. This new approach allows the Center to focus on securing additional government grants and industry sponsored research. The goal for each of these efforts is $3 million and $1 million per year respectively.

Our secondary goals are to have at least five patents applications per year, one license issued per year and more than 50% of our graduated students working in a fluid power related field. 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.

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.

4.2 MEMBERSHIP

Our industry membership grew in year eight from 40 to 45. This was a result of renewed focus on recruiting and retaining strategic members. The CCEFP industry member company logos are shown below and include representatives from across the entire fluid power value chain.

In the process of identifying strategic partners, we 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 F9/F10 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 as well. 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.

Membership Agreement

All members have signed the Center's standard Membership Agreement (MA) shown in Appendix II. The major elements covered include: membership level (Supporter, Principal and Sustaining); escalating dues based on membership level and company sales; terms and conditions regarding patent disclosures; publications; and information concerning access to intellectual property. One element that is not covered in our MA is a blanket NDA. This can be discerning with respect to inadvertent public disclosure of potential IP during Center meetings with industry present. Our approach is to assume everything presented is publicly disclosed and to regularly remind our faculty and students to exercise caution. Feedback from industry indicated that implementing any changes to the existing MA contract was not desirable to industry because of the legal effort and cost required to do so. Rather they proposed waiting until after NSF funding comes to an end. This is a major concern regarding the new partnership with the NFPA Foundation and must be addressed in the new sustainability plan rollout. Meanwhile as a compromise we plan to implement any necessary clarifying changes in a set of by-laws. Legal counsel has suggested that as long as we do not take away from the original agreement, a by-laws modification should be possible.

A tiered royalty rate is used which is tied to membership level at the time of disclosure. The membership dues levels are shown in the table below.

Member's Annual U.S. Fluid Power-Related Revenues	Annual Membership Dues		
	Sustaining Level (Platinum)	Principal Level (Gold)	Supporter Level (Silver)
Less than $25 million	$10,000	$5000	$1,000
$25 - $100 million	$30,000	$15,000	$6,000
$100 - $500 million	$80,000	$40,000	$12,000
Over $500 million	$100,000	$50,000	$15,000

CCEFP Annual Membership Dues Structure

Intellectual Property

The process for handling ERC generated intellectual property (IP) remains 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 all CCEFP members. With this overview is a notice of a web-meeting in which the PI will provide additional details about the invention. Member companies can attend the web-meeting if they have an interest in pursuing their patent rights as a CCEFP member. The other participants in the web-meeting are the technology transfer officer from the University and the ILO.

- During the web-meeting, the member companies attending are provided a deadline by which they must declare their interest in participating in the pursuit of a patent for the invention and sharing the costs.
- If a Member elects not to exercise its option to participate in the pursuit of a patent, or decides to discontinue the financial support of the prosecution or maintenance of the protection, the Member shall have no rights in the invention.
- If only one Member bears the costs of protection, the Inventing University shall grant that Member the first option to a royalty bearing exclusive license to the invention. If only one Member is interested in a license for a particular field of use, the Inventing University shall grant that Member an option to a royalty bearing exclusive license for that field of use. In either case, if the Member is a Sustaining Member, then the Sustaining Member shall have an option to obtain a royalty-free, non-exclusive license, without a right to sublicense, rather than a royalty bearing exclusive license; further, when a Sustaining Member elects to obtain an exclusive license, the royalty shall be at a reduced rate to be negotiated at a discount from a commercially reasonable royalty. If the Member is either a Supporter Member or a Principal Member, the exclusive license shall bear a full reasonable royalty to be negotiated on commercially reasonable terms. Any exclusive licensee under this Paragraph will have a right to sublicense on terms and conditions to be mutually agreed upon. The option shall extend for a time period of (180) days from the date of filing the first patent application, which period may be extended by mutual agreement.
- If more than one Member bears the costs of prosecution, the Inventing University shall grant to each of those Members options to a license to the invention on terms and conditions to be mutually agreed upon. The license shall be exclusive as to the rest of the world, but non-exclusive as among those Members which bear the cost of prosecution, provided that, where only one Member seeks a license for a particular field of use, the preceding paragraph, and not this paragraph, shall apply. The Inventing University shall grant all Sustaining Members that have borne the cost of prosecution of the patent a royalty-free license. The Inventing University shall grant all Principal Members that have borne the cost of prosecution a royalty-bearing license, but the royalty amount will be a reduced rate. The Inventing University shall grant all Supporter Members that have borne the cost of prosecution a royalty-bearing license, the royalty to be negotiated on commercially reasonable terms, but in any event the royalty amount will be higher than the amount paid by Principal Members. Except in cases of fully exclusive licenses as provided in the preceding paragraph (either for all uses or for particular fields of use), there shall be no right to sublicense; provided, however, that with the consent of the Inventing University and of all Members that have entered into licenses, either the University or a Member may sublicense the invention on such terms as the parties may agree.
- If no members elect to exercise their option, or if all members discontinue their support, then the Inventing University shall be free to file or continue prosecuting or maintaining any such application(s), and to maintain any protection issuing thereon in the U.S. and in any foreign country at that University's sole expense.

Industrial Advisory Board

The Industrial Advisory Board (IAB) 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 IAB members. There is a monthly IAB Conference call where topics of particular interest are discussed. This meeting is run by the IAB chair who establishes the meeting agenda in concert with the ILO. Agenda topics include issues of interest to the IAB. These meetings can cover a wide range of topics from future research project areas of interest to sustainability planning. Three times per calendar year the IAB meetings are held on site at a member university per a rotating schedule. These meetings typically last a day and a half. The first day is dedicated to technical presentations by the researchers and usually includes a tour of the university laboratory facilities. An informal dinner is held during the evening. It is 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 members to these site meetings. It allows a perspective member an opportunity to experience firsthand the value of CCEFP membership before deciding to join. These site meetings have proven to be very popular to attendees.

The IAB continues to work within an 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 IAB members. At the beginning of their term, the Chairman becomes a member of the CCEFP Executive Committee (EC) replacing the person who was Chairman four years before their term. Thus, the current IAB Chairman and their three immediate predecessors are the members of the CCEFP Executive Committee (EC).

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4.3 TECHNOLOGY TRANSFER AND NEW BUSINESS DEVELOPMENT

The CCEFP participates in many technology transfer efforts. In addition to the various interactions previously described CCEFP faculty and staff of the CCEFP 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 six invention disclosures that will lead to six patent applications being filed this past year. Since its inception the CCEFP has produced 52 disclosures, 36 patent applications filed, six patents awarded, five licenses issued, three spin-off companies and another two 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 Center sustainability. The table below summarizes the CCEFP Invention disclosures that have occurred since the Center started in 2006.

ERC Intellectual Property Table:

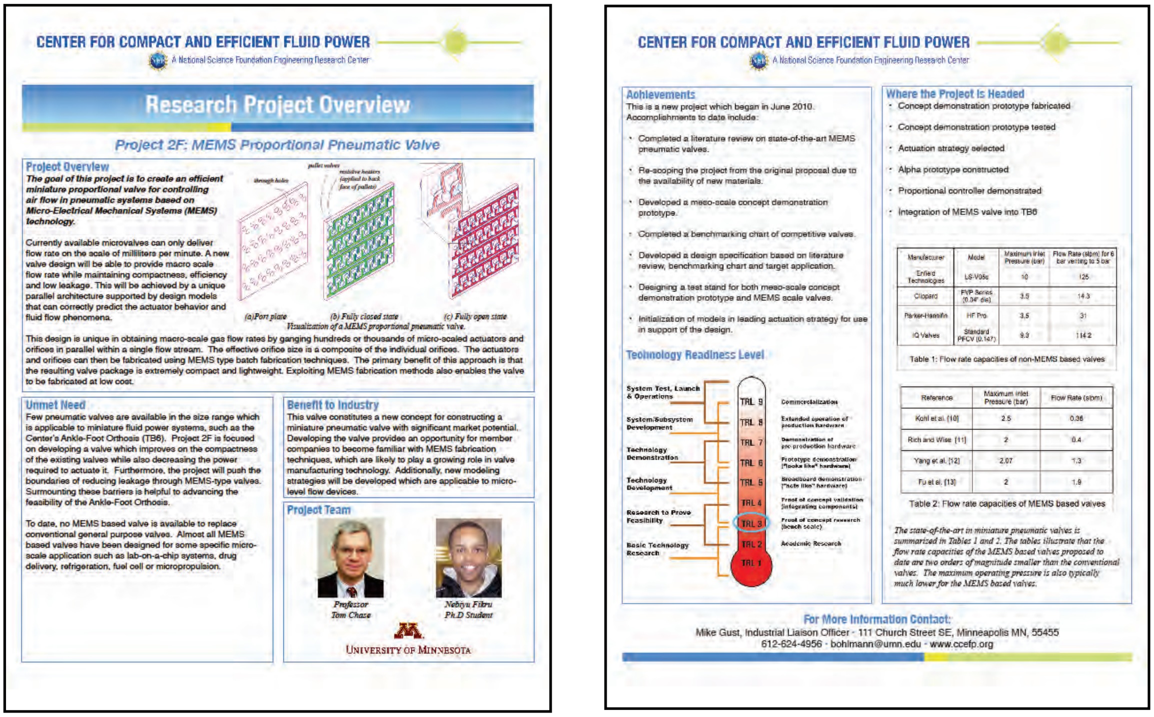
IP File number at the Home University	Home University	IP Title	Provisional Application Date	Patent Application Date	Patent Number	Existing or possible licensing opportunities
Z07054	Minnesota	Open Accumulator Compact Energy Storage for Regenerative Fluid Power Applications	10/10/06	6/30/09	12/445,176	Licensed to SustainX Inc and LightSail Energy Inc
Z07129	Minnesota	Hydro-mechanical Hybrid Drive Train	4/10/07	4/10/08	PCT/US2008/004618	
Z08013	Minnesota	Hydraulic Actuation of a Spool Using an Actuated Pump	8/20/07	4/9/09	12/444,910	Passively marketed. No licensing negotiations
2008P00304	MSOE	Method for reducing torque ripple in hydraulic motors	12/31/08	7/1/2010 7/8/2010	US 12/347,608 WO 2010/076241 A1	
65083	Purdue University	Axial Sliding Bearing with Structural Sliding Surface	4/1/08	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		8/10/09	Pending	Nitta-Moore
HyperCube (ID 2)	MSOE	Dynamic, Multi-Functional, Load-Directed, Composite, Lattice Unit Truss and Unit Cell				
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	4/6/09	3/31/10	PCT/US10/29361	Discussions underway with CCEFP member

IP File number at the Home University	Home University	IP Title	Provisional Application Date	Patent Application Date	Patent Number	Existing or possible licensing opportunities
VU09107	VANDERBILT UNIVERSITY	High Inertance Liquid Piston	4/6/09	4/5/10	8,297,237	
TF09137	UIUC	Ankle-Foot-Orthoses Device	10/5/09	10/5/10	Pending	
65550	Purdue University	Bi-directional Check Valve	1/24/11	1/24/2012 (US)	None issued yet	Available
65293	Purdue University	Piston with Waved Surface for Positive Displacement Pumps and Motors	4/1/09	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		
5345	GT	Multiple Disclosures for Acoustic Management	not yet filed	not yet filed		
5346	GT	Multiple Disclosures for Acoustic Management	not yet filed	not yet filed		
5347	GT	Multiple Disclosures for Acoustic Management	not yet filed	not yet filed		
5348	GT	Multiple Disclosures for Acoustic Management	not yet filed	not yet filed		
5350	GT	Multiple Disclosures for Acoustic Management	not yet filed	not yet filed	NA	
5408	GT	Multiple Disclosures for Acoustic Management	not yet filed	not yet filed		
5480	GT	Piezo-Array Embedded Polymeric Seals for Effective Micro-Control of Sealing	1/28/11			
VU1172	VANDERBILT UNIVERSITY	Elastic Hydraulic Accumulator /Reservoir System	N/A	1/31/11	US 13/017,118 AND PCT PCT/US11/23120	

IP File number at the Home University	Home University	IP Title	Provisional Application Date	Patent Application Date	Patent Number	Existing or possible licensing opportunities
VU1195	VANDERBILT UNIVERSITY	Multiple Accumulator Systems and Methods of Use Thereof	2/3/11	1/30/12	US 13/360,929 AND PCT/US12/23073	
65810	Purdue University	Hydraulic Hybrid Architecture for Systems having Rotary and Linear Actuators	3/16/11	Utility Patent being drafted	None issued yet	Available
5567	GT	Multiple Disclosures for Acoustic Management	not yet filed	not yet filed		
5568	GT	Multiple Disclosures for Acoustic Management	not yet filed	not yet filed		
5569	GT	Multiple Disclosures for Acoustic Management	not yet filed	not yet filed		
20110146	Minnesota	Integrated Portable Pneumatically Powered Ankle-foot Orthosis	3/14/11	3/14/12		
	UIUC	Ankle-Foot-Orthoses Device	3/14/11	3/13/12	Pending	
MSOE Muscle (I0D 1)	MSOE	Fluid Power Actuator (MSOE Muscle)	4/1/12	TBD	N/A	
VU12052	VANDERBILT UNIVERSITY	Continuous Perimeter Clamp	N/A	N/A	N/A	
20120199	Minnesota	Mini HCCI Compressor	6/18/12	Not yet filed		
20120205	Minnesota	Method of Control of FPE	4/2/12	Not yet filed		
20140116	Minnesota	Powered Exoskeleton Using Tiny Hydraulics		Not yet filed		
GTRC ID 6517	Georgia Tech	Control of Voluntary and Involuntary Nerve Impulses for Hemiparesis Rehabilitation and FMRI Study		Note yet filed		
	VANDERBILT UNIVERSITY	Motive Apparatus for use in Magnetically-Sensitive Environments	11/16/11	11/16/12		

IP File number at the Home University	Home University	IP Title	Provisional Application Date	Patent Application Date	Patent Number	Existing or possible licensing opportunities
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		

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. 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 his/her students 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 valuable 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.



CENTER FOR COMPACT AND EFFICIENT FLUID POWER

A National Science Foundation Engineering Research Center

Research Project Overview

Project 2F: MEMS Proportional Pneumatic Valve

Project Overview

The goal of this project is to create an efficient miniature proportional valve for controlling air flow in pneumatic systems based on Micro-Electrical Mechanical Systems (MEMS) technology.

Currently available microvalves can only deliver flow rate on the scale of milliliters per minute. A new valve design will be able to provide macro scale flow rate while maintaining compactness, efficiency and low leakage. This will be achieved by a unique parallel architecture supported by design models that can correctly predict the actuator behavior and fluid flow phenomena.

Visualization of a MEMS proportional pneumatic valve.

This design is unique in obtaining macro-scale gas flow rates by ganging hundreds or thousands of micro-scaled actuators and orifices in parallel within a single flow stream. The effective orifice size is a composite of the individual orifices. The actuators and orifices can then be fabricated using MEMS type batch fabrication techniques. The primary benefit of this approach is that the resulting valve package is extremely compact and lightweight. Exploiting MEMS fabrication methods also enables the valve to be fabricated at low cost.

Unmet Need

Few pneumatic valves are available in the size range which is applicable to miniature fluid power systems, such as the Center's Ankle-Foot Orthosis (TB6). Project 2F is focused on developing a valve which improves on the compactness of the existing valves while also decreasing the power required to actuate it. Furthermore, the project will push the boundaries of reducing leakage through MEMS-type valves. Surmounting these barriers is helpful to advancing the feasibility of the Ankle-Foot Orthosis.

To date, no MEMS based valve is available to replace conventional general purpose valves. Almost all MEMS based valves have been designed for some specific micro-scale application such as lab-on-a-chip systems, drug delivery, refrigeration, fuel cell or micropropulsion.

Benefit to Industry

This valve constitutes a new concept for constructing a miniature pneumatic valve with significant market potential. Developing the valve provides an opportunity for member companies to become familiar with MEMS fabrication techniques, which are likely to play a growing role in valve manufacturing technology. Additionally, new modeling strategies will be developed which are applicable to micro-level flow devices.

Project Team

Professor
Tom Chase

Nebiyu Fikru
Ph.D Student

UNIVERSITY OF MINNESOTA

CENTER FOR COMPACT AND EFFICIENT FLUID POWER

A National Science Foundation Engineering Research Center

Achievements

This is a new project which began in June 2010. Accomplishments to date include:

- Completed a literature review on state-of-the-art MEMS pneumatic valves.
- Re-scoping the project from the original proposal due to the availability of new materials.
- Developed a meso-scale concept demonstration prototype.
- Completed a benchmarking chart of competitive valves.
- Developed a design specification based on literature review, benchmarking chart and target application.
- Designing a test stand for both meso-scale concept demonstration prototype and MEMS scale valves.
- Initialization of models in leading actuation strategy for use in support of the design.

Technology Readiness Level

Where the Project Is Headed

- Concept demonstration prototype fabricated
- Concept demonstration prototype tested
- Actuation strategy selected
- Alpha prototype constructed
- Proportional controller demonstrated
- Integration of MEMS valve into TB6

Manufacturer	Model	Maximum Inlet Pressure (bar)	Flow Rate (slpm) for 6 bar venting to 5 bar
Enfield Technologies	LS-V05s	10	125
Clippard	FVP Series (0.04" dia)	3.5	14.3
Parker-Hannifin	HF Pro	3.5	31
IQ Valves	Standard PFCV (0.147)	9.3	114.2

Table 1: Flow rate capacities of non-MEMS based valves

Reference	Maximum Inlet Pressure (bar)	Flow Rate (slpm)
Kohl et al. [10]	2.5	0.36
Rich and Wise [11]	2	0.4
Yang et al. [12]	2.07	1.3
Fu et al. [13]	2	1.9

Table 2: Flow rate capacities of MEMS based valves

The state-of-the-art in miniature pneumatic valves is summarized in Tables 1 and 2. The tables illustrate that the flow rate capacities of the MEMS based valves proposed to date are two orders of magnitude smaller than the conventional valves. The maximum operating pressure is also typically much lower for the MEMS based valves.

For More Information Contact:

Mike Gust, Industrial Liaison Officer - 111 Church Street SE, Minneapolis MN, 55455
612-624-4956 - bohlmann@umn.edu - www.ccefp.org

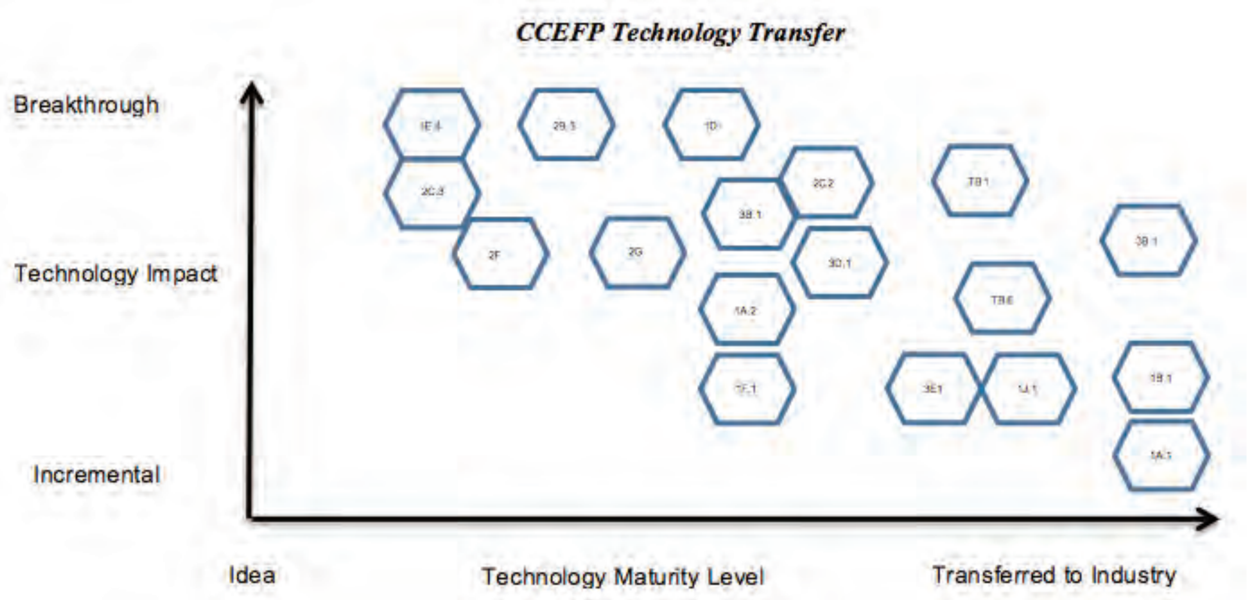
Research Project Summary Sheet

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. If no CCEFP members exercise their rights to the IP they are helpful in targeting other firms. In addition, these sheets are easily available for download in pdf format from the CCEFP website.

Technology Impact

Some of the more impactful CCEFP technologies are mapped in the Impact vs. Maturity chart below. 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
- 1D: Micro- and Nano-Texturing for Low-Friction Fluid Power 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
- Testbed 6: Fluid Power Ankle-Foot Orthosis
- Testbed 1: High Efficiency Excavator
- 3B.1: Passive Noise Control in Fluid Power
- 1B.1: New material combinations/surface shapes for the main tribosystems of piston machines
- 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
- 3D.1: Leakage/Friction Reduction in Fluid Power Systems



4.4 INNOVATION

The fluid power industry is typically 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. This program has begun to expose CCEFP students to venture capitalists and angel investors, I-Corps, SBIRs, STTRs, as well as, insight into how to develop robust business plans. Information has been distributed on an as-interested basis but could benefit from a more formal program. Annual training sessions to make sure all students understand the opportunities that await them will be provided via Center webcasts. The CCEFP is committed to fostering an environment whereby anyone affiliated with the organization who is interested in launching a start-up or spin-off company will feel supported. The CCEFP ILO will own development and administration of this program.

4.5 FUTURE PLANS

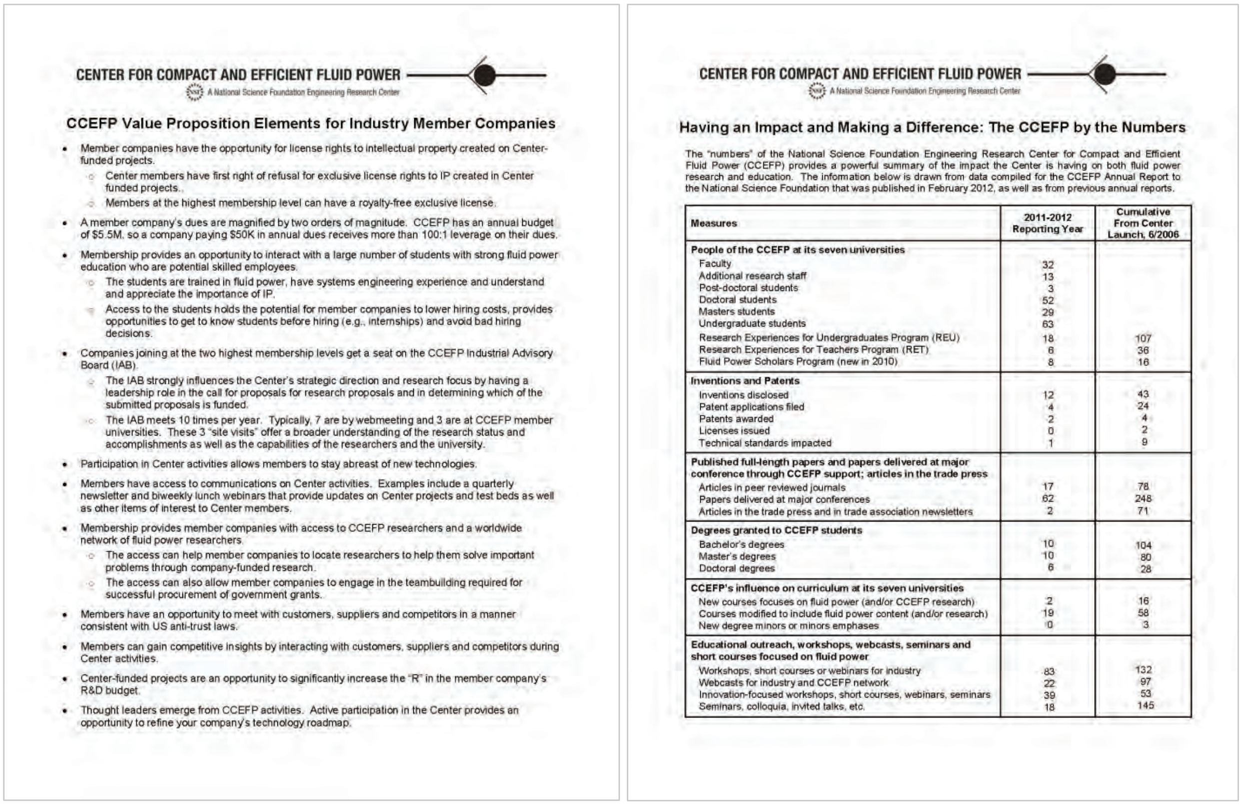
The SWOT developed by the Industrial Advisory Board continues to be a valuable communication vehicle to provide industry feedback to the CCEFP. Throughout the Center's history an area once deemed as a "weakness" by industry has grown over time to an area of "strength". This transformation occurred again this past year with the IAB providing positive feedback regarding the new project review process and active industry participation through onsite IAB Summits. 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.

Method	Frequency	Content	Audience
NFPA Annual Conference	1x per year	Business potential	CEOs
IFPE Conference	1x per 3 years	General	Industry wide
CTO Summit	1x per year	Research Roadmap	CTO
IAB Summit	3x per year	Research Updates	Industry Technologists
Research Webinars	Biweekly	Updates on research and topics of interest	Industry members, faculty and students

CCEFP Communication Methods

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 (NFPA) to improve our industry engagement as part of our sustainability plan. Going forward we envision the CCEFP-NFPA-industry partnership to become a 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. The table below lists the communication method, frequency, content and targeted audience for our Center sustainability plan.

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. Responding to a request from our industry members, the Center recently identified a list of the key value propositions we offer our industry members. The expanded documents are shown in the figure below.



CENTER FOR COMPACT AND EFFICIENT FLUID POWER
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CCEFP Value Proposition Elements for Industry Member Companies

- Member companies have the opportunity for license rights to intellectual property created on Center-funded projects.
    - Center members have first right of refusal for exclusive license rights to IP created in Center funded projects.
    - Members at the highest membership level can have a royalty-free exclusive license.
- A member company's dues are magnified by two orders of magnitude. CCEFP has an annual budget of $5.5M, so a company paying $50K in annual dues receives more than 100:1 leverage on their dues.
- Membership provides an opportunity to interact with a large number of students with strong fluid power education who are potential skilled employees.
    - The students are trained in fluid power, have systems engineering experience and understand and appreciate the importance of IP.
    - Access to the students holds the potential for member companies to lower hiring costs, provides opportunities to get to know students before hiring (e.g., internships) and avoid bad hiring decisions.
- Companies joining at the two highest membership levels get a seat on the CCEFP Industrial Advisory Board (IAB).
    - The IAB strongly influences the Center's strategic direction and research focus by having a leadership role in the call for proposals for research proposals and in determining which of the submitted proposals is funded.
    - The IAB meets 10 times per year. Typically, 7 are by webmeeting and 3 are at CCEFP member universities. These 3 "site visits" offer a broader understanding of the research status and accomplishments as well as the capabilities of the researchers and the university.
- Participation in Center activities allows members to stay abreast of new technologies.
- Members have access to communications on Center activities. Examples include a quarterly newsletter and biweekly lunch webinars that provide updates on Center projects and test beds as well as other items of interest to Center members.
- Membership provides member companies with access to CCEFP researchers and a worldwide network of fluid power researchers.
    - The access can help member companies to locate researchers to help them solve important problems through company-funded research.
    - The access can also allow member companies to engage in the teambuilding required for successful procurement of government grants.
- Members have an opportunity to meet with customers, suppliers and competitors in a manner consistent with US anti-trust laws.
- Members can gain competitive insights by interacting with customers, suppliers and competitors during Center activities.
- Center-funded projects are an opportunity to significantly increase the "R" in the member company's R&D budget.
- Thought leaders emerge from CCEFP activities. Active participation in the Center provides an opportunity to refine your company's technology roadmap.

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

Having an Impact and Making a Difference: The CCEFP by the Numbers

The "numbers" of the National Science Foundation Engineering Research Center for Compact and Efficient Fluid Power (CCEFP) provides a powerful summary of the impact the Center is having on both fluid power research and education. The information below is drawn from data compiled for the CCEFP Annual Report to the National Science Foundation that was published in February 2012, as well as from previous annual reports.

Measures	2011-2012 Reporting Year	Cumulative From Center Launch, 6/2006
People of the CCEFP at its seven universities		
Faculty	32	
Additional research staff	13	
Post-doctoral students	3	
Doctoral students	52	
Masters students	29	
Undergraduate students	63	
Research Experiences for Undergraduates Program (REU)	18	107
Research Experiences for Teachers Program (RET)	6	36
Fluid Power Scholars Program (new in 2010)	8	16
Inventions and Patents		
Inventions disclosed	12	43
Patent applications filed	4	24
Patents awarded	2	4
Licenses issued	0	2
Technical standards impacted	1	9
Published full-length papers and papers delivered at major conference through CCEFP support; articles in the trade press		
Articles in peer reviewed journals	17	78
Papers delivered at major conferences	62	248
Articles in the trade press and in trade association newsletters	2	71
Degrees granted to CCEFP students		
Bachelor's degrees	10	104
Master's degrees	10	80
Doctoral degrees	6	28
CCEFP's influence on curriculum at its seven universities		
New courses focuses on fluid power (and/or CCEFP research)	2	16
Courses modified to include fluid power content (and/or research)	19	58
New degree minors or minors emphases	0	3
Educational outreach, workshops, webcasts, seminars and short courses focused on fluid power		
Workshops, short courses or webinars for industry	83	132
Webcasts for industry and CCEFP network	22	97
Innovation-focused workshops, short courses, webinars, seminars	39	53
Seminars, colloquia, invited talks, etc.	18	145

CCEFP Value Proposition and "By the Numbers" Summary Sheet

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. 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.

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5. INFRASTRUCTURE

5.1 CONFIGURATION AND LEADERSHIP EFFORT

The CCEFP institutional configuration is 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. Table 6 and Figures 6a and 6c are at the end of this section.

The CCEFP institutional configuration is optimal for 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; involve 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 have also been carefully chosen. North Carolina A & T State University (NCAT) is the leading producer of African-American engineering graduates at both 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 has a small graduate program, and effectively uses both undergraduate and graduate students in fluid power research.

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, and REU, Fluid Power Scholar (FPS), and RET participating institutions is shown in Figure 6a. There have been no changes in institutional configuration except for REU student institution. 18 REU students, 28% women and 44% underrepresented racial or ethnic minority status and 8 Fluid Power Scholar students, 12% of underrepresented gender, racial or ethnic minority status have been recruited from ERC and non-ERC institutions. Institutions outside of the CCEFP network which are represented in the 2013 REU and FPS program include: Michigan State University, Rochester Institute of Technology, The Cooper Union for the Advancement of Science and Art, University of Missouri-Columbia, University of South Florida, University of Virginia, Wilkes University, Yale University. Continuous efforts are made to recruit REU and FPS 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 TCUP 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 24 research projects were funded for Years 5-6. To assure adequate funding for each project, this was reduced to 21 projects in Years 7-8. As NSF funds decrease, the number of projects will be further reduced to 14 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. Mike Gust returned last year in the position of Industrial Liaison Officer after a two-year stint in industry. Mike'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.

A change in the last year is that the Deputy Director, Perry Li, has been replaced by two Deputy Co-Directors, Eric Barth and Zongxuan "Sunny" Sun. Both Barth and Sun are Associate Professors who could be key leaders of CCEFP in the future. The Director meets weekly with the Deputy Co-Directors, Industrial Liaison Officer and Sustainability Director to maintain focus on key issues including research strategy, industry membership and Center sustainability.

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 each university. The MC meets on alternate weeks 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. Two recently formed committees, the Industry Relations Committee (IRC) and the Government Relations Committee (GRC), handle industry and government relations. 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.

CCEFP is a complex, distributed multi-institutional organization. For high-level research management, It is important to augment the MC with a group that has broader representation. The Executive Committee (EC) fulfills this role. The Director is Chair of the EC which includes a representative from each member university from the MC, one SLC representative and four industry representatives. Responsibilities include defining and updating of the Center strategy, new project selection and progress tracking.

The SLC updated its SWOT analysis in January 2014. The analysis and CCEFP leadership response are shown below.

Y8 SLC SWOT

The Year 8 Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis of the CCEFP was based on the results of an internet based survey from active student members of the Center. All active Center students were sent email communications inviting them to anonymously participate in the SWOT survey. A total of 21 students responded, and a breakdown of the institutional responses is included in Figure 1.

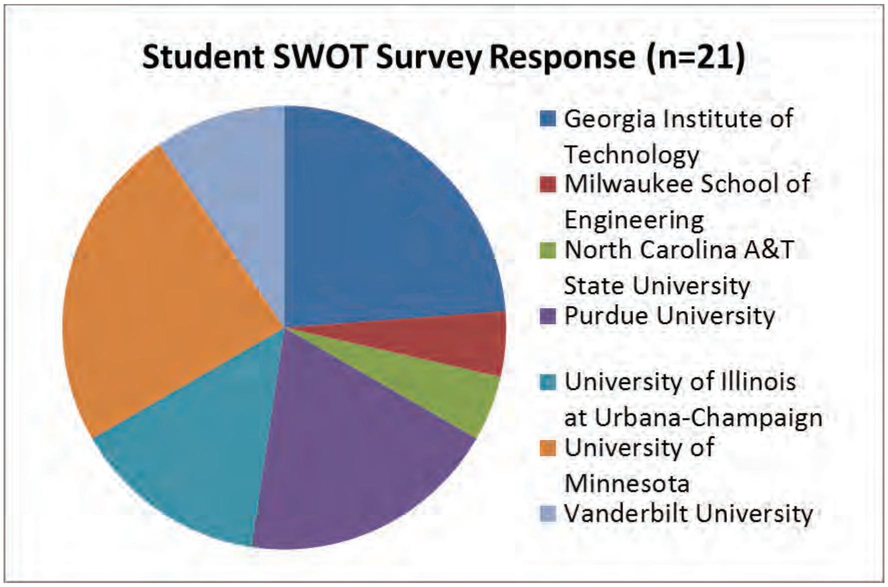


Figure 1: SWOT survey response by center institution.

The online survey form contained a list of 33 attributes, and following a brief definition of each of the SWOT terms, the participants were asked to categorize each attribute as a strength, weakness, opportunity, or threat with a strong, average, or minimal magnitude. It was possible to categorize each attribute as more than one SWOT, for example as both a strength and opportunity.

The responses were weighted such that a strong, average, or minimal SWOT magnitude received a numerical score of 3, 2, or 1 respectively. The scores for each attribute were summed over all the respondents, and the top five attributes from each category are included below:

Top Five Center Strengths:

- Industry interaction and support
- Diversity of research and multidisciplinary work
- Student specialization in fluid power
- Presentation of research progress (i.e. webcasts, poster shows, annual meeting)
- Close communication between faculty and students

Top Five Center Weaknesses:

- Lack of synchronization of efforts between universities on closely related projects
- Isolation of physical resources
- Isolation within each institution
- Student interest in participating on webcast of other projects
- Geographical isolation between researchers

Top Five Center Opportunities:

- Inter-university collaboration and collaborative learning
- Emerging fluid power applications (medical devices, wind turbine powertrains, etc.)
- Close communication between faculty and students
- Fluid power related conferences
- Diversity of research and multidisciplinary work

Top Five Center Threats:

- Decrease in NSF financial support
- Industry economic situation and impact on center participation
- Lack of synchronization of efforts between universities on closely related projects
- Timeliness and effectiveness of scheduling
- Loss of interest or maintaining vision (students/ faculty/ industry)

It is clear that the support of industry coupled with the diversity of unique fluid power research lays the foundation of the Center's strengths. This is reflected simultaneously as a Center threat; if the economic situation of industry restricts their ability to be active supporters and partners with Center research, the efficacy of the Center is likely threatened. While strong communication between faculty and students is both a Center strength and opportunity, Center weaknesses continue to be centered on lack of inter-university communication, lack of synchronization between universities on related projects, and researcher isolation. The Student Leadership Council has attempted to combat these reoccurring concerns regarding lack of inter-university collaboration by sponsoring student travel grants. The purpose of the grant proposals is to award up to $1000 for students to travel to a member (or non-member) institution to collaborate on a project, or similarly to fund travel to an industrial member company to promote project collaboration. Although the travel grant program has resulted in multiple success stories, the weakness regarding inter-university collaboration persists, indicating it is not necessarily a funding issue.

It is promising that emerging fluid power applications are ranked high as a Center opportunity. Especially from a higher education research prospective, developing elegant solutions utilizing fluid power in new market segments has the potential to attract significant talent and excitement to the discipline, more so than only incrementally improving current applications. This sentiment was reflected in a free response field by one student: “One thing I think the CCEFP should work on is the point of emerging fluid power applications. The only one they really have consistently done well is medical applications, largely because it's a well-structured project from a systems perspective.”

The primary threat to the Center as ranked by the survey is financial in nature. World class research requires funding – be it from governmental or industrial sources. Although the Center has proposed limited sustainability plans, the ability of the Center to maintain its breadth is, of course, unknown. Beyond financial threats, the loss of maintaining a clear Center vision and the impact of that potential loss on the Center was noted. This problem is likely compounded due to the natural high turn-over of graduate researchers. Often a Master's student may only have 12-18 months of meaningful involvement making it essential for Center leadership, faculty, and industry to maintain the longer term Center vision and ensure short term goals and projects are effectively fulfilling the vision. One free field response from a student was: “It is a major problem for students, and a waste of resources, when their projects are cancelled prior to completion of a degree.” Clearly, this can be a significant problem for individual students on a case-by-case basis. Although a core center may not be canceled per-say, when the project reaches its funding conclusion, if a future project proposal to continue research is declined the net effect on the student is the same. Here the fault may lie with faculty not maintaining a clear, open, and frank line of communication between students, especially those who are new or considering joining, regarding the future funding situation.

A full list of the suggested center attributes and weighted student SWOT responses is included below in Figure 2.

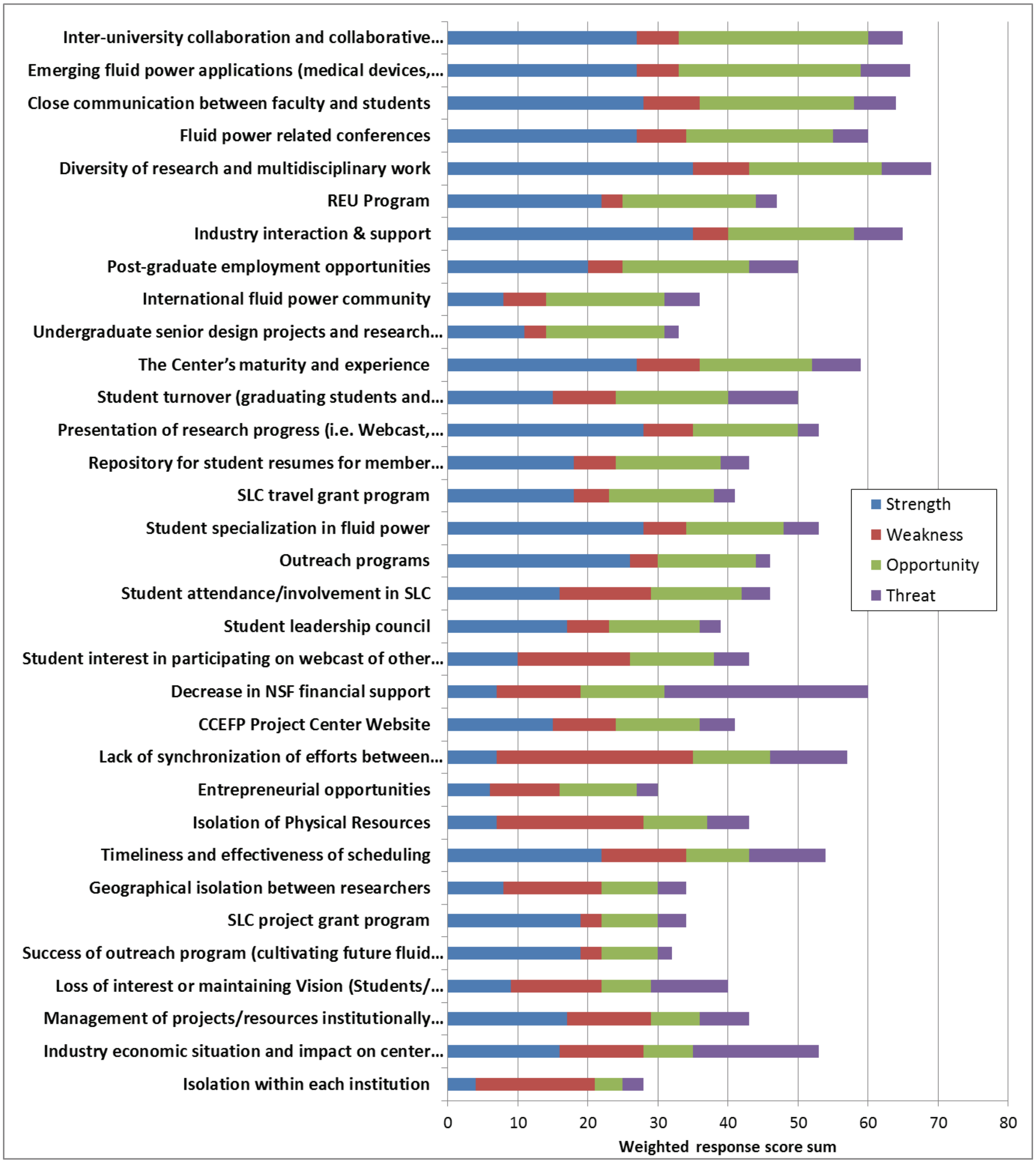


Figure 2: Sum of the weighted SWOT responses from all 21 respondents for 33 center attributes.

CCEFP Response:
We appreciate the SLC's candid, thorough and thoughtful response. It is evident the student perspective and leadership is critical to assessing the successes and challenges of the Center. The CCEFP leadership has also identified communication and collaboration, financial independence and emerging markets for fluid power as key areas of focus presently, near term immediacy and for long-term sustainability. Additionally, the recommendations related to research project funding will be taken seriously as we shift into a post-NSF Engineering Research Center.

Two specific comments from the students merit individual responses. These are comments about emerging areas and continuity of research support. Center leadership fully agrees that we should put more emphasis on emerging applications. This view also has wide support in industry. To do this effectively we need to focus our limited resources. This is why bio-medical applications are receiving so much emphasis. Also, Center leadership and faculty researcher are acutely aware of the need for continuous research support for students. Belonging to the CCEFP provides much more financial stability than depending on single investigator grants. NSF funds about 15% of single investigator grants. CCEFP funds about one-half to two-thirds of submitted proposals. If a project is terminated without a follow-on project, residual funds can often be used to continue student support. Also, CCEFP has university matching funds at each institution, another potential source of support in extraordinary situations. In the upcoming budget cycle, due to decreasing NSF funds, only 14 projects will be funded. Some funds have been set aside to help with continuing student support for projects that are ending.

The CCEFP commits to keeping current academic and industry members aware of the progress towards sustainability – the plan, status, and effort underway. Recent events, notably the MUO between CCEFP and NFPA have greatly improved the likelihood of success. This improved situation must be better communicated to faculty and students to reduce anxiety and increase commitment to the Center's mission. The Center will continue organizational improvements including communications, collaboration across Center institutions and research initiatives, and it research project cancelation and award process.

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.

- The Center for Compact and Efficient Fluid Power (CCEFP) is collaborating closely with the National GEM Consortium to devise a novel interface between NSF Engineering Research Centers, the National GEM Consortium, and Industry. The National GEM Consortium exists to "address the critical shortfall in the production of American engineering and scientific talent." The intersection of the three sectors is synergistic. GEM identifies and fosters top diverse talent in the STEM fields. NSF ERCs are responsible for creating a diverse pathway for students of all ages, with a focus in research at the Masters and PhD levels. Industry, of course, is interested in a qualified workforce. The CCEFP submitted an informal proposal to NSF and was invited to discuss the program, in person, November 2013. NSF ERC leaders were strongly supportive and agreed to provide supplemental funding to extend the CCEFP's pilot program into another year. The formal proposal to NSF will be submitted by end of month, March 2014.

- In response to the withdrawal of the NSF Graduate Research Diversity Supplement (GRDS) award, in which the CCEFP received five years of funding to support four female graduate students, the CCEFP has and will continue to provide an additional $60,000 to supplement the GRDS grant cancelled by NSF, to ensure the students would have sufficient funding sources to focus on their academic goals and accomplishments. For more information, see EO Project C.10.
- In Year 6, modeled after the NSF GRDS program, the CCEFP launched an academic year CCEFP Undergraduates Research Diversity Supplement (URDS) program for students with diverse ethnic, racial, gender, economic, and educational backgrounds. To date, the program has sponsored nine students, all underrepresented, most of whom are racially or ethnically diverse, to research labs in the CCEFP. For more information, see EO Project C.9.
- Two undergraduates in engineering, members of the AISES Student Chapter at UMN, have conducted CCEFP research experiences and now are both hired as engineers in their related industries.
- 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 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 perspective 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 35.3% of Undergrad Non-REU and 41.2% of Undergrad REU students are women as compared to 18.9% nationally. 11% of Center faculty are women, while 27% of the Center's Leadership Team is female.

Racial Minorities – The CCEFP greatly exceeded national averages in nearly all categories. We are particularly pleased with the percentage of Undergrad Non-REU and REU students who are racial minorities, 47.1% and 29.4%, 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 (9.1%), and graduate students at the doctoral level (12.5% domestic students, 11.5% foreign students).

Hispanic/Latinos – Numbers of Hispanic/Latinos and persons with disabilities remain small, although represented at the graduate and undergraduate level. The Center is eager to continue to support the students who have been recruited, while taking steps to address the recruitment of Hispanic and Latino/a personnel.

- 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.
- According to Table 7a, it is clear that the Center for Compact and Efficient Fluid Power is impacting underrepresented populations when compared to the national engineering averages.
    - As in previous years, in 2013, the Center continues to demonstrate a strong representation of women by matching or exceeding national averages at the undergraduate, REU, and faculty level. The percentage of women in CCEFP doctoral and master's programs remains average, although, as previously noted, mechanical engineering typically serves the smallest percentage of females. Sustaining the positive numbers of women across the Center is critical.
    - Representation of women, and ethnic and racial minorities within the CCEFP faculty continues to exceed, or at minimum, equal national averages. We are hopeful for additional diverse faculty hires, which have recently occurred only in small increments due to the poor economy.
    - The Center has experienced sustained improvement in the number of underrepresented racial minorities, well above the national averages in all categories of academic participants.
    - The CCEFP has made it a priority to enhance its recruitment of Hispanic/Latino/a participants while increasing Center mentorship opportunities. The Center will continue to focus new efforts on undergraduate recruitment from institutions with significant numbers of Hispanic/Latino/a students.
    - Participation by persons with disabilities continues to be a concern. The Center will continue to utilize existing resources and identify new resources, organizations and affiliations where CCEFP program information can be disseminated and through which students with disabilities can be reached.

- 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, Research Diversity Supplemental 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. The North Star STEM Alliance fully supports the activities of the giiwed'anang North Star Alliance (Project C.5) and considers this program an official undergraduate activity for Native American students in the LSAMP. 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.

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.

Pre-College: An essential part of the CCEFP strategic plan is to promote the study of science, technology, engineering, and math (STEM), and to encourage a diverse group of young students to enter these fields. A special focus in these efforts lies in Center-supported work to increase the number of Native Americans choosing STEM-related study tracks through its gidaa STEM and robotics programs. For now, the CCEFP's Native American programs are centered at the University of Minnesota because of the large number of tribal colleges in the upper Midwest as well as the large population of Native Americans in Minnesota and surrounding states. In these initiatives, the Center envisions that project successes will be duplicated within larger networks. At the national level, the Center's partnership with Project Lead The Way (PLTW), and its work with the Science Museum of Minnesota (SMM), a recognized leader in museum-based education, support STEM initiatives that involve diverse student populations. Years 3 - 5 marked progress in developing fluid power content for selected PLTW courses and in creating the prototype of a pneumatics workshop that can be used by many students including FIRST Robotics teams. In year 7, our focus is on helping teachers to effectively understand and teach this content. Further, our partnership with PLTW and our RET program continues; several RETs are also PLTW teachers, five in 2009, three in 2010, four in 2011, 2012 and 2013.

College: At the university level, the Center continues to build the communications and database networks needed to recruit undergraduate and graduate students, faculty, and researchers from a diverse population. To accomplish this, the Center has identified key schools and programs at institutions that cater specifically to these target populations, creating formal and informal relationships that will support recruitment efforts. The Center is also driving its diversity and recruiting efforts by developing formal alliances and collaborations among several other National Science Foundation-funded organizations and with professional and national organizations. The CCEFP's outreach database grew to over 1000 direct and unique contacts.

Major Initiatives

Each research and education project at CCEFP institutions is committed to actively recruiting underrepresented and minority students to participate as the following examples illustrate.

Research Experiences for Undergraduates - REU (Project C.1)

REU is an NSF program whose purpose is to provide undergraduate STEM students with summer experiences in university research labs. An objective of the program is to increase the number of top students, reflecting the racial, ethnic, and gender composition of our country, who attend graduate schools in STEM areas. Every summer the CCEFP hosts an average of 15 REU students. Within this total, the number of participants from outside the Center's network should be greater than the number of students admitted from its seven universities. The CCEFP's REU students begin the summer with a Fluid Power Boot camp and instruction in fluid power technology, its applications and the research activities of the CCEFP. Continuing interaction among CCEFP REU students at the seven sites occurs weekly during the summer through a research blog where REU students submit descriptions and updates of their own research activities. The CCEFP actively recruits underrepresented students in STEM including racial and ethnic minorities, women, persons with disabilities, and recent war veterans for its REU program. NSF awarded CCEFP a three-year NSF REU Site Award.

Y8 Outcomes:

Research Experiences for Undergraduates	**2013**	**TOTAL (Y2-Y8)**
Number of Students	18	148
Male	13	100
Female	5	48
Percentage of students from underrepresented groups 1 racial or ethnic minority 2 gender minority 3 disability	1) 44% 2) 28% 3) 0%	1) 37% 2) 32% 3) .01%

CCEFP Research Diversity (RDS) Supplement (Projects C.9 /10)
Recognizing the need for additional programs to strengthen its efforts to recruit and retain a diverse student population, the CCEFP launched two new programs in year 6. The short and long-term goals of these programs are: 1) to provide CCEFP faculty with the means to involve additional graduate students on CCEFP research projects; 2) to identify a graduate student who might not otherwise consider a research opportunity in CCEFP laboratories; 3) to encourage students to consider graduate study or an employment position in the fluid power industry by fostering a learning and career advancement centered environment; 4) to further provide exposure to fluid power technology to a diverse audience; 5) to answer the country's need of greater retention of underrepresented students in engineering.

Y7 Outcomes:

Undergraduate and Graduate Research Diversity Supplement	**2013**	**TOTAL**
Number of Students	5	9
Male	4	0
Female	1	9
Percentage of students from underrepresented groups 1) racial minority 2) gender minority 3) disability	1) 67% 2) 0% 3) 0%	1) 67% 2) 55% 3) 0%

gidaa Robotics Program (Project B.4c)
Under the *gidaa* STEM Program umbrella, staff and teachers have drawn on lessons learned through FIRST robotics and introduced K-12 robotics day and after-school curricula using Lego Wedo-Webots, Lego Mindstorms robots, and software. The *odaangiina anaangoog* Shooting for the Stars Robotics Program enables students in and around the Fond du Lac Indian Reservation to use concrete learning experiences with robotics to better understand physics concepts; develop mathematical thinking, problem solving, and programming skills; and participate in team-building exercises through hands-on engineering construction. This program currently engages challenged students at the elementary, middle and high school levels.

Y8 Outcomes:

gidaa Robotics Program*	**2013**	**TOTAL**
Number of Students	100	374
Male	55	213
Female	45	161

**Initiated program in 2009, Y3*

giiwed'anang North Star AISES Alliance (Project C.5)
The American Indian Science and Engineering Society (AISES) is a national organizations with a goal: to increase the number of Native American college students in STEM fields. In 2007, the CCEFP launched the giiwed'anang North Star Alliance which helped to form partnerships between the AISES student chapters in Minnesota. It exists to provide tools and resources to assist students of AISES Chapters. Since inception, the alliance has found its niche – to continue to be a resource, a small centralized organization-bridging people together. Now its primary function is student travel support to attend AISES related events.

In Y8, CCEFP, with the support of various other sponsoring organizations, funded over 8 students to attend the AISES National Conference in Denver, CO. The giiwed'anang Alliance also hosted a dinner of over 20 AISES students and chapter advisors during the National Conference. As the Center experiences a decline core NSF funding, program and student support will decrease for giiwed'anang, however, other organizations have since flourished to step-in and carry the load. The CCEFP has had two Native American students participate in research experiences at UMN due to this program. Both have since been hired as engineers into industry.

5.3 MANAGEMENT EFFORT

The CCEFP operational organization chart appears below:

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.

Dr. Perry Li is the Deputy Director of the CCEFP and has served in this role since the Center's inception in 2006. Due to other commitments he has decided to step down from this role although he will still be active leading Center research projects. Two co-Deputy Directors have been announced to assume this role. Professor Zongxuan Sun will focus on hydraulic related research while Professor Eric Barth will focus on pneumatics research. The role of the deputy directors is to provide technology guidance for the center. They own the strategic plan for technology and oversee the test bed integration. They also provide leadership for the bi-annual research project reviews.

The other positions at the CCEFP provide the following support:

- 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 – Responsible for operations and financial management of the center.
- Education Director – Leads the Education and Outreach activities.

- 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 are summarized below.

Executive Committee (EC)

This committee is charged with defining CCEFP policy and strategies, then monitoring their effectiveness. Committee members also guide the research project selection and tracking processes. The Center Director chairs the Executive Committee. Committee members include a representative from each of the Center's seven universities, a representative of the Student Leadership Council, and four industry representatives—all drawn from the leadership of the Industrial Liaison Board. The Executive Committee meets at least three times each year, with additional meetings scheduled when needed.

Executive Committee Members:

Andrew Alleyne - University of Illinois - Urbana-Champaign
Eric Barth - Vanderbilt University
Wayne J. Book - Georgia Institute of Technology
Andrew Schenk - SLC Representative
Vito R. Gervasi - Milwaukee School of Engineering
Steven Herzog – Evonik RohMax USA, Inc.
David Holt - ExxonMobil Research Engineering
Monika Ivantysynova - Purdue University
Ray Collett - Parker Hannifin Corporation
Perry Y. Li - University of Minnesota
Eui Park - North Carolina A&T State University
Gary Kassen - CNH
Kim A. Stelson - University of Minnesota

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 twice each month.

Management Committee Members:

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

Industrial Advisory Board (IAB)

The CCEFP Industrial Advisory Board (IAB) provides advice and guidance on CCEFP research directions and policies. IAB members, representing companies supporting the Center at either the principal or sustaining level, meet regularly for discussions on key issues. Four representatives from the IAB serve on the CCEFP Executive Committee (EC), which sets the overall governing policies and strategic direction for CCEFP.

Current IAB Members:

Brian Rhode - Afton Chemical
Ed Greif - Bosch Rexroth Corp.
Gary Kassen - Case New Holland
Bill Durr - Caterpillar Inc.
Eric Bretey - Danfoss
Marcus Royal - Deltrol Fluid Products
Qinghui Yuan - Eaton Corp.
Jonathon Gamble - Enfield Technologies
Steven Herzog - Evonik RohMax USA, Inc.
David Holt - ExxonMobil Research and Engineering
Patrick Lee - Gates Corporation
Joe Pfaff - HUSCO International
Scott Lane - Linde Hydraulics Corp.
Shubha Basu - Lubrizol
Eric Lanke - National Fluid Power Association
Bill Edwards - Netshape Technologies
Paul Paluszewski - Pall Corporation
Ray Collett - Parker Hannifin Corp.
Gilles Lemaire - Poclain Hydraulics
Eric Cummings - Ross Controls
Larry Castleman - Trelleborg Sealing Solutions

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 Executive Committee in developing Center strategy.

Scientific Advisory Board Members:

Dr. Hans Aichlmayr - Lawrence Livermore National Laboratory
Prof. Richard Burton - University of Saskatchewan
Dr. Robert J. Cloutier - Stevens Institute of Technology
Prof. Frank Fronczak - University of Wisconsin
Prof. Toshiharu Kagawa - Tokyo Institute of Technology
Dr. Joseph Kovach – Former Vice President for Parker Hannifin
Dr. Lonnie J. 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 – Former Vice President, Technology and Chief Technology Officer for Eaton Corp.
Professor 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:

Andrew Schenk - President – Purdue University
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
Michael Johnston – University of Illinois at Urbana-Champaign
Melih Turkseven - Georgia Institute of Technology
Jonathon Slightham - Milwaukee School of Engineering
Anna Winkelmann – Vanderbilt University

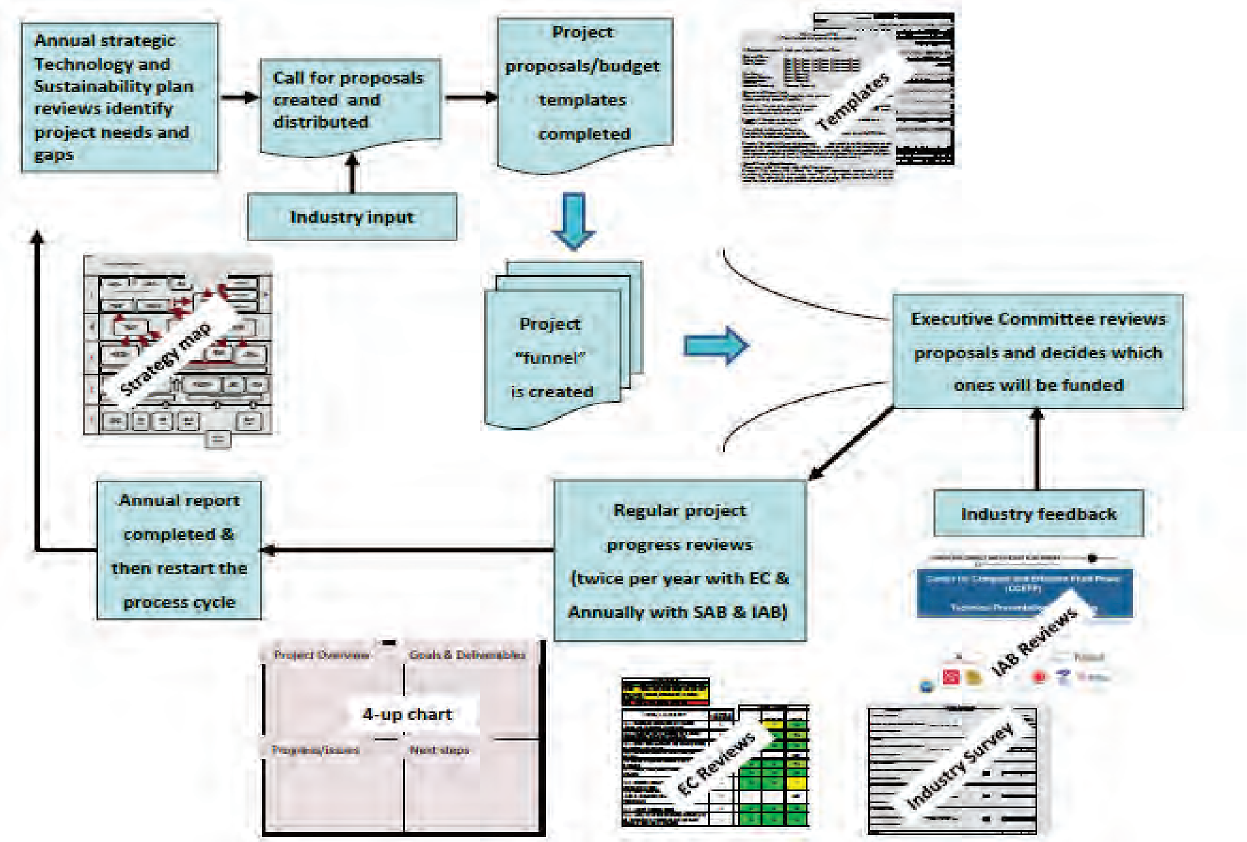
MANAGEMENT OF THE CCEFP

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 the diagram below. The process begins with a review of the CCEFP Strategic Research and Sustainability plans. The Executive Committee with input from Industry via an industry research roadmap creates a call for proposals citing areas of need. The Executive Committee reviews the proposals and with input from the IAB, selects the funded projects.

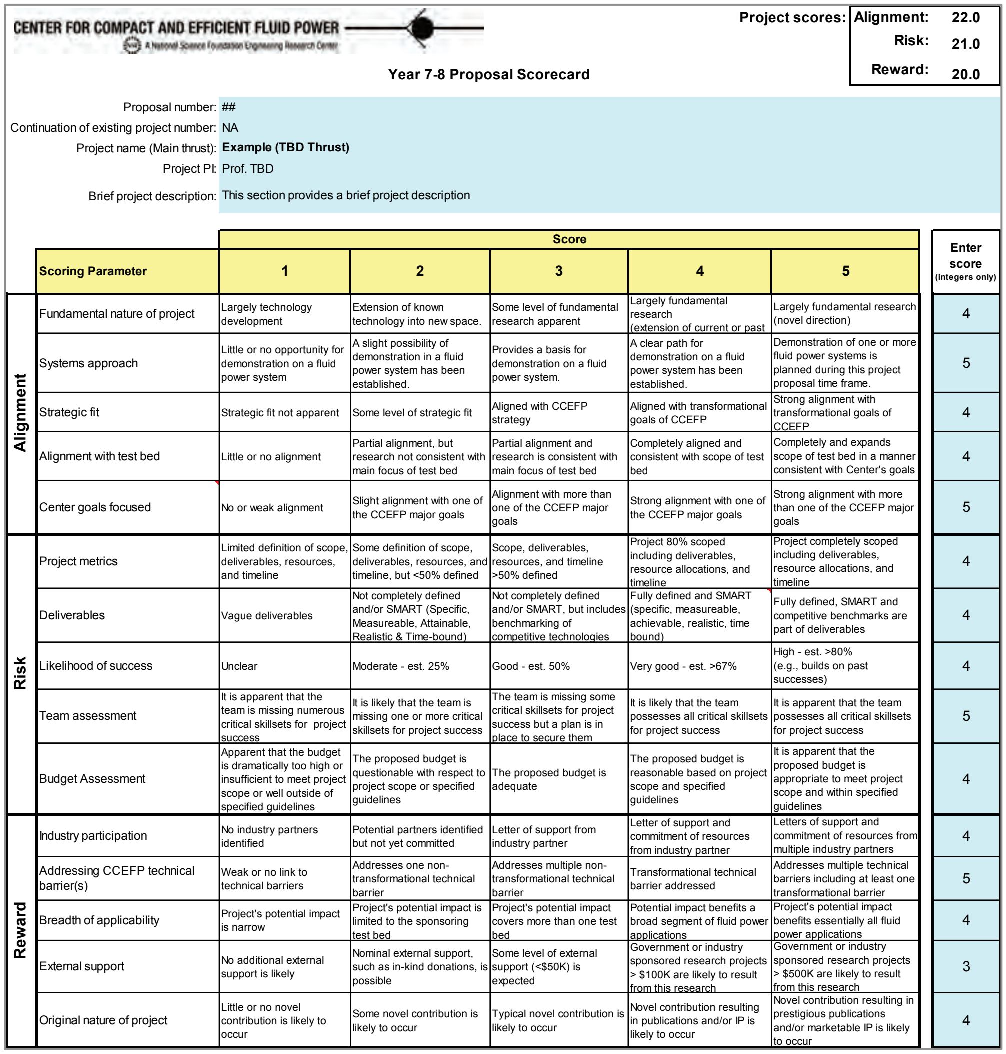


Project Selection and Management

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. 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 IAB enthusiastically embraces the project selection process. They assigned 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 appears below. The review results are discussed extensively during IAB teleconferences until a final outcome is reached and forwarded to the IAB representatives on the CCEFP Executive Committee (EC).



CENTER FOR COMPACT AND EFFICIENT FLUID POWER
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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

		Score					**Enter score** (integers only)
	Scoring Parameter	**1**	**2**	**3**	**4**	**5**	
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
	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
	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 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
	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
	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
	Likelihood of success	Unclear	Moderate - est. 25%	Good - est. 50%	Very good - est. >67%	High - est. >80% (e.g., builds on past successes)	4
	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
	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
	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
	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
	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
	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

Standardized Proposal Review Template

For the Y7-Y8 funding cycle a total of thirty-two research proposals were received although available budget allowed for only twenty-one of these projects to be funded. 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 list of Y7- Y8 approved projects appears below:

1. Technology Transfer Process for Energy Management Systems
2. New Directions in the Rheology of Elastohydrodynamics
3. Advanced Strain Energy Accumulator
4. Controlled Stirling Thermocompressors (New)
5. Teleoperation Efficiency Improvements by Operator Interface
6. MEMS Proportional Valve
7. Pressure Ripple Energy Harvester (New)
8. Miniature HCCI Free-Piston Engine Compressor
9. Pump Switching and Prognostics for Displacement Controlled Multi-Actuator Hydraulic Hybrid Machines (New)
10. Next Steps towards Virtual Prototyping of Pumps and Motors
11. Human Performance Modeling and User Centered Design
12. Microtextured Surfaces for Low Friction / Leakage
13. System Configuration & Control Using Hydraulic Transformers (New)
14. Actively Controlled Digital Pump/Motor
15. High Performance Valves Enabled by Kinetic Energy (New)
16. Energy Efficient Fluids
17. Leakage/Seal Friction Reduction in Fluid Power Systems
18. Free-Piston Engine Hydraulic Pump
19. Active Vibration Damping of Mobile Hydraulic Machines (New)
20. Variable Displacement External Gear Machine (New)
21. Fluid-Powered Surgery & Rehabilitation via Compact, Integrated Systems

The list of Y9-Y10 approved projects appears below:

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

Project Reviews: There are several project reviews throughout the year. The Executive Committee reviews each project twice a year. The SAB reviews the projects annually and provides a written report to CCEFP management. The PI's present project reviews during the IAB meetings held at member universities. The IAB members provide feedback. The IAB also responds to an annual survey on each project to provide the PI's and management feedback about the value of the project from an industry perspective. Corrective action is taken in response to each of these reviews. The NSF site review team also provides feedback to the CCEFP with recommendations.

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 and center operations. Budget proposals are submitted to the CCEFP director and are reviewed and approved by the management committee. Regular reports are created by the Administrative Director (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. This topic is discussed in more detail in the financial section of this report.

RET & REU Integration

Eighteen REU students participated in summer 2013, the seventh year of the program: five at the University of Minnesota, five at Purdue University, two at the University of Illinois Urbana-Champaign, two at North Carolina A & T, two at Georgia Institute of Technology and two at the Milwaukee School of Engineering. None of these REU students had previous CCEFP REU experience. Six of the 18 students were recruited from outside the CCEFP's core institutions.

Four teachers participated as RETs in summer 2013, the seventh year of the CCEFP RET program: two at Purdue University and two at North Carolina A&T State University. 46 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.

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.

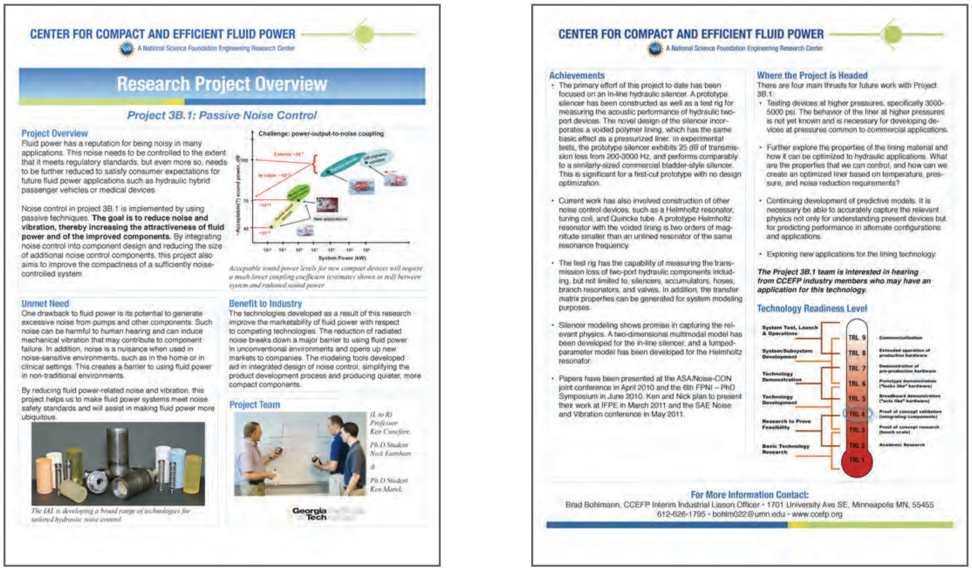
A brief description of key communications tools used to reach our many stakeholders follows:

Meetings - 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 collocated with the ASME/Bath symposium
    CCEFP Student Retreat at Caterpillar, Inc.
2014 – CCEFP annual meeting at Vanderbilt University
    CCEFP Student Retreat at TBD

The 2014 Site Visit will take place at the University of Minnesota and the Annual Meeting will take place at Vanderbilt University.

Research Project Overviews – 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. They are currently online at the CCEFP website (www.ccefp.org). An example is shown below.



CENTER FOR COMPACT AND EFFICIENT FLUID POWER

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Research Project Overview

Project 3B.1: Passive Noise Control

Project Overview

Fluid power has a reputation for being noisy in many applications. This noise needs to be controlled to the extent that it meets regulatory standards, but even more so, needs to be further reduced to satisfy consumer expectations for future fluid power applications such as hydraulic hybrid passenger vehicles or medical devices.

Noise control in project 3B.1 is implemented by using passive techniques. **The goal is to reduce noise and vibration, thereby increasing the attractiveness of fluid power and of the improved components.** By integrating noise control into component design and reducing the size of additional noise control components, this project also aims to improve the compactness of a sufficiently noise-controlled system.

Acceptable sound power levels for new compact devices will require a much lower coupling coefficient (estimates shown in red) between system and radiated sound power

Unmet Need

One drawback to fluid power is its potential to generate excessive noise from pumps and other components. Such noise can be harmful to human hearing and can induce mechanical vibration that may contribute to component failure. In addition, noise is a nuisance when used in noise-sensitive environments, such as in the home or in clinical settings. This creates a barrier to using fluid power in non-traditional environments.

By reducing fluid power-related noise and vibration, this project helps us to make fluid power systems meet noise safety standards and will assist in making fluid power more ubiquitous.

The IAL is developing a broad range of technologies for tailored hydraulic noise control.

Benefit to Industry

The technologies developed as a result of this research improve the marketability of fluid power with respect to competing technologies. The reduction of radiated noise breaks down a major barrier to using fluid power in unconventional environments and opens up new markets to companies. The modeling tools developed aid in integrated design of noise control; simplifying the product development process and producing quieter, more compact components.

Project Team

(L to R) Professor Ken Cunefare, Ph.D Student Nick Earnhart & Ph.D Student Ken Marek.

Georgia Tech

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Achievements

- The primary effort of this project to date has been focused on an in-line hydraulic silencer. A prototype silencer has been constructed as well as a test rig for measuring the acoustic performance of hydraulic two-port devices. The novel design of the silencer incorporates a voided polymer lining, which has the same basic effect as a pressurized liner. In experimental tests, the prototype silencer exhibits 25 dB of transmission loss from 200-3000 Hz, and performs comparably to a similarly-sized commercial bladder-style silencer. This is significant for a first-cut prototype with no design optimization.
- Current work has also involved construction of other noise control devices, such as a Helmholtz resonator, tuning coil, and Quincke tube. A prototype Helmholtz resonator with the voided lining is two orders of magnitude smaller than an unlined resonator of the same resonance frequency.
- The test rig has the capability of measuring the transmission loss of two-port hydraulic components including, but not limited to, silencers, accumulators, hoses, branch resonators, and valves. In addition, the transfer matrix properties can be generated for system modeling purposes.
- Silencer modeling shows promise in capturing the relevant physics. A two-dimensional multimodal model has been developed for the in-line silencer, and a lumped-parameter model has been developed for the Helmholtz resonator.
- Papers have been presented at the ASA/Noise-CON joint conference in April 2010 and the 6th FPNI – PhD Symposium in June 2010. Ken and Nick plan to present their work at IFPE in March 2011 and the SAE Noise and Vibration conference in May 2011.

Where the Project is Headed

There are four main thrusts for future work with Project 3B.1:

- Testing devices at higher pressures, specifically 3000-5000 psi. The behavior of the liner at higher pressures is not yet known and is necessary for developing devices at pressures common to commercial applications.
- Further explore the properties of the lining material and how it can be optimized to hydraulic applications. What are the properties that we can control, and how can we create an optimized liner based on temperature, pressure, and noise reduction requirements?
- Continuing development of predictive models. It is necessary be able to accurately capture the relevant physics not only for understanding present devices but for predicting performance in alternate configurations and applications.
- Exploring new applications for the lining technology.

The Project 3B.1 team is interested in hearing from CCEFP industry members who may have an application for this technology.

Technology Readiness Level

For More Information Contact:

Brad Bohlmann, CCEFP Interim Industrial Liason Officer • 1701 University Ave SE, Minneapolis MN, 55455
612-626-1795 • bohlm022@umn.edu • www.ccefp.org

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Research Project Overviews

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.

Welcome to the CCEFP Project Center

The 2013 NSF Site Visit will take place on **Tuesday, April 23rd and Wednesday, April 24th** at Purdue University in Lafayette, Indiana.

Hotel information and the meeting agenda are posted at:

http://www.ccefp.org/events/2013-nsf-site-visit

We're glad you're here.

This is an internal, community-maintained site where you can track your contributions to the CCEFP, follow what others are doing, and make connections with like-minded people in academics and industry.

This site will also function as our primary data collection point for required NSF reporting so the contents CCEFP researchers and industry partners would like to know more about the work you're doing. If you haven't done so already, please take a few minutes to add CCEFP projects you're involved with, publications you've authored, etc.

Edit My Profile: Begin here. Your current profile includes only a small amount of information that may or may not be 100% accurate. Please "edit" the content and "add" missing items.

Connect With Others: The Entire CCEFP community is here, or will be soon. Check out what they are doing, update information for those who have left.

Explore Projects: Review existing Core and Associated projects. Add new projects and modify previous year's projects.

Promote My Work & My Entries: A summary of all activities on which you are currently named. This includes items you have entered and items others have entered on your behalf.

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Resources for Effective Presentation Skills – CCEFP provides resources for students to improve their presentation skills. Using the Center's webcast capability, we have made available on our website a video tutorial presented by JoAnn Syverson, Senior Lecturer of the University of Minnesota's Carlson School of Business. Additionally, CCEFP's prospective speakers can review technical presentation guidelines, also available on www.ccefp.org, which were written to enhance presentations for our industry partners. In the future, we will make available more resources of this nature to provide students and faculty with tools to enhance their presentation capabilities.

Website - The CCEFP website, www.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 the widest audience and content is updated regularly. 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.

CENTER FOR COMPACT AND EFFICIENT FLUID POWER

nsf A National Science Foundation Engineering Research Center

CHANGING THE WAY FLUID POWER IS RESEARCHED, APPLIED AND TAUGHT

Hydraulically Actuated Orthosis

A superior power to weight ratio makes fluid power ideal for applications like orthoses where space and weight area at a premium. A fluid power orthoses will greatly improve the quality of life for numerous patients.

Research

Transforming fluid power to dramatically reduce energy consumption and create whole new fields of use for fluid power technology.

Education & Outreach

Training tomorrow's leaders while enhancing fluid power education and increasing public awareness.

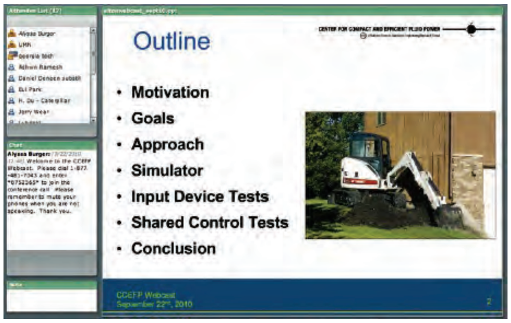
Industry

Partnering with the Fluid Power industry to help bring real-world solutions to the challenges in advancing fluid power.

Industry CEO Letters from the Director - Once per quarter, CCEFP mails letters to all industry member CEOs highlighting achievements and important discoveries that have transpired in the previous three months. In this way, industry executives are made aware of the progress within the Center from a high-level view. Whenever possible, the Center also seeks to highlight the collaborative efforts of individual IAB representatives and Project Champions, so CEOs are aware of the efforts taking place on behalf of their companies.

E-mail Newsblasts - CCEFP Newsblasts provide updates on a variety of activities taking place in and around the Center. The abbreviated format of the stories enables the reader to see a brief synopsis of each with the option to read more.

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.



Outline

- Motivation
- Goals
- Approach
- Simulator
- Input Device Tests
- Shared Control Tests
- Conclusion

CCEFP Webcast
September 22nd, 2010

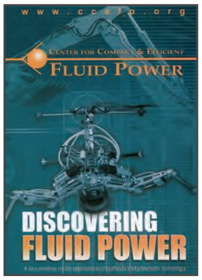
CCe-FP Electronic Newsletter

The CCEFP newsletter is published quarterly to allow for more in-depth content, specifically in the research areas. It is circulated electronically via our comprehensive e-mail lists and reaches subscribers in all stakeholder areas including academia, the trade press, industry, K-12 education, and many others both in the U.S. and internationally.

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** (http://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.*

SUSTAINABILITY

Sustainability planning has been ongoing effort of the CCEFP for the last few years, with the intensity growing substantially the last two years. Center sustainability was again front and center at the 2013 CCEFP Annual Meeting. It was the main topic of discussion at the IAB and SAB meetings held during the event. In addition, the Center held another joint IAB-SAB meeting at the Annual Meeting to let the groups share their thoughts and ideas about Center sustainability. Support from both the IAB and SAB for a self-sustaining Center continues to be very strong and many excellent suggestions and insights were gained. Major themes that came from this session were:

1) It is paramount that the post-NSF Center strives to be inclusive. This means not only any US university is eligible for research funding but that all of the fluid power industry, regardless of technology focus or size, are involved in a meaningful way.
2) Industry must continue to have meaningful input into the Center's research strategy, project selection, project progress/results and Center governance.
3) The post NSF should strive to optimize administrative costs. What activities (and related costs) can be eliminated? Can the Center share activities (and related costs) with NFPA or other organizations?

Based on this feedback the CCEFP has undertaken major improvements to its Sustainability Plan. The plan still calls for three major elements 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 research. Negotiations with the NFPA have resulted in a plan for them to take the lead in fund raising for pre-competitive research. They intend to launch a Pascal Society initiative that will utilize their existing 501c3 Foundation to raise gifts from industry that will be targeted for pre-competitive research. Funds from these efforts will be awarded in the form of annual grants to the Center. The partnership has enlisted the services of a renowned Minneapolis-based marketing firm, Padilla CRT, to help form the message and accompanying marketing campaign. The initial grant will provide a guaranteed two year amount equal to or greater than the Center's industry membership dues. In exchange the Center will turn over its membership base to the Foundation fund raising efforts. Each year the Foundation will guarantee funding for another year thus ensuring a minimum two year funding window. During these discussions a five year funding forecast will also be provided. Specific details of the grant agreement are still being finalized and will be provided during the upcoming NSF Site Visit. In addition the Center has formed two committees to focus on securing additional government grants and increasing sponsored research.

The CCEFP Government Relations committee 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, National Fluid Power Association
- Brad Bohlmann, CCEFP Sustainability Director

The CCEFP Industry Relations committee is led by the CCEFP ILO Mike Gust and has the following members:

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

High level goals, strategies and tactics will be presented and discussed at the upcoming NSF Site Visit.

Executive summary

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 document 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 approximately 45 industry members, 20 of which are on the Industrial Advisory Board. 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 $793K in industry dues. Center researchers also received more than $2M in funding from government and industry sources for associated sponsored research projects in FY8. 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.

Financial Tables

Table 8 shows the planned functional budget for the current award year 8 (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 (33%), Compactness Thrust (26%), Effectiveness Thrust (21%) and Test Beds (18%). The percentage distribution of the functional budget is shown in Figure 8a. The major expense is research, shown at 24.9% of the budget, with funding for education and outreach activities (including REU and RET) at 6.2 %. Anticipated residual funds remaining (43%) are the result of delayed billing and payment of incurred expenses and not actual residuals as most have been budgeted or are waiting to be expended with the approval and release of 33% of Y8 funding, upon approval from the Engineering Review Board (ERB). Table 9 shows an increase in member company dues. Industry dues have increased in the current award year, Year 8 to $793K, over Year 7 - $586K; and Year 6 - $736K. CCEFP strategized with NFPA to energize recruitment of industry members and fees, and we expect the Year 8 level of funding to be sustained and grow to more than $1M in the years ahead.

The number of industry members has remained steady at 45. As described in Sections 1 and 4, the core strategic partners remain in place and efforts to improve engagement are underway. New members joined in the last year, Hitachi Construction Machinery, Idemitsu Kosan, JCB and Pall. JCB's member agreement has been received; however they are not shown in the member tables because of the NSF reporting requirement that dues be received by end of reporting year, January 31, 2014. Hitachi and JCB are construction equipment manufacturers, Idemitsu Kosan is a fluid provider and Pall is a filtration company. These four new members epitomize our approach to recruitment; each one had been specifically targeted because they are aligned with our strategy.

It is anticipated that this basic distribution will continue into the future with only minor modifications. It is expected that industry membership fees, associated projects from industry and government will continue to grow in year 9. Equipment donations in Year 8 were valued at $303K, representing one third of all donations since CCEFP inception. 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 has remained steady, with just more than $2M in Y8 reported, $2.4 in Y7, $2.3M in Y6, and $1.8M in Y5.

Table 8b below shows the Year 8 budget distribution by university. The largest recipient of direct cash funding is the lead university with 49%. The largest recipient of associated project funding in year 8 is Purdue with 61%. 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	$2,412,632	$340,596	$2,753,228	49%	17%
Georgia Tech	$657,913	$159,327	$817,240	13%	8%
Milwaukee School of Engineering	$174,809	$0	$174,809	4%	0%
North Carolina A & T	$177,443	$0	$177,443	4%	0%
Purdue University	$819,866	$1,221,540	$2,041,406	17%	61%
UIUC	$262,766	$28,124	$290,890	5%	1%
Vanderbilt University	$316,196	$266,766	$582,962	6%	13%
Science Museum of Minnesota	$90,000	$0	$90,000	2%	0%
Quality Evaluation Design (QED)	$41,204	$0	N/A	N/A	N/A
FolsomTechnologies International	$0	$0	N/A	N/A	N/A
Grand Total	$4,952,829	$2,016,353	$6,927,978		

Table 8c: Current Award Year Education Budget, a part of the overall ERC 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	$53,321	$1,000	$54,321	$0	**$54,321**
University Education	$92,540	$0	$92,540	$0	**$92,540**
Student Leadership Council	$24,800	$0	$24,800	$0	**$24,800**
Young Scholars	$1,000	$0	$1,000	$0	**$1,000**
REU	$159,574	$0	$159,574	$0	**$159,574**
RET	$34,250	$0	$34,250	$0	**$34,250**
Assessment	$50,000	$0	$50,000	$0	**$50,000**
Community College activities	$9,800	$0	$9,800	$10,000	**$19,800**
Other (Public Education)	$95,980	$0	$95,980	$0	**$95,980**
Education Program Total	**$521,265**	**$1,000**	**$522,265**	**$0**	**$532,265**

Table 9a shows the funding history of the Center and includes funding amounts on the base grant for years 1-8, plus supplements since inception. In year 8, CCEFP provided $28K toward two diversity graduate students using NSF CORE research funding, in the absence of the NSF Graduate Diversity Supplements. The local institutions provided the balance needed to fund these graduate students.

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	$29,480,000	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 (Appendix I) shows the sources of support, and Table 9b (next page) includes the cost sharing by institution. In year 7, the Core Partner universities contributed $840,545 in cost-share spending toward the obligated $800,000. Since inception, when some partners fell short, overall the goal has been met or exceeded in year 7 as in past years.

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 Commitment**	
Institution	**Committed**	**Actual**	**Committed**	**Actual**		
U. of Minnesota	$339,537	$602,309	$339,537	-	$2,070,294	
Georgia Tech	$130,232	$61,944	$130,232	-	$1,060,551	
MSOE	$0	-	$0	-	$10,800	
Purdue	$152,557	$56,262	$152,557	-	$1,127,526	
UIUC	$92,093	$84,695	$92,093	-	$899,740	
Vanderbilt	$85,581	$35,335	$85,581	-	$692,630	

Table 10 (Appendix I) shows the annual expenditures and budgets, with Table 10a below showing unexpended residuals. Referring to the residual amounts in Table 10a (next page), the carry-forward amount of $2,170,383 and $0 residuals, shows that all money was either committed or encumbered, at the start of year 8. The residual balance of $0, after committed/encumbered/obligated funds, demonstrates that all funds have been committed. In July, 2013, NSF instructed CCEFP to expend only 67% of the $4M granted in Y8, until the NSF Engineering Review Board (ERB) officially approves CCEFP's renewal. At press, 33% of the Y8 funding has not been expended nor budgeted and is reflected in this balance. The unexpended funds are needed to complete Y8 projects. In year 8, a stricter billing and payroll process was implemented to mitigate delays. Those delays can cause an inaccurate picture of the Center's financial standing. The Center continues to spend in a disciplined pattern as it starts year 9.

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	$2,170,383	$3,723,347
Committed, Encumbered, Obligated funds (obligated = planned for)	$2,170,383	$3,723,347
Residual Funds Without Specified Use	$0	$0

Table 11 (Appendix I) details the modes of recent and historical support provided by Industry Members and non-member organizations alike.

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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.

In previous years, CCEFP hired twelve faculty members: Douglas Adams (VU), Randy Ewoldt (UIUC), Zongliang Jiang (NCAT), Thomas Kurfess (GT), Michael Leamy (GT), Ashlie Martini (PU), Zongxuan Sun (UM), Jun Ueda (GT), Andrea Vacca (PU), Pietro Valdastri (VU), James Van de Ven (UM) and Robert Webster (VU), thus fulfilling its commitment to hire twelve new faculty hires for the center. The University of Minnesota hired one additional faculty member, Cari Dutcher, this year.

The 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 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 9

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

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	NSF Funded Person-months 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	$12,000	$4,032	
3.	Paul		Imbertson	Dr.	0.00	0.00	2.00	$13,000	$4,368	
4.	Thomas		Chase	Dr.	0.00	0.00	1.00	$13,319	$4,475	
6.	Zongxuan		Sun	Dr.	0.00	0.00	1.00	$15,000	$5,040	
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)								107,240	$36,033	

	CAL	ACAD	SUMR	Funds Requested By Proposer	Fringe	Funds Granted by NSF
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)						
1. 0) POST DOCTORAL ASSOCIATES	0.00	0.00	0.00			
2. 1) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	12.00	0.00	0.00	$10,000	$3,680	
3. 9) GRADUATE STUDENTS	12.00			$235,000	$169,200	
4. 3) UNDERGRADUATE STUDENTS	12.00			$34,163	$0	
5. 1.5) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)	12.00					
6. 3) OTHER	12.00			$98,000	$36,064	
TOTAL SALARIES AND WAGES (A+B)				$484,403	$208,944	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				$244,977		
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)				$729,380		
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)				$23,350		
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				$9,500		
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		
5. SUBAWARDS				$1,610,766		
6. OTHER				$0		
TOTAL OTHER DIRECT COSTS				$1,625,266		
H. TOTAL DIRECT COSTS (A THROUGH G) Rate				$2,381,995		
I. INDIRECT COSTS (SPECIFY RATE AND BASE) 0						
TOTAL INDIRECT COSTS				$298,004		
J. TOTAL DIRECT AND INDIRECT COSTS (H+I)				$2,680,000		
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)				$2,680,000		
M. COST SHARING: PROPOSED LEVEL AGREED LEVEL IF DIFFERENT $				$536,000		

Grad fringe and eqpt exempt idc
stipends, reduced idc 25%
Equip. exempt idc

Direct costs	$771,229.14	
Less Grad fringe, equipment Ex	$169,200.00	49.50%
Total DC	$602,029.14	
Total IDC	$298,004.42	

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

*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
Do not enter anything in the red cells
You should be entering the values yo
FastLane will ignore all data in cells t
If you want to create additional years
The "create new budget years" butto

PLEASE DO NOT ENTER CENTS II

YEAR 9

FOR NSF USE ONLY

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

6/1/2014 - 5/30/2015

	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By Proposer	
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		
1. J. S Newlin Director, Physical Sciences	0.00	0.00	0.00	$2,000	
(1) TOTAL SENIOR PERSONNEL (1-6)				$2,000	
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	$23,100	
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)				$25,100	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				$10,793	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)				$35,893	
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)				$1,200	
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				$5,075	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				$0	
3. CONSULTANT SERVICES				$0	
4. COMPUTERS SERVICES				$0	
5. SUBAWARDS				$0	
6. OTHER				$0	
TOTAL OTHER DIRECT COSTS				$5,075	
H. TOTAL DIRECT COSTS (A THROUGH G)				$42,168	
I. INDIRECT COSTS (SPECIFY RATE AND BASE) Name of indirect cost item Amount Rate TDC less equipment $42,168 ###### 18132					
TOTAL INDIRECT COSTS				$18,132	
J. TOTAL DIRECT AND INDIRECT COSTS (H+I)				$60,300	
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)				$60,300	
M. COST SHARING: PROPOSED LEVEL AGREED LEVEL IF DIFFERENT $				$0	

PI/PD NAME J. Shipley Newlin Jr. J. Newlin	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 9**

	FOR NSF USE ONLY		
ORGANIZATION **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**				**2,379**	
2. **Jun Ueda**				**1,305**	
3. **Scott Bair**				**9,847**	
4. **Ken Cunefare**				**2,659**	
5. **Richard Salant**				**3,364**	
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)					
7. (**0**) TOTAL SENIOR PERSONNEL (1-6)				**19,553**	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (**3**) POST DOCTORAL ASSOCIATES				**22,028**	
2. (**0**) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)					
3. (**7**) GRADUATE STUDENTS				**99,270**	
4. (**0**) UNDERGRADUATE STUDENTS					
5. (**0**) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)					
6. (**0**) OTHER					
TOTAL SALARIES AND WAGES (A + B)				**140,851**	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				**12,674**	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)				**153,525**	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TOTAL EQUIPMENT				**0**	
E. TRAVEL 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)				**14,752**	
2. FOREIGN					
F. PARTICIPANT SUPPORT COSTS					
1. STIPENDS **$10,000 ($5000 per student X 2)**					
2. TRAVEL **$2,000 ($1000 per student X 2)**					
3. SUBSISTENCE **$2,240 ($1120 per student X 2)**					
4. OTHER **$4,000 ($2000 per student X 1)**					
( ) TOTAL PARTICIPANT COSTS				**18,240**	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				**20,274**	
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 tuitio**n =	**Tuition =**			**58,885**	
TOTAL OTHER DIRECT COSTS				**79,159**	
H. TOTAL DIRECT COSTS (A THROUGH G)				**265,676**	
I. INDIRECT COSTS (F&A) (SPECIFY RATE AND BASE) 51.0% Modified Total Direct Costs					
TOTAL INDIRECT COSTS (F&A)	Base Amount:		**$188,551**	**99,052**	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				**364,728**	
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)				**364,728**	
M. COST SHARING: PROPOSED LEVEL $ 130232	AGREED LEVEL IF DIFFERENT $			**86,930**	

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

NSF Form 1030 (10/99) Supersedes All Previous Editions

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

YEAR 9

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	Funds Granted by NSF	

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	1.00	$14,510	
2. Steven Jiang	0.00	0.00	1.00	$12,056	
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)				$26,568	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. 0) 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)				$60,568	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				$8,767	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)				$69,335	
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)				$7,000	
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				$1,993	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				$500	
3. CONSULTANT SERVICES				$0	
4. COMPUTERS SERVICES				$0	
5. SUBAWARDS				$0	
6. OTHER (tuition for graduate students)				$24,001	
TOTAL OTHER DIRECT COSTS				$0	
H. TOTAL DIRECT COSTS (A THROUGH G)				$92,829	
I. INDIRECT COSTS (SPECIFY RATE AND BASE) Name of Indirect cost Item / Amount $27,531 / Rate 40.00% $0					
TOTAL INDIRECT COSTS				$27,531	
J. TOTAL DIRECT AND INDIRECT COSTS (H+I)				$120,360	
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)				$120,360	
M. COST SHARING: PROPOSED LEVEL AGREED LEVEL IF DIFFERENT $				$0	

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

4/10/12

Celestine Ntuen, PhD.

Interim Vice-Chancellor for Research and Economic Development

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SUMMARY PROPOSAL BUDGET – YEAR 9

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. (3) GRADUATE STUDENTS				90,156	
4. (1) UNDERGRADUATE STUDENTS				5,408	
5. ( ) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				0	
6. ( ) OTHER				0	
TOTAL SALARIES AND WAGES (A + B)				95,564	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				5,643	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				101,207	
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)				5,968	
2. FOREIGN					
F. PARTICIPANT SUPPORT 1. STIPENDS $ 6,700 2. TRAVEL 0 3. SUBSISTENCE 0 4. OTHER 6,566					
TOTAL NUMBER OF PARTICIPANTS () TOTAL PARTICIPANT COSTS				13,266	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				24,829	
2. PUBLICATION/DOCUMENTATION/DISSEMINATION				0	
3. CONSULTANT SERVICES				5,000	
4. COMPUTER SERVICES				0	
5. SUBAWARDS				0	
6. OTHER Tuition Remission line B.3. x 37.0%				33,358	
TOTAL OTHER DIRECT COSTS				63,187	
H. TOTAL DIRECT COSTS (A THROUGH G)				183,628	
I. INDIRECT COSTS (F&A) (SPECIFY RATE AND BASE) 25% of Participant support stipend of $6,700 53% of all other MTDC					
TOTAL INDIRECT COSTS (F&A)				74,287	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				257,915	
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)				257,915	$

M. COST SHARING: PROPOSED LEVEL $63,279	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

NSF Form 1030 (10/99) ***Supersedes All Previous Editions***

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

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SUMMARY PROPOSAL BUDGET

FOR NSF USE ONLY			
ORGANIZATION Vanderbilt University Year 9 Budget	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. (0) POSTDOCTORAL ASSOCIATES					
2. ( ) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)					
3. (3) GRADUATE STUDENTS					79,200
4. (4) UNDERGRADUATE STUDENTS					16,000
5. ( ) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)					
6. ( ) OTHER					
TOTAL SALARIES AND WAGES (A + B)					104,759
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)					1,969
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)					106,728
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)					10,000
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					12,507
2. PUBLICATION/DOCUMENTATION/DISSEMINATION					1,500
3. CONSULTANT SERVICES					
4. COMPUTER SERVICES					
5. SUBAWARDS					
6. OTHER					
TOTAL OTHER DIRECT COSTS					14,007
H. TOTAL DIRECT COSTS (A THROUGH G)					164,735
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 ($130,735 MTDC Base)					
TOTAL INDIRECT COSTS (F&A)					74,943
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)					239,678
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)				$	$239,678

M. COST SHARING: PROPOSED LEVEL $	AGREED LEVEL IF DIFFERENT: $57,125			
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

NSF Form 1030 (10/99) ***Supersedes All Previous Editions***

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

2014-2015 Year 9 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	6,500
2.				0
3.				0
4.				0
5.				0
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)	-	-	-	0
7. ( ) TOTAL SENIOR PERSONNEL (1-6)	-	-	-	6,500
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)				
1. ( ) POST DOCTORAL ASSOCIATES				0
2. ( ) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)				0
3. ( ) GRADUATE STUDENTS				20,000
4. ( ) UNDERGRADUATE STUDENTS				13,000
5. ( ) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				0
6. ( ) OTHER				0
TOTAL SALARIES AND WAGES (A+B)				39,500
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				6,240
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)				45,740
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)				15,008
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				32,723
2. PUBLICATION/DOCUMENTATION/DISSEMINATION				0
3. CONSULTANT SERVICES				0
4. COMPUTER SERVICES				0
5. SUBAWARDS				0
6. OTHER				23,565
TOTAL OTHER DIRECT COSTS				56,288
H. TOTAL DIRECT COSTS (A THROUGH G)				146,436
I. INDIRECT COSTS (F&A) (SPECIFY RATE AND BASE)				
40% on salaries & fringe base $45,740				
25% on REU stipends base = $10,000				
TOTAL INDIRECT COSTS (F&A)				20,796
J. TOTAL DIRECT AND INDIRECT COSTS (H+I)				167,232
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)				167,232
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 2/26/13	Date Checked	Date of Rate Sheet	

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SUMMARY PROPOSAL BUDGET

FOR NSF USE ONLY

ORGANIZATION Purdue University (YEAR 9)	PROPOSAL NO.	DURATION (MONTHS) Proposed	DURATION (MONTHS) 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	25,853	$
2. John Lumkes, Associate Professor			1.0	11,210	
3. Andrea Vacca, Assistant Professor			1.0	10,312	
4.					
5.					
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)					
7. ( ) TOTAL SENIOR PERSONNEL (1-6)					
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (1) POSTDOCTORAL ASSOCIATES	100			60,109	
2. ( ) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)					
3. (2) GRADUATE STUDENTS				52,423	
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)				37,843	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				197,750	
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				67,553	
2. PUBLICATION/DOCUMENTATION/DISSEMINATION					
3. CONSULTANT SERVICES					
4. COMPUTER SERVICES					
5. SUBAWARDS					
6. OTHER Grad Fee Remission				22,666	
TOTAL OTHER DIRECT COSTS					
H. TOTAL DIRECT COSTS (A THROUGH G)				287,969	
I. INDIRECT COSTS (F&A) (SPECIFY RATE AND BASE) 52.5% of MDTC (Base used $265,303)				139,284	
TOTAL INDIRECT COSTS (F&A)				139,284	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				427,253	
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 $101,832	AGREED LEVEL IF DIFFERENT: $
PI/PD TYPED NAME AND SIGNATURE*	DATE
ORG. REP. TYPED NAME & SIGNATURE* Amy J. Wright-Signature on Cumulative Budget	DATE

FOR NSF USE ONLY

INDIRECT COST RATE VERIFICATION

Date Checked	Date of Rate Sheet	Initials-ORG

NSF Form 1030 (10/99) ***Supersedes All Previous Editions***

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

CCEFP/QED Year 9	**CCEFP Budget: June-May, 2014-2015**		
	CAL person months		
A. Senior Personnel			
Gary Lichtenstein	0.12	$12,000.00	
Maggie Miller	0.04	$3,000.00	
Others			
7. TOTAL SENIOR PERSONNEL		$15,000.00	
B. Other Personnel			
Post Doc			
Other Professionals (e.g. computer programmer)			
Clerical (if charged directly)			
Other			
TOTAL SALARIES & WAGES		$15,000.00	
Fringe Benefit (if charged as direct cost)		$0.00	
TOTAL SALARIES & WAGES + Fringe (A+B+C)		$15,000.00	
D. Total Equipment		$0.00	
a.			
b.			
c.			
E. Travel			
E. Travel-- Domestic (incl. Canada, Mex, U.S. Possessions)		$3,000.00	
E. Travel--Foreign		$0.00	
F. Participant Support (Grad Students, those being trained)		$0.00	
Travel			
Stipends			
Subsistence			
Other			
G. Other Direct Costs		$15,500.00	
1. MATERIALS AND SUPPLIES	500		
2. PUBLICATION/DOCUMENTATION/DISSEMINATION			
3. CONSULTANT SERVICES	15000		
4. COMPUTER SERVICES			
5. SUBAWARDS			
6. OTHER			
H. TOTAL DIRECT COSTS (A-G)		$33,500.00	
I. Indirect Coss		$0.00	
RATE:			
J. Total Direct & Indirect (sum H+I)		$33,500.00	
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)		**$33,500.00**	

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APPENDIX I

Data Tables and Figures

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Table 1: Quantifiable Outputs

Outputs	Early Cumulative Total [1]	Feb-01-2009 - Jan-31-2010	Feb-01-2010 - Jan-31-2011	Feb-01-2011 - Jan-31-2012	Feb-01-2012 - Jan-31-2013	Feb-01-2013 - Jan-31-2014	All Years
Publications Resulting From Core Funding							
In Peer-Reviewed Technical Journals	12	27	22	12	22	24	119
In Peer-Reviewed Conference Proceedings	76	51	59	52	32	23	293
In Trade Journals	3	23	0	2	0	3	31
With Multiple Authors:	82	101	76	51	54	50	414
Co-authored With ERC Students	63	71	50	51	40	35	310
Co-authored With Industry	2	4	3	2	2	0	13
With Authors From Multiple Engineering Disciplines	4	12	3	6	7	4	36
With Authors From Both Engineering and Non-Engineering Fields	11	7	2	6	2	7	35
With Authors From Multiple Institutions	11	7	10	9	0	8	45
Publications Resulting From Associated Projects in the Strategic Plan							
In Peer-Reviewed Technical Journals	14	16	6	5	7	8	56
In Peer-Reviewed Conference Proceedings	37	23	7	10	13	17	107
Publications Resulting From Sponsored Projects							
In Peer Reviewed Technical Journals	0	6	0	0	0	2	8
In Peer-Reviewed Conference Proceedings	0	24	0	0	0	3	27
Participating Organizations							
Industrial Practitioner Members	172	54	54	48	41	45	414
Innovation Partners	0	0	0	1	1	1	3
Funders of Sponsored Projects	0	0	0	0	0	1	1
Funders of Associated Projects	14	5	15	8	8	10	60
Contributing Organizations	0	2	5	9	6	4	26
ERC Technology Transfer							
Inventions Disclosed (by researchers or tech transfer office)	15	9	7	12	3	6	52
Total Patent Applications Filed	10	6	4	4	6	6	36
Provisional Patent Applications Filed [1]	N/A	N/A	N/A	N/A	3	5	8
Full Patent Applications Filed [1]	N/A	N/A	N/A	N/A	3	1	4
Patent Awarded	1	0	1	2	1	1	6
Licenses Issued	0	0	2	0	2	1	5
Spin-off Companies Started	0	1	0	0	1	1	3
Estimated Number of Spin-off Company Employees	0	0	0	0	1	1	2
Building Codes Impacts	0	0	0	0	0	0	0
Technology Standards Impacts	2	2	4	1	1	1	11
New Surgical and Other Medical Procedures Adopted	0	0	0	0	0	0	0
Degrees to ERC Students							
Bachelor's Degrees Granted	32	44	18	10	10	7	121
Master's Degrees Granted	24	32	14	10	10	7	97
Doctoral Degrees Granted	8	5	9	6	12	11	51
Job Sector of ERC Graduates							
Undergraduates Hired by:							
Industry:	N/A	N/A	N/A	4	0	1	5
ERC Member Firms	N/A	N/A	N/A	0	0	1	1
Other U.S. Firms	N/A	N/A	N/A	4	0	0	4
Other Foreign Firms	N/A	N/A	N/A	0	0	0	0
Government	N/A	N/A	N/A	0	0	0	0
Academic Institutions	N/A	N/A	N/A	4	3	0	7
Other	N/A	N/A	N/A	0	1	0	1
Undecided/Still Looking/Unknown	N/A	N/A	N/A	2	6	6	14
Undergraduate ERC Graduates Total	0	0	0	10	10	7	27
Master's Graduates Hired by:							
Industry:	N/A	N/A	N/A	8	1	0	9
ERC Member Firms	N/A	N/A	N/A	2	1	0	3
Other U.S. Firms	N/A	N/A	N/A	6	0	0	6
Other Foreign Firms	N/A	N/A	N/A	0	0	0	0
Government	N/A	N/A	N/A	0	0	0	0
Academic Institutions	N/A	N/A	N/A	2	0	0	2
Other	N/A	N/A	N/A	0	2	2	4
Undecided/Still Looking/Unknown	N/A	N/A	N/A	0	7	5	12
Master's ERC Graduates Total	0	0	0	10	10	7	27
Ph.D.s Hired by:							
Industry:	N/A	N/A	N/A	2	0	1	3
ERC Member Firms	N/A	N/A	N/A	1	0	1	2
Other U.S. Firms	N/A	N/A	N/A	1	0	0	1
Other Foreign Firms	N/A	N/A	N/A	0	0	0	0
Government	N/A	N/A	N/A	0	0	1	1
Academic Institutions	N/A	N/A	N/A	3	0	0	3
Other	N/A	N/A	N/A	0	4	1	5
Undecided/Still Looking/Unknown	N/A	N/A	N/A	1	8	8	17
Ph.D. ERC Graduates Total	0	0	0	6	12	11	29
ERC Influence on Curriculum							
New Courses Based on ERC Research That Have Been Approved by the Curriculum Committee and Are Currently Offered [2]	4	2	8	2	0	4	20
Currently Offered, ongoing Courses With ERC Content	15	12	12	19	28	29	N/A
New Textbooks Based on ERC Research	2	1	1	0	0	0	4
New Textbook Chapter Based on ERC Research	0	1	0	0	0	0	1
Free-Standing Course Modules or Instructional CDs	0	0	0	3	5	2	10
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	2	1	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	0	1710	1700	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]	31	9	9	83	85	62	279
Number of Participants That Attended Events	0	86	135	2322	5189	500	8232
Innovation-focused Workshops, Short courses, Webinars, and Seminars	N/A	N/A	5	39	14	1	59
Number of Participants That Attended Events	N/A	N/A	25	1172	1120	25	2342

Table 1: Quantifiable Outputs

Outputs	Early Cumulative Total [1]	Feb-01-2009 - Jan-31-2010	Feb-01-2010 - Jan-31-2011	Feb-01-2011 - Jan-31-2012	Feb-01-2012 - Jan-31-2013	Feb-01-2013 - Jan-31-2014	All Years
Seminars, Colloquia, Invited Talks, Etc.	68	24	35	18	7	10	162
ERC Sponsored Educational Outreach Events for K-12 Students	0	14	28	15	19	25	101
Number of Students That Attended Events	0	4365	3251	10926	11000	40513	70055
Number of Teachers That Attended Events	0	26	30	100	500	5141	5797
ERC Sponsored Educational Outreach Events for Community Colleges	0	8	9	9	4	1	31
Number of Community College Students That Attended Events	0	244	125	5000	250	10	5629
Number of Community College Faculty That Attended Events	0	24	9	50	4	0	87
ERC Sponsored Educational Outreach Events for Non-ERC Undergraduate Students	0	N/A	N/A	N/A	N/A	15	15
Number of Non-ERC Undergraduate Students That Attended Events	0	N/A	N/A	N/A	N/A	25	25
Number of Undergraduate Faculty That Attended Events	0	N/A	N/A	N/A	N/A	0	0
Personnel Exchanges							
Student Internships in Industry	23	4	14	12	9	5	67
Faculty Working at Member Firm	0	1	1	1	0	0	3
Member Firm Personnel Working at ERC	4	6	0	0	0	1	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: 2013 Average Metrics Benchmarked Against All Active ERCs and the Center's Tech Sector

Metric	Average All Active ERCs FY 2013	Average Advanced Manufacturing Sector FY 2013	Average Class of 2006 FY 2013	Minnesota Twin Cities-CCEFP Total	Minnesota Twin Cities-CCEFP Total
	(20 ERCs)	(5 ERCs)	(5 ERCs)	FY 2013	FY 2014
Organizations Within Non-Industry Sectors	**18**	**13**	**22**	**7**	**4**
Organizations Within Industry Sectors	**20**	**29**	**33**	**49**	**57**
Small	42%	41%	49%	39%	46%
Medium	9%	9%	10%	12%	7%
Large	49%	50%	41%	49%	47%
Industrial/Practitioner Member Firms	**18**	**26**	**30**	**41**	**45**
Innovation Partners	**7**	**4**	**5**	**1**	**1**
Funders of Sponsored Projects	**0**	**1**	**0**	**0**	**1**
Funders of Associated Projects	**11**	**10**	**17**	**8**	**10**
Contributing Organizations	**2**	**2**	**2**	**6**	**4**
Total Number of Organizations	**38**	**42**	**55**	**56**	**61**
Total Membership Fees Received	**$260,106**	**$483,276**	**$401,372**	**$581,100**	**$726,717**

Direct Sources of Support [1]	**$5,361,593**	**$5,576,589**	**$5,897,468**	**$5,496,400**	**$6,292,503**
NSF	68%	75%	76%	74%	70%
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)	7%	11%	9%	11%	17%
University (U.S. and Foreign)	20%	14%	13%	15%	13%
Other	3%	0%	2%	0%	0%

Associated Project Support	**$3,692,281**	**$5,525,905**	**$6,496,463**	**$2,428,713**	**$2,016,854**

ERC Personnel and Educational Participants	**2,920**	**3,213**	**4,369**	**12,057**	**45,945**
Leadership Team [2]	15	14	13	9	11
Faculty [3]	43	35	46	33	32
Graduate Students	78	79	83	81	89
Undergraduate Students	49	82	84	137	112
REU Students	18	26	39	26	23
Community College RET	0	0	0	0	0
K-12 Teachers (RET and non-RET)	11	25	7	17	14
K-12 Students (Young Scholars)	13	22	24	0	0
Faculty/Teachers That Attended ERC Sponsored Educational Outreach Events for K-12 Students [4]	177	127	192	500	5,141
Students That Attended ERC Sponsored Educational Outreach Events for K-12 Students [4]	2,331	2,570	3,667	11,000	40,513
Faculty That Attended ERC Sponsored Educational Outreach Events for Community Colleges [4]	25	62	15	4	0
Educational Outreach Events for Community Colleges [4]	159	171	199	250	10
% Women [5]	30%	32%	32%	22%	22%
% Underrepresented Racial Minorities [6]	13%	12%	14%	29%	24%
% Hispanic [6]	11%	12%	12%	4%	2%

Publications	**Average**	**Average**	**Average**	**Total**	**Total**
In Peer-Reviewed Technical Journals	26	31	39	22	24
In Peer-Reviewed Conference Proceedings	22	17	31	32	23
Multiple Authors: Co-Authored With ERC Students	34	34	48	40	35
Multiple Authors: Co-Authored With Industry	4	1	3	2	0

Intellectual Property	**Average**	**Average**	**Average**	**Total**	**Total**
Invention Disclosures	5	6	9	3	6
Patent Applications (Provisional and Full)	6	7	7	6	6
Patents Awarded	0	0	1	1	1
Licenses (patents, software)	1	1	1	2	1

Education and Outreach Outputs	**Average**	**Average**	**Average**	**Total**	**Total**
New Courses Developed	3	1	3	0	4
Currently Offered, Ongoing Courses With ERC Content	15	12	23	28	29
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

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	$703,335	$0	$1,323,162	$2,026,497	$2,182,500
2: Compactness	$549,299	$0	$0	$549,299	$578,869
3: Effectiveness	$460,924	$0	$398,304	$859,228	$880,230
Test Beds	$386,729	$0	$294,890	$681,619	$597,669

Table 2: Estimated Budgets by Research Thrust [1]

Thrust	Project Name	Organizational Sponsor	Project Leader	Investigators	Current Year Budget	Estimated Next Year Budget
	1A.1: Integrated Algorithms for Optimal Energy Use in Mobile Fluid Power Systems (Center Controlled Project)	NSF ERC Program	Kim A. Stelson (University of Minnesota-Mechanical Engineering)	Andrew G. Alleyne (University of Illinois at Urbana-Champaign)	$1	
	1A.2: Control and Prognostics for Hybrid Displacement Control Systems (Center Controlled Project)	NSF ERC Program	Monika M. Ivantysynova (Purdue University)		$90,200	
	1B.1: Next Steps towards Virtual Prototyping of Pumps and Motors (Center Controlled Project)	NSF ERC Program	Monika M. Ivantysynova (Purdue University)		$90,200	
	1D: Microtextured Surfaces for Low Friction / Leakage (Center Controlled Project)	NSF ERC Program	William King (University of Illinois at Urbana-Champaign-Mechanical Science and Engineering)	Randy H. Ewoldt (University of Illinois at Urbana-Champaign-Department of Mechanical Science and Engineering)	$89,514	
	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)	$1	
	1E.3: Actively Controlled Digital Pump Motor (Center Controlled Project)	NSF ERC Program	John H. Lumkes (Purdue University)	Monika M. Ivantysynova (Purdue University)	$74,230	
	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)	$1	
	1E.5: System Configuration & Control Using Hydraulic Transformers (Center Controlled Project)	NSF ERC Program	Perry Y. Li (University of Minnesota)		$74,615	
	1E.6: High Performance Valves Enabled by Kinetic Energy (Center Controlled Project)	NSF ERC Program	John H. Lumkes (Purdue University)	Monika M. Ivantysynova (Purdue University) Andrea Vacca (Purdue University)	$45,483	
	1F.1: Variable Displacement External Gear Machine (Center Controlled Project)	NSF ERC Program	Andrea Vacca (Purdue University)		$99,341	
	1G.1: Energy Efficient Fluids (Center Controlled Project)	NSF ERC Program	Paul W. Michael (Milwaukee School of Engineering-Fluid Power Institute)		$99,393	
	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)	$40,356	
	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)		$37,200	
	A Characterization of the Pressure-Viscosity Response of Four lubricating Oils (Associated Project)	Shell Global Solutions	Scott S. Bair (Georgia Institute of Technology-School of Mechanical Engineering)		$13,462	
	Advances in modeling external spur gear machines and development of innovative solutions (Associated Project)	Casappa S.p.A.	Andrea Vacca (Purdue University)		$11,875	
	Design of low noise emission internal gear machines (Associated Project - translational research)	Confidential Organization (optional use for associated or sponsored projects only)	Andrea Vacca (Purdue University)		$66,667	
	Development of a Gasoline Engine Driven Ultra High Pressure Hydraulic Pump (Associated Project)	Dae Jin Hydraulics - TECPOS	Andrea Vacca (Purdue University)		$50,000	
	Dynamic model development for hydraulic pumps (Associated Project - translational research)	Confidential Organization (optional use for associated or sponsored projects only)	Monika M. Ivantysynova (Purdue University)		$138,634	
	EFRI-RESTOR: Novel Compressed Air Approach for Off-shore Wind Energy Storage (Associated Project - NSF)		Perry Y. Li (University of Minnesota)	James D. Van de Ven (University of Minnesota-Mechanical Engineering)	$340,596	
	Energy Saving Hydraulic System Architecture utilizing displacement control (Associated Project - translational research)	Confidential Organization (optional use for associated or sponsored projects only)	Monika M. Ivantysynova (Purdue University)		$141,746	
	Evaluation And Design Improvements For A Hydraulic Pump (Associated Project - translational research)	Confidential Organization (optional use for associated or sponsored projects only)	Monika M. Ivantysynova (Purdue University)		$96,428	
	Evaluation of a proprietary gear pump (Associated Project)	Triumph Aerospace Systems	Andrea Vacca (Purdue University)		$21,000	

Table 2: Estimated Budgets by Research Thrust [1]

Thrust	Project Name	Organizational Sponsor	Project Leader	Investigators	Current Year Budget	Estimated Next Year Budget
	generating of FSTI gap design input parameters (Associated Project - translational research)	Confidential Organization (optional use for associated or sponsored projects only)	Monika M. Ivantysynova (Purdue University)		$26,187	
	Modeling and analysis of swash plate type piston motor (Associated Project - translational research)	Confidential Organization (optional use for associated or sponsored projects only)	Monika M. Ivantysynova (Purdue University)		$114,291	
	MODELING OF AXIAL PISTON PUMPS AND MOTORS (Associated Project - translational research)	Confidential Organization (optional use for associated or sponsored projects only)	Monika M. Ivantysynova (Purdue University)		$33,957	
	Modeling of lubricating features of external gear machines and development of quieter solutions (Associated Project)	Casappa S.p.A.	Andrea Vacca (Purdue University)		$92,225	
	New system concept for Electrical Hydraulic Actuation system (Associated Project)	Midwest Precision	Andrea Vacca (Purdue University)		$18,750	
	Optimal Design of a Hydro-Mechanical Transmission Power Split Hybrid Hydraulic Bus (Associated Project)		Kim A. Stelson (University of Minnesota-Mechanical Engineering)	Muhammad Shah Ramdan (Malaysian Ministry of Higher Education (MOHE), University of Minnesota)	$1	
	Pump Dynamic Model Development (Associated Project - translational research)	Confidential Organization (optional use for associated or sponsored projects only)	Monika M. Ivantysynova (Purdue University)		$120,143	
Translational Research Projects Within Thrust					**$738,053**	
Subtotal (all projects) for Thrust					**$2,026,497**	**$2,182,500**
Total Number of Undergraduate Students in Thrust					**1**	
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 K. Durfee (University of Minnesota-Mechanical Engineering)	David B. Kittelson (University of Minnesota-Mechanical Engineering)	$55,356	$578,869
	2B.3: Free Piston Engine Hydraulic Pump (Center Controlled Project)	NSF ERC Program	Zongxuan Sun (University of Minnesota)		$80,278	
	2B.4: Controlled Stirling Thermocompressors (Center Controlled Project)	NSF ERC Program	Eric J. Barth (Vanderbilt University)		$74,514	
	2C.2: Advanced Strain Energy Accumulator (Center Controlled Project)	NSF ERC Program	Eric J. Barth (Vanderbilt University)		$78,945	
	2C.3: Flywheel Accumulator for Compact Energy Storage (Center Controlled Project)	NSF ERC Program	James D. Van de Ven (University of Minnesota-Mechanical Engineering)		$46,000	
	2F: MEMS Proportional Pneumatic Valve (Center Controlled Project)	NSF ERC Program	Thomas R. Chase (University of Minnesota)		$86,522	
	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)	$127,684	
Translational Research Projects Within Thrust					**$0**	
Subtotal (all projects) for Thrust					**$549,299**	**$578,869**
Total Number of Undergraduate Students in Thrust					**1**	
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					**27**	
	3A.1: Teleoperation Efficiency Improvements by Operator Interface (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)	$82,262	
	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)	$100,200	
	3B.3: Active Vibration Damping of Mobile Hydraulic Machines (Center Controlled Project)	NSF ERC Program	Andrea Vacca (Purdue University)		$65,500	
	3D.1: Leakage/Seal Friction Reduction in Fluid Power Systems (Center Controlled Project)	NSF ERC Program	Richard F. Salant (Georgia Institute of Technology)		$71,819	

Table 2: Estimated Budgets by Research Thrust [1]

Thrust	Project Name	Organizational Sponsor	Project Leader	Investigators	Current Year Budget	Estimated Next Year Budget
3: Effectiveness Thrust Leader: Wayne J. Book (Georgia Institute of Technology)	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)		$71,866	$880,230
	3E.1: Pressure Ripple Energy Harvester (Center Controlled Project)	NSF ERC Program	Kenneth A. Cunefare (Georgia Institute of Technology)		$69,277	
	Adaptive ride control for construction machines (Associated Project - translational research)	CNH America, Inc.	Andrea Vacca (Purdue University)		$101,807	
	Determining Water Content at Saturation for Three Common Wind Turbine Gearbox Oils: Mobilgear SHC XMP 320, AMSOIL EP Gear Lube ISO-320 and Castrol Optigear A320 (Associated Project - translational research)		Matthew Whitten (University of Minnesota)		$1	
	High Pressure Compliant Material Development (Associated Project - translational research)	Danfoss	Kenneth A. Cunefare (Georgia Institute of Technology)		$6,662	
	High Pressure Viscosity and Density Measurements on Diesel Fuels (Associated Project)	Cummins Engines	Scott S. Bair (Georgia Institute of Technology-School of Mechanical Engineering)		$39,000	
	High Pressure Viscosity and Density Measurements on Krytox Fluids (Associated Project - translational research)	DuPont	Scott S. Bair (Georgia Institute of Technology-School of Mechanical Engineering)		$5,182	
	Model Predictive Control of Pneumatic Actuators (Associated Project - translational research)	Bimba Manufacturing Company, Festo Corporation, National Defense Science and Engineering Fellowship Grant (NDSEG)	Wayne J. Book (Georgia Institute of Technology)		$10,629	
	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	
	optimization of valve plate to reduce noise and maintain low control effort (Associated Project - translational research)	Confidential Organization (optional use for associated or sponsored projects only)	Monika M. Ivantysynova (Purdue University)		$60,170	
	Rheology Modeling for Mechanical Face Seals (Associated Project)	John Crane	Scott S. Bair (Georgia Institute of Technology-School of Mechanical Engineering)		$14,615	
	Self-powered leak detection system for pipeline monitoring (Associated Project - translational research - NSF)	Veraphotonics, Mistras	Kenneth A. Cunefare (Georgia Institute of Technology)		$32,578	
Translational Research Projects Within Thrust					**$217,029**	
Subtotal (all projects) for Thrust					**$859,228**	**$880,230**
Total Number of Undergraduate Students in Thrust					**8**	
Total Number of Graduate Students (M.S. and Ph.D.) in Thrust					**12**	
Total Number of Postdocs in Thrust					**0**	
Total Number of Personnel in Thrust					**30**	
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)		$79,707	$597,669
	Test Bed 3: Highway Vehicles -- Hydraulic Hybrid Passenger Vehicle (Center Controlled Project)	NSF ERC Program	Perry Y. Li (University of Minnesota)	Thomas R. Chase (University of Minnesota)	$100,242	
	Test Bed 4: Patient Transfer Device (Center Controlled Project)	NSF ERC Program	Wayne J. Book (Georgia Institute of Technology)		$99,174	
	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)		$107,606	
	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)	$212,766	
	I-Corps: CO2 Insufflator for Minimally Invasive Procedures (Associated Project - translational research - NSF)	EndoInSight LLC	Pietro Valdastri (Vanderbilt University-Mechanical Engineering)		$54,000	
	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)		$28,124	
Translational Research Projects Within Thrust					**$54,000**	
Subtotal (all projects) for Thrust					**$681,619**	**$597,669**
Total Number of Undergraduate Students in Thrust					**2**	
Total Number of Graduate Students (M.S. and Ph.D.) in Thrust					**3**	
Total Number of Postdocs in Thrust					**0**	
Total Number of Personnel in Thrust					**13**	

[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

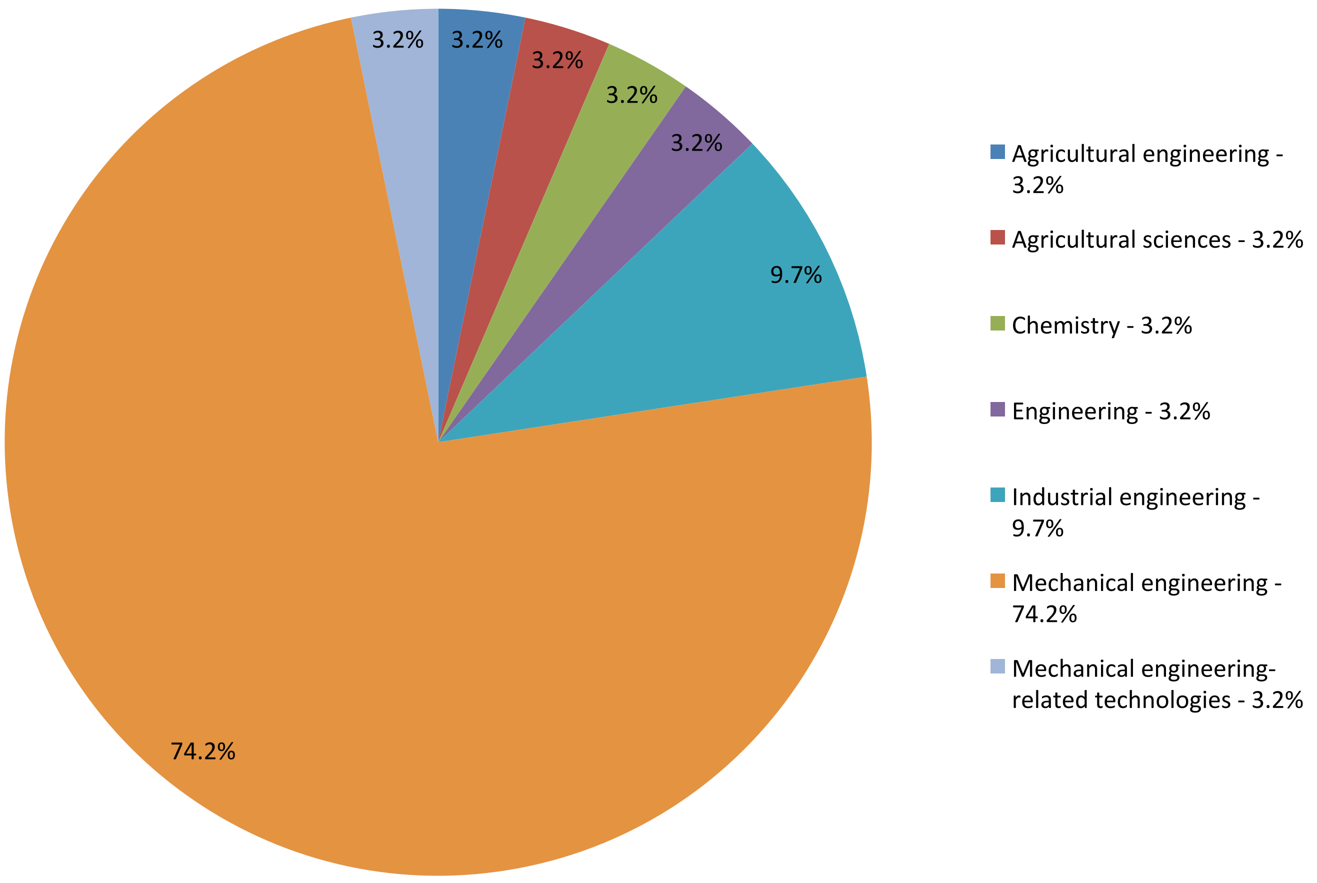
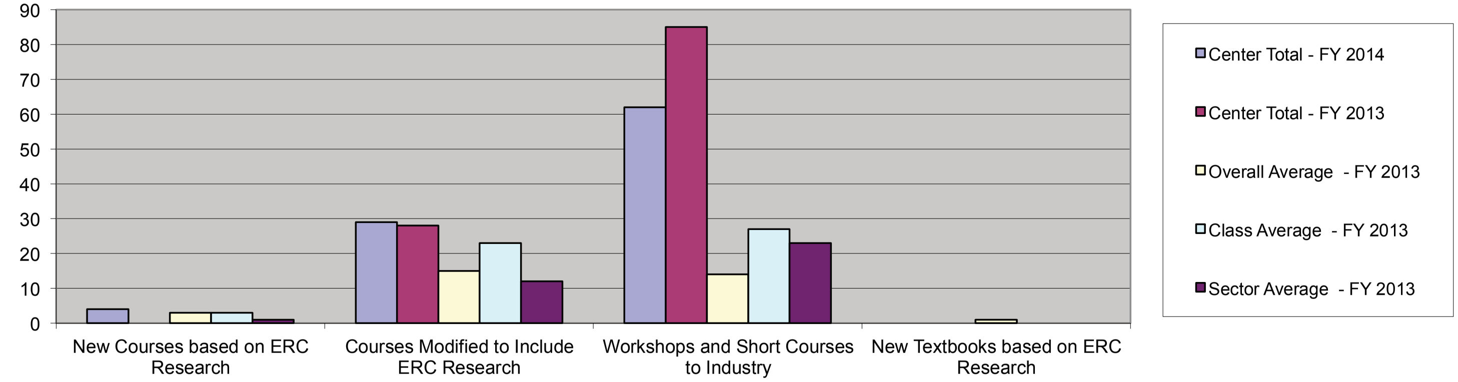


Table 3a: Educational Impact

	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, 2013-Jan 31, 2014	Percent	Feb 01, 2013-Jan 31, 2014	Percent	Feb 01, 2013-Jan 31, 2014	Percent	Feb 01, 2013-Jan 31, 2014	Percent	Feb 01, 2013-Jan 31, 2014	Percent	Feb 01, 2013-Jan 31, 2014	Percent	
New Courses Currently Offered [1]	4	2	50%	4	100%	1	25%	3	75%	1	25%	0	0%	20
Currently Offered Ongoing Courses With ERC Content [2]	29	15	52%	4	14%	4	14%	19	66%	8	28%	2	7%	N/A
Workshops, Short Courses, and Webinars	62	47	76%	15	24%	5	8%	31	50%	31	50%	47	76%	279
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 2013	49	78	1.6	18	145	13	158
2013	82	79	1.0	26	187	22	209
Average for Class of 2006 FY 2013	84	83	1.0	39	207	24	231
Minnesota Twin Cities-CCEFP FY 2013	137	81	0.6	26	244	0	244
Minnesota Twin Cities-CCEFP FY 2014	**112**	**89**	**0.8**	**23**	**224**	**0**	**224**

Table 4: Industrial/Practitioner Members, Innovation Partners, Funders of Sponsored Projects, Funders of Associated Projects, and Contributing Organizations

Summary:
45 - Industrial/Practitioner Members
1 - Innovation Partner
1 - Funder of Sponsored Projects
10 - Funders of Associated Projects
4 - Contributing Organizations

Section 1: 45 Industrial/Practitioner Members

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
Industrial/Practitioner Members That Have Already Provided Current Award Year Support.									
Air Logic	Industry	Fluid power components and systems	Unrestricted Cash Donations	Participates in science/engineering research projects	Domestic	Small (<500 employees)	No	0	0
AS Pindel	Industry	Fluid power components and systems	Unrestricted Cash Donations	Participates in science/engineering research projects	Domestic	Small (<500 employees)	Yes	0	0
Bobcat	Industry	Vehicle OEM	Unrestricted Cash Donations	Participates in science/engineering research projects	Domestic	Large (>1000 employees)	No	0	0
Caterpillar, Inc.	Industry	Vehicle OEM	Unrestricted Cash Donations	Member of Center's Industrial Advisory Board Participates in science/engineering research projects Participation in education/outreach activities Involvement in Technology Transfer	Domestic	Large (>1000 employees)	No	0	0
CNH America, Inc.	Industry	Vehicle OEM	Unrestricted Cash Donations Associated Project Support	Member of Center's Industrial Advisory Board Participates in science/engineering research projects Participation in education/outreach activities Involvement in Technology Transfer	Domestic	Large (>1000 employees)	No	0	1
Concentric AB/Haldex	Industry	Fluid power components and systems	Unrestricted Cash Donations	Participates in science/engineering research projects Involvement in Technology Transfer	Foreign	Medium (500-1000 employees)	No	0	0
Danfoss	Industry	Fluid power components and systems	Unrestricted Cash Donations Associated Project Support In-Kind Donations	Member of Center's Industrial Advisory Board Involvement in Technology Transfer	Domestic	Large (>1000 employees)	No	0	1
Deere and Company	Industry	Vehicle OEM	Unrestricted Cash Donations Associated Project Support	Participates in science/engineering research projects Participation in education/outreach activities Participation in translational research	Domestic	Large (>1000 employees)	No	0	1
Donaldson Company	Industry	Fluid power components and systems	Associated Project Support In-Kind Donations	Participates in science/engineering research projects Involvement in Technology Transfer	Domestic	Large (>1000 employees)	No	0	0
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	0	0
Enfield Technologies	Industry	Fluid power components and systems	Unrestricted Cash Donations	Member of Center's Industrial Advisory Board Participates in science/engineering research projects Involvement in Technology Transfer	Domestic	Small (<500 employees)	No	0	0
Evonik Additives, USA, Inc.	Industry	Chemical manufacturer	Unrestricted Cash Donations	Member of Center's Industrial Advisory Board Participates in science/engineering research projects Involvement in Technology Transfer	Domestic	Large (>1000 employees)	No	0	0
Exxon Mobil	Industry	Fluid power components and systems	Unrestricted Cash Donations	Member of Center's Industrial Advisory Board Participates in science/engineering research projects Involvement in Technology Transfer	Domestic	Large (>1000 employees)	No	0	0

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
Freudenberg - NOK	Industry	Fluid power components and systems	Unrestricted Cash Donations	Involvement in Technology Transfer	Domestic	Large (>1000 employees)	No	0	0
Gates Corporation	Industry	Fluid power components and systems	Unrestricted Cash Donations	Member of Center's Industrial Advisory Board Participates in science/engineering research projects	Domestic	Large (>1000 employees)	No	0	0
Heco Gear, Inc.	Industry	Fluid power components and systems	Unrestricted Cash Donations	Participates in science/engineering research projects	Domestic	Small (<500 employees)	No	0	0
Hitachi Construction Machinery	Industry	Construction equipment	Unrestricted Cash Donations	Participates in science/engineering research projects	Foreign	Large (>1000 employees)	Yes	0	0
Hoowaki, LLC	Industry	Manufacturing Technology	Unrestricted Cash Donations	Participates in science/engineering research projects	Domestic	Small (<500 employees)	No	0	0
Husco International, Inc.	Industry	Fluid power components and systems	Unrestricted Cash Donations	Member of Center's Industrial Advisory Board Participates in science/engineering research projects Involvement in Technology Transfer	Domestic	Large (>1000 employees)	No	0	0
Idemitsu Kosan Co., Ltd.	Industry	Petrochemical	Unrestricted Cash Donations	Participates in science/engineering research projects	Foreign	Large (>1000 employees)	No	0	0
Linde Hydraulics Corp.	Industry	Fluid power components and systems	Unrestricted Cash Donations In-Kind Donations	Member of Center's Industrial Advisory Board Involvement in Technology Transfer	Foreign	Small (<500 employees)	No	0	0
Main Manufacturing Products, Inc.	Industry	Fluid power components and systems	Unrestricted Cash Donations	Participates in science/engineering research projects	Domestic	Small (<500 employees)	No	0	0
Master Pneumatic-Detroit, Inc.	Industry	Fluid power components and systems	Unrestricted Cash Donations	Participates in science/engineering research projects	Domestic	Small (<500 employees)	No	0	0
National Fluid Power Association	Industrial Association	N/A	Unrestricted Cash Donations	Member of Center's Industrial Advisory Board Involvement in Technology Transfer	Domestic	N/A	No	0	0
National Tube Supply Company	Industry	Fluid power components and systems	Unrestricted Cash Donations	Participates in science/engineering research projects	Domestic	Small (<500 employees)	No	0	0
Netshape Technologies	Industry	Fluid power components and systems	Unrestricted Cash Donations	Member of Center's Industrial Advisory Board	Domestic	Medium (500-1000 employees)	No	0	0
Pall Corporation	Industry	Engineering services	Unrestricted Cash Donations	Participates in science/engineering research projects	Domestic	Small (<500 employees)	Yes	0	0
Parker Hannifin Corporation	Industry	Fluid power components and systems	Unrestricted Cash Donations In-Kind Donations	Member of Center's Industrial Advisory Board Involvement in Technology Transfer	Domestic	Large (>1000 employees)	No	0	0
Poclain Hydraulics	Industry	Fluid power components and systems	Unrestricted Cash Donations	Member of Center's Industrial Advisory Board Involvement in Technology Transfer	Foreign	Large (>1000 employees)	No	0	0
Ross Controls	Industry	Fluid power components and systems	Unrestricted Cash Donations	Member of Center's Industrial Advisory Board	Domestic	Small (<500 employees)	No	0	0
Shell Global Solutions	Industry	Petrochemical	Unrestricted Cash Donations Associated Project Support	Participates in science/engineering research projects	Foreign	Large (>1000 employees)	No	0	1
Simerics, Inc.	Industry	Fluid power components and systems	Unrestricted Cash Donations	Participates in science/engineering research projects	Domestic	Small (<500 employees)	No	0	0
Sun Hydraulics	Industry	Fluid power components and systems	Unrestricted Cash Donations	Participates in science/engineering research projects Participation in education/outreach activities Involvement in Technology Transfer	Domestic	Medium (500-1000 employees)	No	0	0
Takako Industries	Industry	Fluid power components and systems	Unrestricted Cash Donations In-Kind Donations	Participates in science/engineering research projects	Foreign	Small (<500 employees)	No	0	0
The Lubrizol Corporation	Industry	Petrochemical	Unrestricted Cash Donations	Member of Center's Industrial Advisory Board	Domestic	Large (>1000 employees)	No	0	0
Trelleborg Sealing Solutions	Industry	Fluid power components and systems	Unrestricted Cash Donations	Member of Center's Industrial Advisory Board	Foreign	Large (>1000 employees)	No	0	0
Woodward, Inc.	Industry	Aerospace	Unrestricted Cash Donations		Domestic	Large (>1000 employees)	No	0	0
Industrial/Practitioner Members That Will Provide Support by the End of the Current Award Year.									
Afton Chemical Corp.	Industry	Fluid power components and systems	Unrestricted Cash Donations	Member of Center's Industrial Advisory Board Participates in science/engineering research projects Involvement in Technology Transfer	Domestic	Large (>1000 employees)	No	0	0
Bosch Rexroth Corporation	Industry	Fluid power components and systems	Unrestricted Cash Donations	Member of Center's Industrial Advisory Board Involvement in Technology Transfer	Foreign	Large (>1000 employees)	No	0	0

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
Deltrol Fluid Products	Industry	Fluid power components and systems	Unrestricted Cash Donations	Member of Center's Industrial Advisory Board Participates in science/engineering research projects Participation in education/outreach activities Involvement in Technology Transfer	Domestic	Small (<500 employees)	No	0	0
Moog, Inc.	Industry	Fluid power components and systems	Unrestricted Cash Donations	Participates in science/engineering research projects	Domestic	Large (>1000 employees)	No	0	0
Nexen Group, Inc.	Industry	Fluid power components and systems	Unrestricted Cash Donations	Participates in science/engineering research projects	Domestic	Small (<500 employees)	No	0	0
Quality Control Corporation	Industry	Fluid power components and systems	Unrestricted Cash Donations	Participates in science/engineering research projects	Domestic	Small (<500 employees)	No	0	0
StorWatts Inc.	Industry	Energy solutions	Unrestricted Cash Donations	Participates in science/engineering research projects	Domestic	Small (<500 employees)	No	0	0
Walvoil Fluid Power	Industry	Fluid power components and systems	Unrestricted Cash Donations	Participates in science/engineering research projects	Foreign	Large (>1000 employees)	No	0	0

Section 2: 1 Innovation Partner

Organization	Sector	Product Focus (Industry only)	Type of Involvement	Domestic / Foreign	Size (Industry Only)	New Partner (Yes/No)
EndoInSight LLC	Venture Capitalists	N/A	Participates in science/engineering research projects Participation in translational research	Domestic	N/A	Yes

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)	Yes	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
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
Cummins Engines	Industry	Aerospace	Associated Project Support	Participates in science/engineering research projects	Domestic	Medium (500-1000 employees)	Yes	1
Dae Jin Hydraulics - TECPOS	Industry	Power Solutions	Associated Project Support	Participates in science/engineering research projects	Foreign	Small (<500 employees)	Yes	1
DuPont	Industry	Market driven science technology	Associated Project Support	Participates in science/engineering research projects	Domestic	Small (<500 employees)	Yes	1
John Crane	Industry	Engineering services	Associated Project Support	Participates in science/engineering research projects	Domestic	Small (<500 employees)	Yes	1
Midwest Precision	Industry	Precision Manufacturing	Associated Project Support	Participates in science/engineering research projects	Domestic	Small (<500 employees)	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
Triumph Aerospace Systems	Industry	Aerospace	Associated Project Support	Participates in science/engineering research projects	Domestic	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)	Yes	1

Section 5: 4 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.							
Hydac Corporation	Industry	Fluid power components and systems	In-Kind Donations	Participates in science/engineering research projects	Domestic	Large (>1000 employees)	No
Keller America, Inc.	Industry	Engineering services	In-Kind Donations	Participates in science/engineering research projects Involvement in Technology Transfer	Domestic	Small (<500 employees)	Yes
Mico, Inc.	Industry	Fluid power components and systems	Unrestricted Cash Donations	Participation in education/outreach activities	Domestic	Small (<500 employees)	No
Contributing Organizations That Will Provide Support by the End of the Current Award Year.							
Stanadyne Corporation	Industry	Automotive	In-Kind Donations	Participates in science/engineering research projects	Domestic	Large (>1000 employees)	Yes

Section 6: Summary

Sector	Industrial/Practitioner Members	Percent Foreign	Percent Small	Percent Medium	Percent Large
Industry	44	23%	39%	7%	55%
Industrial Association	1	0%	N/A	N/A	N/A
Total	**45**	**22%**	**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, 2010 - May 31, 2011	Jun 01, 2011 - May 31, 2012	Jun 01, 2012 - May 31, 2013	Jun 01, 2013 - May 31, 2014 [1]
Industrial/Practitioner Members	54	48	41	45
Innovation Partners	0	1	1	1
Funders of Sponsored Projects	0	0	0	1
Funders of Associated Projects	15	8	8	10
Contributing Organizations	5	9	6	4
Total Participating Organizations	**74**	**66**	**56**	**61**
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	$636,250	$707,817	$583,100	$634,066
Membership Fees Expected from Prior Year Members [2]	N/A	N/A	N/A	$158,500
Member-Sponsored Projects Total Dollar Amount	$0	$0	$0	$0
Member-Associated Projects Total Dollar Amount	$166,864	$95,295	$78,336	$159,132
Member In-Kind Total Dollar Amount [3]	$121,261	$92,150	$12,257	$38,567
Total Dollar Amount, Industrial/Practitioner Member Support to Center	**$924,375**	**$895,262**	**$673,693**	**$990,265**

[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.

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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
Afton Chemical Corp.		✔							1B.1: New Material Combinations...,
Air Logic									
AS Pindel									
Bobcat									
Bosch Rexroth Corporation	✔				✔	✔		✔	
Casappa S.p.A.									
Caterpillar, Inc.		✔					✔	✔	Technology Licensing Opportunities Fluid Power Scholars
CNH America, Inc.							✔		Bi-weekly webinars to discuss projects and testbeds.
Concentric AB/Haldex							✔		
Confidential Organization (optional use for associated or sponsored projects only)									
Cummins Engines									
Dae Jin Hydraulics - TECPOS									
Danfoss		✔			✔				
Deere and Company									
Deltrol Fluid Products							✔		
Donaldson Company		✔	✔						
DuPont									
Eaton Corporation	✔	✔			✔	✔	✔		
EndoInSight LLC									
Enfield Technologies									Research project support CEO on Executive Committee
Evonik Additives, USA, Inc.								✔	
Exxon Mobil								✔	
FORCE America									
Freudenberg - NOK									Support Research Projects
Gates Corporation									
Heco Gear, Inc.									
Hitachi Construction Machinery									
Hoowaki, LLC									
Husco International, Inc.			✔					✔	
Hydac Corporation									
Idemitsu Kosan Co., Ltd.									
John Crane									
Keller America, Inc.									Donated a Hydraulic Test Stand to the University of Minnesota
Linde Hydraulics Corp.		✔							
Main Manufacturing Products, Inc.									
Master Pneumatic-Detroit, Inc.									
Mico, Inc.									
Midwest Precision									
Moog, Inc.									
National Defense Science and Engineering Fellowship Grant (NDSEG)									
National Fluid Power Association		✔							
National Tube Supply Company									
Netshape Technologies									
Nexen Group, Inc.									
Pall Corporation									
Parker Hannifin Corporation							✔		
Poclain Hydraulics		✔							
Quality Control Corporation									
Ross Controls									
Shell Global Solutions									
Simerics, Inc.									
Stanadyne Corporation									
StorWatts Inc.									
Sun Hydraulics							✔		
Takako Industries									
The Lubrizol Corporation									
Trelleborg Sealing Solutions									
Triumph Aerospace Systems									
Veraphotonics, Mistras									
Walvoil Fluid Power									
Woodward, Inc.									

Figure 5b: Lifetime Industrial/Practitioner Membership History

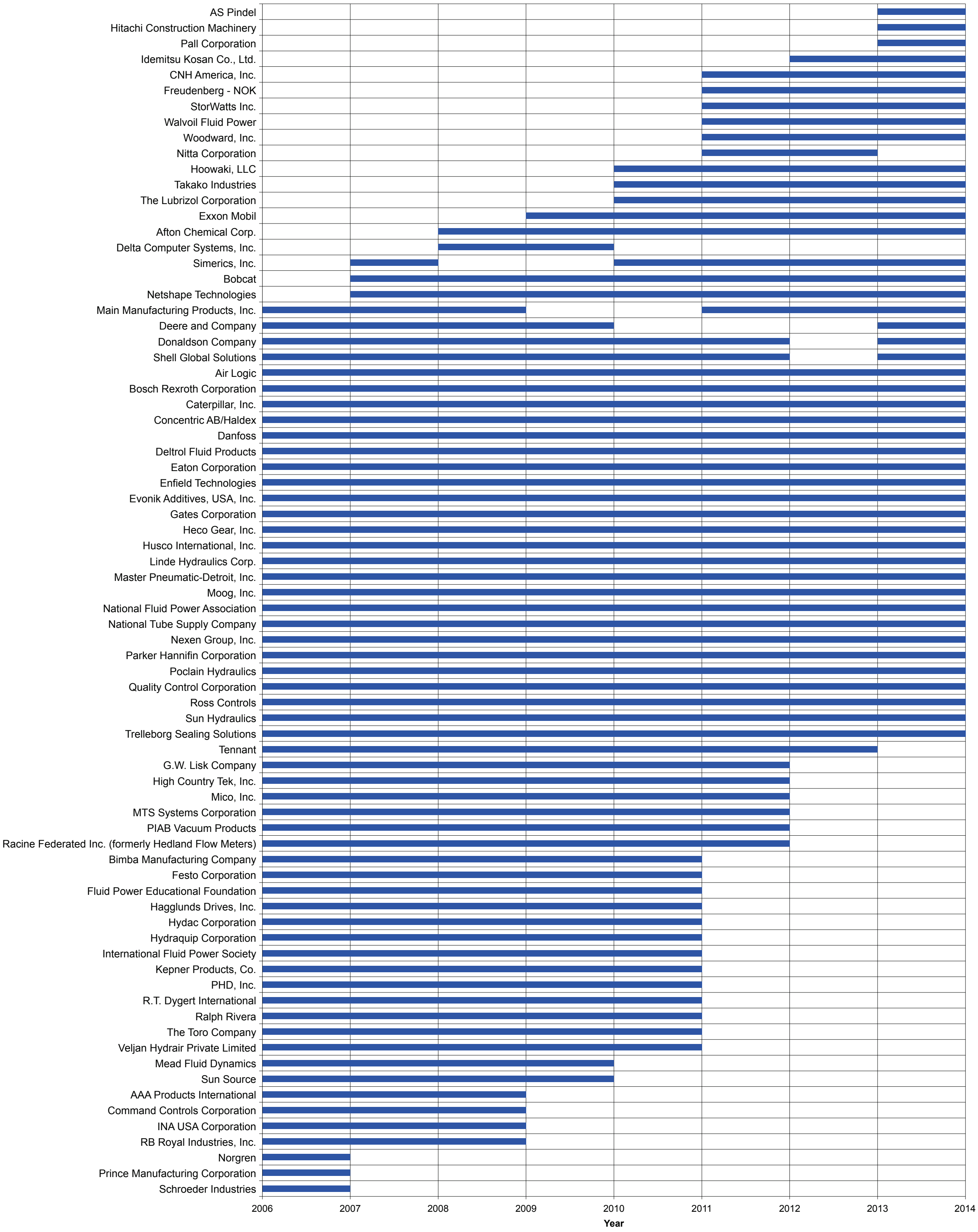


Figure 5c: Total Number of Industrial/Practitioner Members

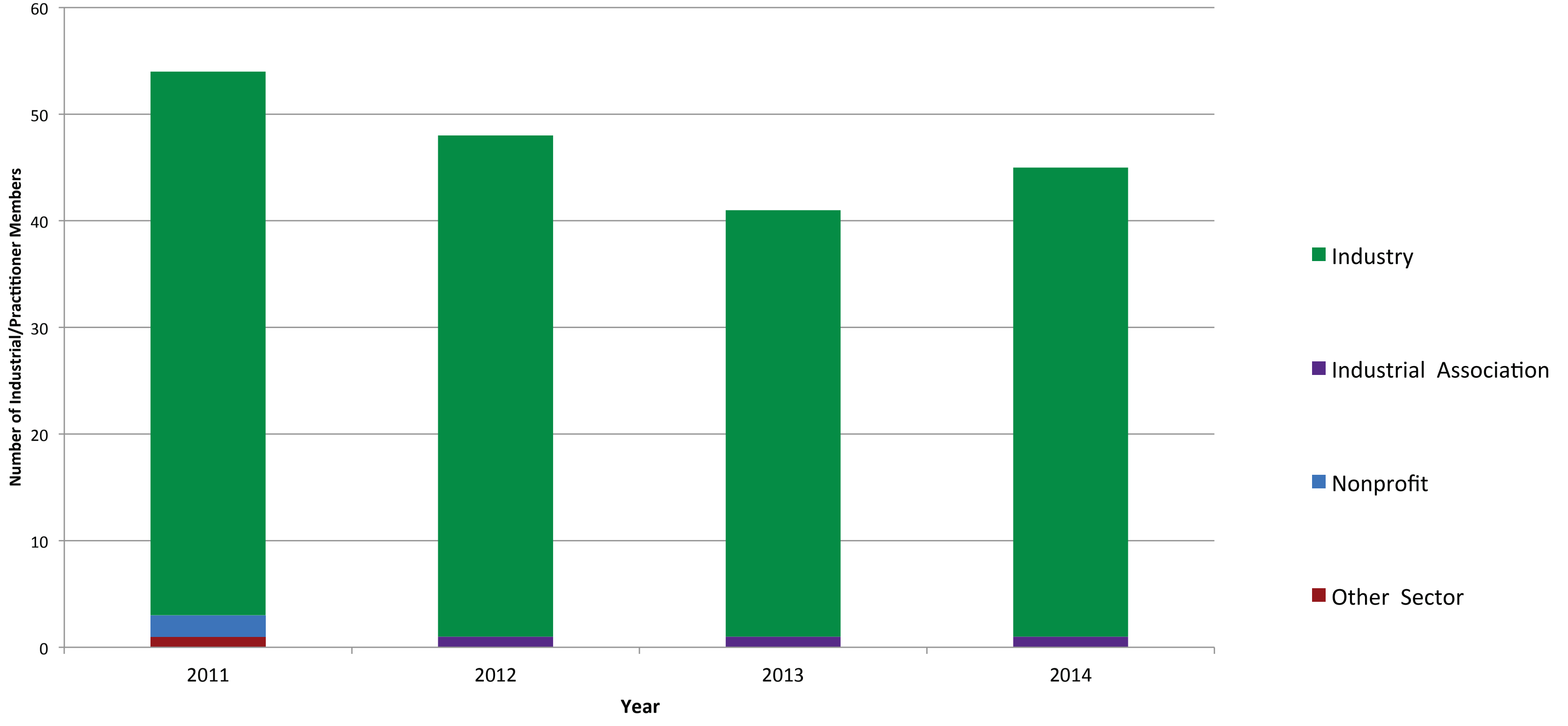
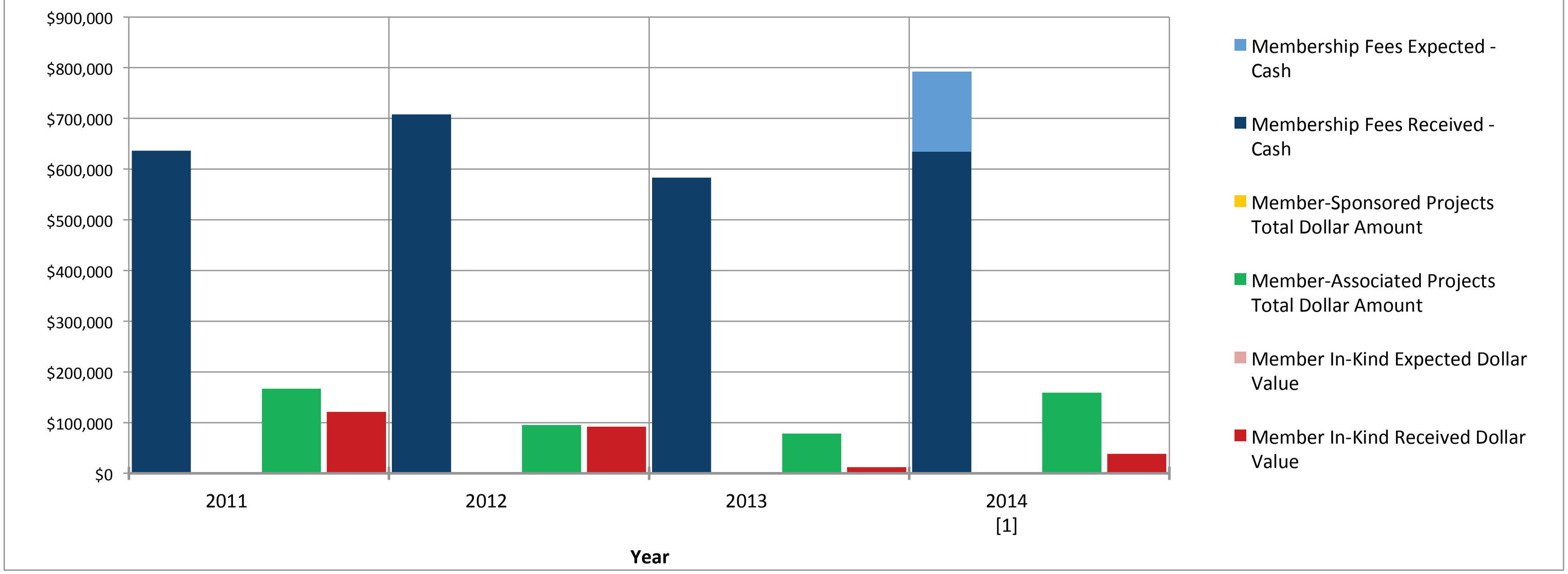


Figure 5d: Industrial/Practitioner Member Support by Year, FY 2014



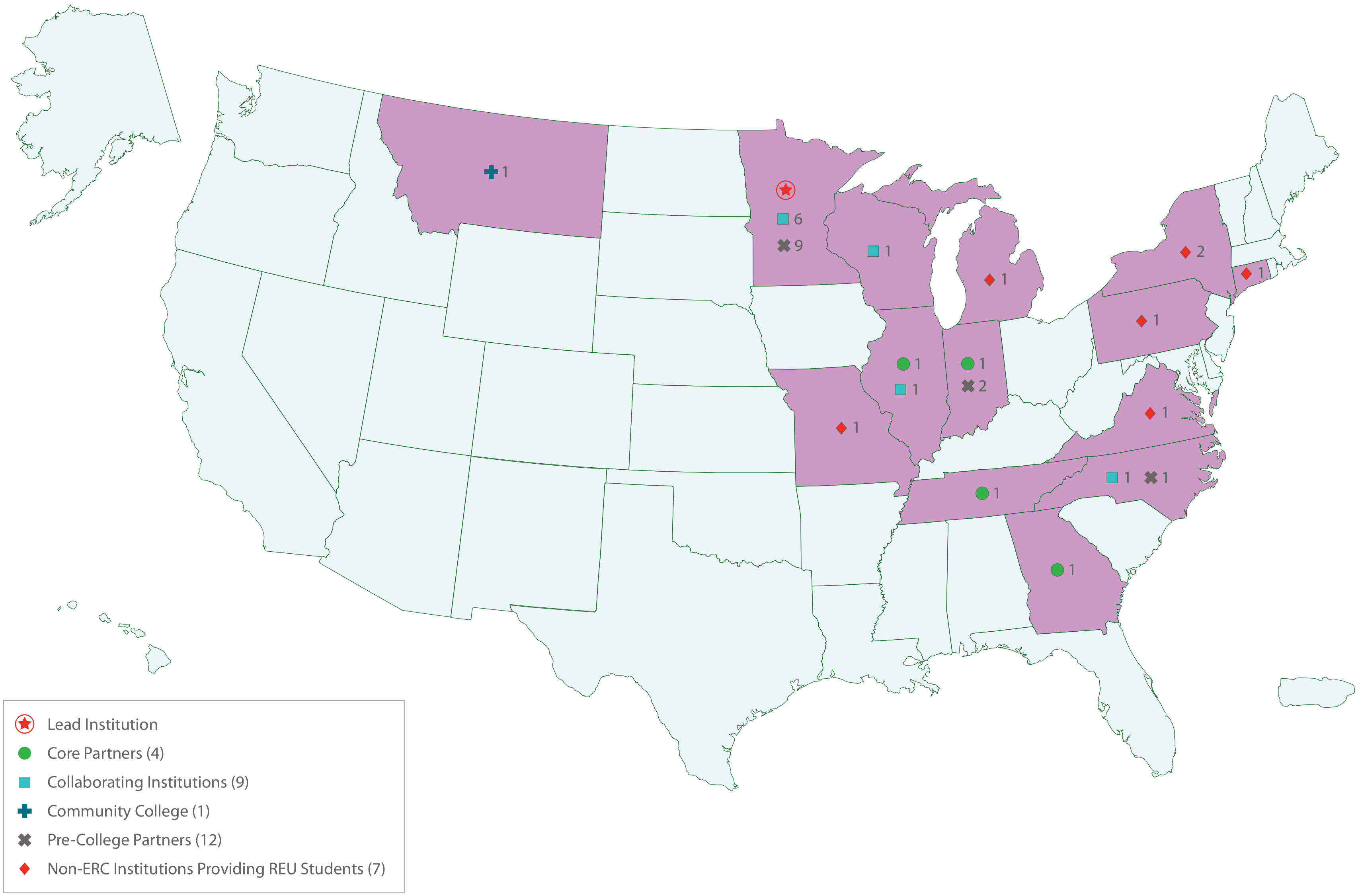
[1] - Member support provided through end of current reporting year (includes only partial data)

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

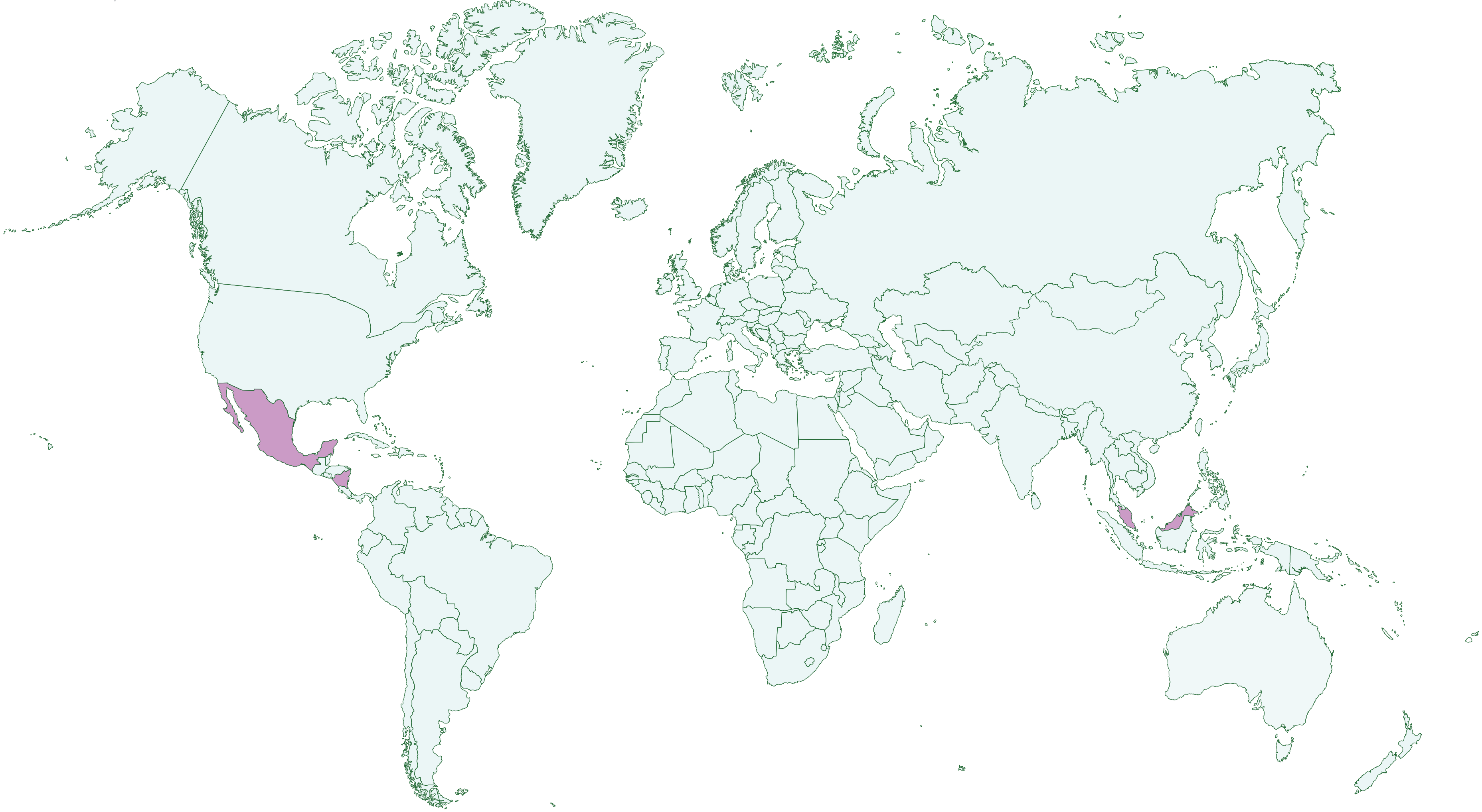
Institutions							Personnel in ERC Activities [1]									
Name and Type	Total	Female Serving	Minority Serving	HBCU	Hispanic Serving	Large Number of URM Students in Engineering	Faculty	Community College RET	Teachers (K-12)		Postdocs	Students				Young Scholars
									RET	Non-RET		Graduate		UG Non-REU	REU	
												Doctoral	Masters			
I. Lead	**1**	**0**	**0**	**0**	**0**	**0**	**12**	**N/A**	**N/A**	**N/A**	**2**	**20**	**14**	**30**	**5**	**N/A**
University of Minnesota, Minneapolis, MN							12	N/A	N/A	N/A	2	20	14	30	5	N/A
II. Core Partners	**4**	**0**	**0**	**0**	**0**	**0**	**18**	**N/A**	**N/A**	**N/A**	**0**	**31**	**14**	**36**	**11**	**N/A**
Georgia Institute of Technology, Atlanta, GA							7	N/A	N/A	N/A	0	7	3	10	2	N/A
Purdue University, West Lafayette, IN							3	N/A	N/A	N/A	0	15	5	12	6	N/A
University of Illinois at Urbana-Champaign, Urbana, IL							4	N/A	N/A	N/A	0	4	2	13	2	N/A
Vanderbilt University, Nashville, TN							4	N/A	N/A	N/A	0	5	4	1	1	N/A
III. Collaborating Institutions	**12**	**0**	**1**	**0**	**1**	**0**	**8**	**N/A**	**N/A**	**N/A**	**0**	**4**	**7**	**39**	**6**	**N/A**
Bradley University, Peoria, IL							0	N/A	N/A	N/A	0	0	1	5	0	N/A
Eolos Wind Energy Research Consortium, Minneapolis, MN							0	N/A	N/A	N/A	0	0	0	0	0	N/A
Hennepin Technical College, Brooklyn Park, MN							1	N/A	N/A	N/A	0	0	0	0	0	N/A
Malaysian Ministry of Higher Education (MOHE), Putrajaya							0	N/A	N/A	N/A	0	1	0	0	0	N/A
Milwaukee School of Engineering, Milwaukee, WI							1	N/A	N/A	N/A	0	0	5	4	2	N/A
National Center for Earth-surface Dynamics, Minneapolis, MN							0	N/A	N/A	N/A	0	0	0	0	0	N/A
National University of Engineering (UNI), Managua							1	N/A	N/A	N/A	0	0	0	0	0	N/A
North Carolina Agriculture and Technical State University, Greensboro, NC							3	N/A	N/A	N/A	0	3	1	4	4	N/A
Science Museum of Minnesota, St. Paul, MN							0	N/A	N/A	N/A	0	0	0	0	0	N/A
STEM Education Center, Minneapolis, MN							2	N/A	N/A	N/A	0	0	0	0	0	N/A
Universidad Tecnológica de Querétaro, Querétaro			✔		✔		0	N/A	N/A	N/A	0	0	0	1	0	N/A
University of Minnesota - Morris, Morris, MN							0	N/A	N/A	N/A	0	0	0	25	0	N/A
IV. Non-ERC Institutions Providing REU Students	**7**	**0**	**0**	**0**	**0**	**0**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**7**	**N/A**
Michigan State Univeristy, East Lansing, MI							N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	1	N/A
Rochester Institute of Technolgy, Rochester, NY							N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	1	N/A
The Cooper Union for the Advancement of Science and Art, New York, NY							N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	1	N/A
University of Missouri-Columbia, Columbia, MO							N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	1	N/A
University of Virginia, Charlottesville, VA							N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	1	N/A
Wilkes University, Wilkes-Barre, PA							N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	1	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	**5**	**0**	**2**	**0**	**2**	**3**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**0**	**0**	**1**	**1**	**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**	**0**	**1**	**N/A**
North Star STEM Alliance			✔		✔	✔	N/A	N/A	N/A	N/A	N/A	0	0	0	1	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)	**4**	**0**	**1**	**0**	**1**	**2**	**1**	**N/A**	**N/A**	**N/A**	**0**	**0**	**0**	**1**	**0**	**N/A**
Circle of Life School							1	N/A	N/A	N/A	0	0	0	0	0	N/A
Leech Lake Tribal College							0	N/A	N/A	N/A	0	0	0	1	0	N/A
Northstar STEM Program						✔	0	N/A	N/A	N/A	0	0	0	0	0	N/A
The National GEM Consortium			✔		✔	✔	0	N/A	N/A	N/A	0	0	0	0	0	N/A
VI. Precollege Partners	**12**	**0**	**1**	**0**	**0**	**0**	**N/A**	**N/A**	**4**	**11**	**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
Burnsville High School, Burnsville, 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	1	N/A	N/A	N/A	N/A	N/A	0
Cloquet High School, Cloquet, MN							N/A	N/A	0	1	N/A	N/A	N/A	N/A	N/A	0
Cloquet Middle School, Cloquet, MN							N/A	N/A	0	1	N/A	N/A	N/A	N/A	N/A	0
Guilford Middle School, Greensboro, NC							N/A	N/A	2	0	N/A	N/A	N/A	N/A	N/A	0
Lafayette Jefferson High School, Lafayette, IN							N/A	N/A	1	0	N/A	N/A	N/A	N/A	N/A	0
McCutcheon High School, Lafayette, IN							N/A	N/A	1	0	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
Orono Middle School, Orono, MN							N/A	N/A	0	1	N/A	N/A	N/A	N/A	N/A	0
Osakis Middle School, Osakis, MN							N/A	N/A	0	1	N/A	N/A	N/A	N/A	N/A	0
South Ridge School (formerly Albrook School), Culver, MN			✔				N/A	N/A	0	3	N/A	N/A	N/A	N/A	N/A	0
VII. Community Colleges	**1**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**N/A**	**N/A**	**0**	**0**	**0**	**8**	**0**	**N/A**
Salish Kootenai College, Pablo, MT			✔				0	0	N/A	N/A	0	0	0	8	0	N/A
Total	**42**	**0**	**5**	**0**	**3**	**3**	**39**	**0**	**4**	**11**	**2**	**55**	**35**	**114**	**30**	**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



6b Location of Foreign Collaborating Institutions and/or Foreign Partner Institutions

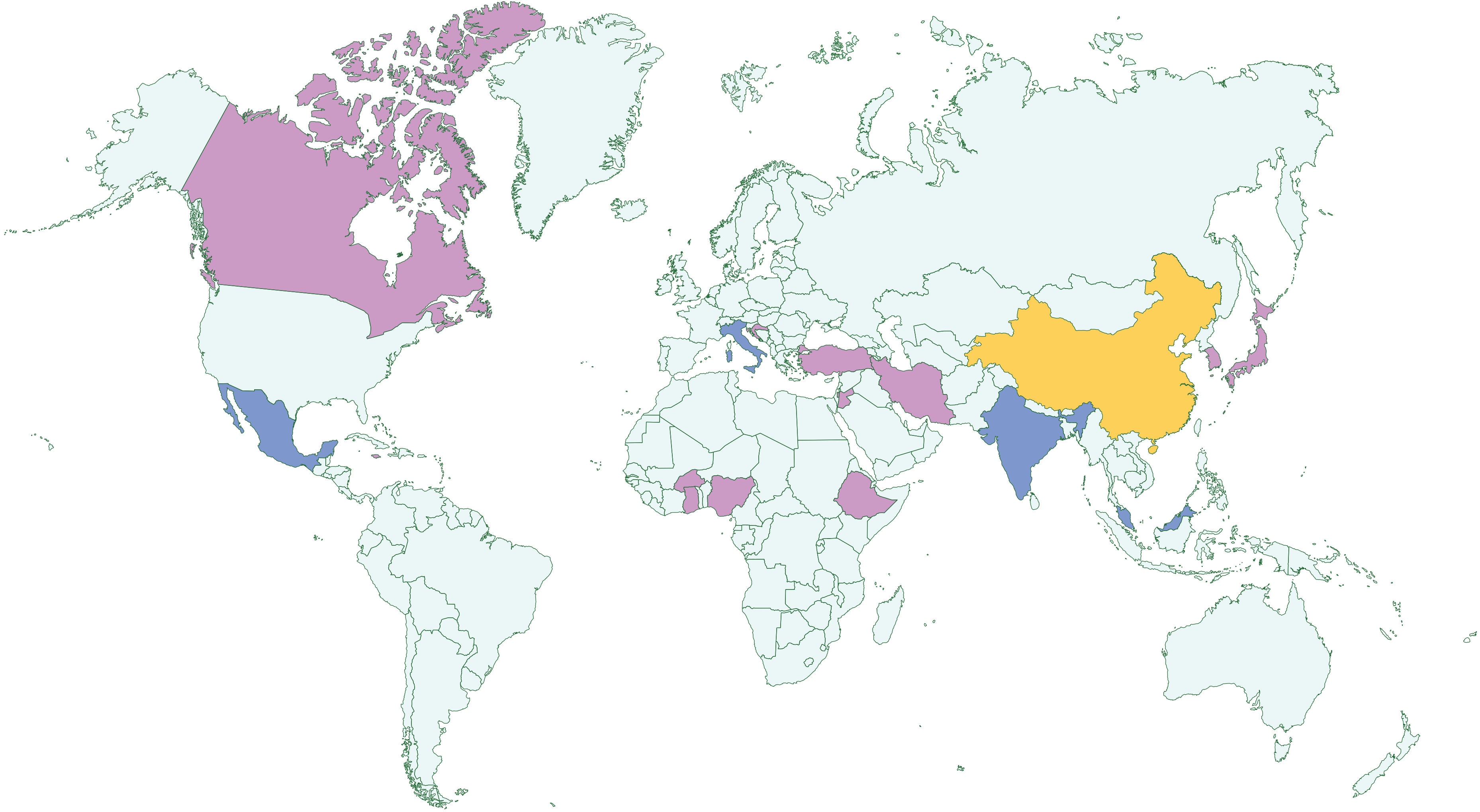


🏢 = Number of institutions
👤 = Number of participants

	🏢	👤
Malaysia	1	1
Mexico	1	1
Nicaragua	1	1

6c

Country of Citizenship for ERC Foreign Personnel



👤 = Number of ERC personnel from this country

🟪	1 person
🟦	2–10 people
🟨	11+ people

1 person 👤		
Burkina Faso	Iran	Nigeria
Canada	Jamaica	Palestine
Croatia	Japan	South Korea
Ethiopia	Jordan	Turkey
Ghana		

2–10 people	👤
India	9
Italy	3
Malaysia	2
Mexico	2

11+ people	👤
China	17

	👤
Country Not Reported	0*

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

Table 7: ERC Personnel

Personnel Type	Total[1]	Gender			Citizenship Status									Ethnicity: Hispanic			Disability
					Race—U.S. citizens and permanent residents only							Citizenship Foreign/Temp Visa	Citizenship Not Reported	U.S. Citizen/Perm Resident	Citizenship Foreign/Temp Visa	Citizenship Not Reported	
		Male	Female	Gender Not Reported	AI/AN	NH/PI	B/AA	W	A	More than one race reported, minority	Race Not Reported						
Total All Institutions																	
Total [2]	279	185	60	34	34	0	9	129	10	5	15	46	31	5	2	0	3
Leadership/Administration																	
Directors	4	2	0	0	0	0	0	1	1	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
Industrial Liaison Officer (ILO)	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Education Program Leaders	2	3	1	0	0	0	0	4	0	0	0	0	0	0	0	0	0
Administrative Director	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Staff	6	4	2	1	0	0	1	3	0	0	2	0	1	0	0	0	0
Subtotal	**17**	**12**	**5**	**1**	**0**	**0**	**1**	**12**	**1**	**1**	**2**	**0**	**1**	**0**	**0**	**0**	**0**
Research Under Strategic Research Plan																	
Senior Faculty	15	13	2	0	0	0	0	10	2	0	1	0	2	0	0	0	0
Junior Faculty	10	8	1	1	0	0	0	6	1	0	0	2	1	0	0	0	0
Research Staff	6	5	0	1	0	0	0	5	0	0	0	0	1	0	0	0	0
Visiting Faculty	1	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Industry Researchers	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Total Postdocs	2	1	0	1	0	0	0	0	0	0	0	1	1	0	0	0	0
Total Doctoral Students	46	37	6	3	0	0	2	14	2	0	1	23	4	0	1	0	1
Total Master's Students	30	21	5	4	0	0	0	19	1	0	3	3	4	0	0	0	0
Total Undergraduate Students	21	11	4	6	1	0	3	8	0	0	1	3	5	0	0	0	0
Subtotal	**132**	**98**	**18**	**16**	**1**	**0**	**5**	**63**	**6**	**0**	**7**	**32**	**18**	**0**	**1**	**0**	**1**
Curriculum Development and Outreach																	
Senior Faculty	9	7	2	0	0	0	0	6	2	0	1	0	0	0	0	0	0
Junior Faculty	7	6	1	0	0	0	0	6	1	0	0	0	0	0	0	0	0
Research Staff	15	7	6	2	2	0	1	9	0	0	2	0	1	0	0	0	2
Visiting Faculty	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Total Doctoral Students	20	15	4	1	1	0	1	11	1	0	1	5	0	1	1	0	1
Total Master's Students	9	5	2	2	0	0	0	7	0	0	0	0	2	0	0	0	0
Total Undergraduate Students	98	53	30	15	31	0	4	28	3	4	7	13	8	4	1	0	0
Subtotal	**157**	**93**	**45**	**19**	**33**	**0**	**6**	**67**	**7**	**4**	**11**	**18**	**11**	**5**	**2**	**0**	**3**
ERC REU Students																	
NSF REU Site Award Students	17	12	5	0	0	0	2	8	1	1	1	4	0	2	0	0	0
ERC's Own REU Students	6	4	2	0	0	0	2	1	1	0	0	1	1	0	0	0	0
Subtotal	**23**	**16**	**7**	**0**	**0**	**0**	**4**	**9**	**2**	**1**	**1**	**5**	**1**	**2**	**0**	**0**	**0**
Precollege (K-12)																	
Teachers (non-RET)	10	8	2	0	0	0	0	10	0	0	0	0	0	0	0	0	0
Teachers (RET)	4	2	2	0	0	0	1	2	0	0	0	0	1	0	0	0	0
Subtotal	**14**	**10**	**4**	**0**	**0**	**0**	**1**	**12**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**
University of Minnesota - Lead Institution																	
Total [2]	91	64	15	12	6	0	2	42	3	1	6	19	12	3	0	0	1
Leadership/Administration																	
Directors	2	2	0	0	0	0	0	1	1	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
Education Program Leaders	2	1	1	0	0	0	0	2	0	0	0	0	0	0	0	0	0
Administrative Director	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Staff	6	3	2	1	0	0	1	2	0	0	2	0	1	0	0	0	0
Subtotal	**12**	**7**	**4**	**1**	**0**	**0**	**1**	**7**	**1**	**0**	**2**	**0**	**1**	**0**	**0**	**0**	**0**
Research Under Strategic Research Plan																	
Senior Faculty	5	4	1	0	0	0	0	5	0	0	0	0	0	0	0	0	0
Junior Faculty	3	2	1	0	0	0	0	2	1	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
Total Postdocs	2	1	0	1	0	0	0	0	0	0	0	1	1	0	0	0	0
Total Doctoral Students	17	15	1	1	0	0	0	3	1	0	0	12	1	0	0	0	0
Total Master's Students	11	10	0	1	0	0	0	9	0	0	0	1	1	0	0	0	0
Total Undergraduate Students	6	2	2	2	0	0	1	2	0	0	0	1	2	0	0	0	0
Subtotal	**45**	**35**	**5**	**5**	**0**	**0**	**1**	**22**	**2**	**0**	**0**	**15**	**5**	**0**	**0**	**0**	**0**
Curriculum Development and Outreach																	
Senior Faculty	4	3	1	0	0	0	0	3	1	0	0	0	0	0	0	0	0
Junior Faculty	3	2	1	0	0	0	0	2	1	0	0	0	0	0	0	0	0
Research Staff	7	1	4	2	2	0	0	3	0	0	1	0	1	0	0	0	1
Total Doctoral Students	4	3	0	1	1	0	0	2	0	0	0	1	0	0	0	0	0
Total Master's Students	3	2	0	1	0	0	0	2	0	0	0	0	1	0	0	0	0
Total Undergraduate Students	26	20	4	2	3	0	1	9	0	1	4	4	4	3	0	0	0
Subtotal	**47**	**31**	**10**	**6**	**6**	**0**	**1**	**21**	**2**	**1**	**5**	**5**	**6**	**3**	**0**	**0**	**1**
ERC REU Students																	
NSF REU Site Award Students	4	4	0	0	0	0	1	1	0	0	1	1	0	1	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
Subtotal	**5**	**5**	**0**	**0**	**0**	**0**	**1**	**2**	**0**	**0**	**1**	**1**	**0**	**1**	**0**	**0**	**0**
Georgia Institute of Technology - Core Partner																	
Total [2]	30	23	2	5	0	0	0	19	1	0	0	4	6	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
Staff	1	1	0	0	0	0	0	1	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**
Research Under Strategic Research Plan																	
Senior Faculty	4	4	0	0	0	0	0	3	0	0	0	0	1	0	0	0	0
Junior Faculty	2	1	0	1	0	0	0	0	0	0	0	1	1	0	0	0	0
Research Staff	2	1	0	1	0	0	0	1	0	0	0	0	1	0	0	0	0
Total Doctoral Students	5	3	2	0	0	0	0	4	0	0	0	1	0	0	0	0	0
Total Master's Students	3	2	0	1	0	0	0	2	0	0	0	0	1	0	0	0	0
Total Undergraduate Students	6	4	0	2	0	0	0	4	0	0	0	0	2	0	0	0	0
Subtotal	**22**	**15**	**2**	**5**	**0**	**0**	**0**	**14**	**0**	**0**	**0**	**2**	**6**	**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
Total Doctoral Students	4	3	1	0	0	0	0	3	0	0	0	1	0	1	0	0	0
Total Undergraduate Students	4	4	0	0	0	0	0	2	1	0	0	1	0	0	0	0	0
Subtotal	**9**	**8**	**1**	**0**	**0**	**0**	**0**	**6**	**1**	**0**	**0**	**2**	**0**	**1**	**0**	**0**	**0**
ERC REU Students																	
NSF REU Site Award Students	2	2	0	0	0	0	0	1	1	0	0	0	0	1	0	0	0
Subtotal	**2**	**2**	**0**	**0**	**0**	**0**	**0**	**1**	**1**	**0**	**0**	**0**	**0**	**1**	**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	Race Not Reported	Citizenship Foreign/Temp Visa	Citizenship Not Reported	U.S. Citizen/Perm Resident	Citizenship Foreign/Temp Visa	Citizenship Not Reported	
Purdue University - Core Partner																	
Total [2]	35	29	5	1	0	0	0	15	1	0	1	17	1	0	2	0	0
Leadership/Administration																	
Thrust Leaders	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Subtotal	**1**	**0**	**1**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Research Under Strategic Research Plan																	
Junior Faculty	2	2	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
Total Doctoral Students	15	15	0	0	0	0	0	4	0	0	1	10	0	0	1	0	0
Total Master's Students	5	2	2	1	0	0	0	3	0	0	0	1	1	0	0	0	0
Total Undergraduate Students	2	2	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0
Subtotal	**24**	**21**	**2**	**1**	**0**	**0**	**0**	**10**	**0**	**0**	**1**	**12**	**1**	**0**	**1**	**0**	**0**
Curriculum Development and Outreach																	
Junior Faculty	2	2	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
Total Doctoral Students	4	4	0	0	0	0	0	1	0	0	1	2	0	0	1	0	0
Total Master's Students	2	0	1	1	0	0	0	1	0	0	0	0	1	0	0	0	0
Total Undergraduate Students	11	9	2	0	0	0	0	4	1	0	0	6	0	0	1	0	0
Subtotal	**19**	**15**	**3**	**1**	**0**	**0**	**0**	**8**	**1**	**0**	**1**	**8**	**1**	**0**	**2**	**0**	**0**
ERC REU Students																	
NSF REU Site Award Students	5	4	1	0	0	0	0	2	0	0	0	3	0	0	0	0	0
ERC's Own REU Students	1	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Subtotal	**6**	**4**	**2**	**0**	**0**	**0**	**0**	**2**	**1**	**0**	**0**	**3**	**0**	**0**	**0**	**0**	**0**
University of Illinois at Urbana-Champaign - Core Partner																	
Total [2]	23	16	6	1	0	0	0	15	2	1	0	2	3	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
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Research Under Strategic Research Plan																	
Senior Faculty	2	1	1	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
Total Doctoral Students	3	2	0	1	0	0	0	1	1	0	0	0	1	0	0	0	1
Total Master's Students	2	2	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
Total Undergraduate Students	2	1	1	0	0	0	0	1	0	0	0	1	0	0	0	0	0
Subtotal	**10**	**7**	**2**	**1**	**0**	**0**	**0**	**6**	**2**	**0**	**0**	**1**	**1**	**0**	**0**	**0**	**1**
Curriculum Development and Outreach																	
Senior Faculty	1	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Junior Faculty	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Total Doctoral Students	3	2	1	0	0	0	0	2	1	0	0	0	0	0	0	0	1
Total Master's Students	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Total Undergraduate Students	12	8	4	0	0	0	0	9	0	0	0	1	2	1	0	0	0
Subtotal	**18**	**12**	**6**	**0**	**0**	**0**	**0**	**13**	**2**	**0**	**0**	**1**	**2**	**1**	**0**	**0**	**1**
ERC REU Students																	
NSF REU Site Award Students	2	0	2	0	0	0	0	2	0	0	0	0	0	0	0	0	0
Subtotal	**2**	**0**	**2**	**0**	**0**	**0**	**0**	**2**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Vanderbilt University - Core Partner																	
Total [2]	14	11	3	0	0	0	1	7	0	0	3	1	2	0	0	0	0
Research Under Strategic Research Plan																	
Senior Faculty	2	2	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0
Junior Faculty	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Total Doctoral Students	4	2	2	0	0	0	1	2	0	0	0	0	1	0	0	0	0
Total Master's Students	4	3	1	0	0	0	0	1	0	0	3	0	0	0	0	0	0
Subtotal	**11**	**8**	**3**	**0**	**0**	**0**	**1**	**5**	**0**	**0**	**3**	**0**	**2**	**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
Total Doctoral Students	4	2	2	0	0	0	1	3	0	0	0	0	0	0	0	0	0
Total Undergraduate Students	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Subtotal	**6**	**4**	**2**	**0**	**0**	**0**	**1**	**4**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**
ERC REU Students																	
ERC's Own REU Students	1	1	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**	**1**	**0**	**0**	**0**	**0**	**0**
Bradley University - Collaborating Institution																	
Total [2]	6	4	2	0	0	0	0	4	1	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
Total Undergraduate Students	5	3	2	0	0	0	0	3	1	0	1	0	0	0	0	0	0
Subtotal	**6**	**4**	**2**	**0**	**0**	**0**	**0**	**4**	**1**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**
Eolos Wind Energy Research Consortium - Collaborating Institution																	
Total [2]	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Research Under Strategic Research Plan																	
Research Staff	1	1	0	0	0	0	0	1	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**
Hennepin Technical College - Collaborating Institution																	
Total [2]	1	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Research Under Strategic Research Plan																	
Visiting Faculty	1	1	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**	**1**	**0**	**0**	**0**	**0**	**0**	**0**
Malaysian Ministry of Higher Education (MOHE) - Collaborating Institution																	
Total [2]	1	1	0	0	0	0	0	0	0	0	0	1	0	0	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	0	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**
Milwaukee School of Engineering - Collaborating Institution																	
Total [2]	15	10	3	2	0	0	0	10	1	0	1	1	2	0	0	0	0
Leadership/Administration																	
Education Program Leaders	1	1	0	0	0	0	0	1	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**

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	Race Not Reported	Citizenship Foreign/Temp Visa	Citizenship Not Reported	U.S. Citizen/Perm Resident	Citizenship Foreign/Temp Visa	Citizenship Not Reported	
Research Under Strategic Research Plan																	
Research Staff	3	3	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0
Industry Researchers	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Total Master's Students	4	1	2	1	0	0	0	1	1	0	0	1	1	0	0	0	0
Total Undergraduate Students	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0
Subtotal	**9**	**5**	**2**	**2**	**0**	**0**	**0**	**5**	**1**	**0**	**1**	**1**	**1**	**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
Research Staff	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Total Master's Students	2	1	1	0	0	0	0	2	0	0	0	0	0	0	0	0	0
Total Undergraduate Students	4	2	1	1	0	0	0	2	0	0	1	0	1	0	0	0	0
Subtotal	**8**	**5**	**2**	**1**	**0**	**0**	**0**	**6**	**0**	**0**	**1**	**0**	**1**	**0**	**0**	**0**	**0**
ERC REU Students																	
NSF REU Site Award Students	2	1	1	0	0	0	0	2	0	0	0	0	0	0	0	0	0
Subtotal	**2**	**1**	**1**	**0**	**0**	**0**	**0**	**2**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
National Center for Earth-surface Dynamics - Collaborating Institution																	
Total [2]	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Curriculum Development and Outreach																	
Research Staff	1	0	1	0	0	0	0	1	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**
National University of Engineering (UNI) - Collaborating Institution																	
Total [2]	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Leadership/Administration																	
Education Program Leaders	1	1	0	0	0	0	0	1	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**
Curriculum Development and Outreach																	
Senior Faculty	1	1	0	0	0	0	0	1	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**
North Carolina Agriculture and Technical State University - Collaborating Institution																	
Total [2]	11	7	3	1	0	0	4	1	1	1	1	2	1	0	0	0	0
Research Under Strategic Research Plan																	
Senior Faculty	2	2	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0
Junior Faculty	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Total Doctoral Students	2	0	1	1	0	0	1	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
Total Undergraduate Students	2	2	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0
Subtotal	**8**	**6**	**1**	**1**	**0**	**0**	**3**	**1**	**1**	**0**	**1**	**1**	**1**	**0**	**0**	**0**	**0**
Curriculum Development and Outreach																	
Senior Faculty	1	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Total Doctoral Students	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Total Undergraduate Students	4	2	2	0	0	0	3	0	0	1	0	0	0	0	0	0	0
Subtotal	**6**	**4**	**2**	**0**	**0**	**0**	**3**	**0**	**0**	**1**	**1**	**1**	**0**	**0**	**0**	**0**	**0**
ERC REU Students																	
NSF REU Site Award Students	2	1	1	0	0	0	1	0	0	1	0	0	0	0	0	0	0
ERC's Own REU Students	2	1	1	0	0	0	2	0	0	0	0	0	0	0	0	0	0
Subtotal	**4**	**2**	**2**	**0**	**0**	**0**	**3**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Science Museum of Minnesota - Collaborating Institution																	
Total [2]	5	4	1	0	0	0	0	5	0	0	0	0	0	0	0	0	1
Curriculum Development and Outreach																	
Research Staff	5	4	1	0	0	0	0	5	0	0	0	0	0	0	0	0	1
Subtotal	**5**	**4**	**1**	**0**	**0**	**0**	**0**	**5**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**
STEM Education Center - Collaborating Institution																	
Total [2]	2	0	2	0	0	0	0	2	0	0	0	0	0	0	0	0	0
Research Under Strategic Research Plan																	
Senior Faculty	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Junior Faculty	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Subtotal	**2**	**0**	**2**	**0**	**0**	**0**	**0**	**2**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Curriculum Development and Outreach																	
Senior Faculty	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Junior Faculty	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Subtotal	**2**	**0**	**2**	**0**	**0**	**0**	**0**	**2**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Universidad Tecnológica de Querétaro - Collaborating Institution																	
Total [2]	1	1	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0
Curriculum Development and Outreach																	
Total Undergraduate Students	1	1	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**1**	**0**	**0**
University of Minnesota - Morris - Collaborating Institution																	
Total [2]	25	3	16	6	20	0	0	0	0	2	1	0	2	0	0	0	0
Research Under Strategic Research Plan																	
Total Undergraduate Students	2	0	1	1	1	0	0	0	0	0	0	0	1	0	0	0	0
Subtotal	**2**	**0**	**1**	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**
Curriculum Development and Outreach																	
Total Undergraduate Students	23	3	15	5	19	0	0	0	0	2	1	0	1	0	0	0	0
Subtotal	**23**	**3**	**15**	**5**	**19**	**0**	**0**	**0**	**0**	**2**	**1**	**0**	**1**	**0**	**0**	**0**	**0**
Michigan State Univeristy - 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
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
Subtotal	**1**	**0**	**1**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Rochester Institute of Technolgy - Non-ERC Institution Providing REU Students																	
Total [2]	1	1	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	1	0	0	1	0	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**1**	**0**	**0**	**0**
The Cooper Union for the Advancement of Science and Art - 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	Race Not Reported	Citizenship Foreign/Temp Visa	Citizenship Not Reported	U.S. Citizen/Perm Resident	Citizenship Foreign/Temp Visa	Citizenship Not Reported	
Total [2]	1	1	0	0	0	0	0	0	1	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
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
University of Missouri-Columbia - Non-ERC Institution Providing REU Students																	
Total [2]	1	1	0	0	0	0	0	0	0	0	0	0	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
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**
University of Virginia - Non-ERC Institution Providing REU Students																	
Total [2]	1	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	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Wilkes 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
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
Subtotal	**1**	**0**	**1**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Yale 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
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
Subtotal	**1**	**0**	**1**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Salish Kootenai College - Community College																	
Total [2]	8	2	0	6	8	0	0	0	0	0	0	0	0	0	0	0	0
Curriculum Development and Outreach																	
Total Undergraduate Students	8	2	0	6	8	0	0	0	0	0	0	0	0	0	0	0	0
Subtotal	**8**	**2**	**0**	**6**	**8**	**0**	**0**	**0**	**0**	**0**	**0**	**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
Precollege (K-12)																	
Teachers (non-RET)	1	1	0	0	0	0	0	1	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**
Burnsville High School - Pre-college Partner																	
Total [2]	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Precollege (K-12)																	
Teachers (non-RET)	1	0	1	0	0	0	0	1	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**
Capitol Hill Gifted and Talented Magnet - Pre-college Partner																	
Total [2]	1	1	0	0	0	0	0	1	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
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Cloquet High School - Pre-college Partner																	
Total [2]	1	1	0	0	0	0	0	1	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
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Cloquet Middle School - Pre-college Partner																	
Total [2]	1	1	0	0	0	0	0	1	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
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Guilford Middle School - Pre-college Partner																	
Total [2]	2	0	2	0	0	0	1	0	0	0	0	0	1	0	0	0	0
Precollege (K-12)																	
Teachers (RET)	2	0	2	0	0	0	1	0	0	0	0	0	1	0	0	0	0
Subtotal	**2**	**0**	**2**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**
Lafayette Jefferson High School - Pre-college Partner																	
Total [2]	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Precollege (K-12)																	
Teachers (RET)	1	1	0	0	0	0	0	1	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**
McCutcheon High School - Pre-college Partner																	
Total [2]	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Precollege (K-12)																	
Teachers (RET)	1	1	0	0	0	0	0	1	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**
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
Precollege (K-12)																	
Teachers (non-RET)	1	1	0	0	0	0	0	1	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**
Orono Middle School - Pre-college Partner																	
Total [2]	1	1	0	0	0	0	0	1	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
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Osakis Middle School - Pre-college Partner																	
Total [2]	1	1	0	0	0	0	0	1	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
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
South Ridge School (formerly Albrook School) - Pre-college Partner																	

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	Race Not Reported	Citizenship Foreign/Temp Visa	Citizenship Not Reported	U.S. Citizen/Perm Resident	Citizenship Foreign/Temp Visa	Citizenship Not Reported	
Total [2]	3	2	1	0	0	0	0	3	0	0	0	0	0	0	0	0	0
Precollege (K-12)																	
Teachers (non-RET)	3	2	1	0	0	0	0	3	0	0	0	0	0	0	0	0	0
Subtotal	**3**	**2**	**1**	**0**	**0**	**0**	**0**	**3**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
North Star STEM Alliance - LSAMP																	
Total [2]	1	1	0	0	0	0	0	0	0	0	0	1	0	0	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	0	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**
Circle of Life School - Alliance with NSF Diversity Awardees																	
Total [2]	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Curriculum Development and Outreach																	
Visiting Faculty	1	1	0	0	0	0	0	1	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**
Leech Lake Tribal College - Alliance with NSF Diversity Awardees																	
Total [2]	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
Curriculum Development and Outreach																	
Total Undergraduate Students	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
Subtotal	**1**	**0**	**0**	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Northstar STEM Program - Alliance with NSF Diversity Awardees																	
Total [2]	2	0	1	1	0	0	0	0	0	0	1	0	1	0	0	0	0
Curriculum Development and Outreach																	
Research Staff	2	0	1	1	0	0	0	0	0	0	1	0	1	0	0	0	0
Subtotal	**2**	**0**	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**1**	**0**	**0**	**0**	**0**
The National GEM Consortium - Alliance with NSF Diversity Awardees																	
Total [2]	1	1	0	0	0	0	1	0	0	0	0	0	0	0	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
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**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	**11**	**27**	**0**	**24**	**27**	**85**	**17**	**0**	**2**	**1**	**26**	**3**	**14**	**0**	**3**	**1**	**4**	**5**	**13**
Women																			
Category Total	3	3	0	6	4	30	7	0	0	0	1	1	1	0	0	0	0	0	2
Center Percent	27.3%	11.1%	0	25.0%	14.8%	35.3%	41.2%	0	0.0%	0.0%	3.8%	33.3%	7.1%	0	0.0%	0.0%	0.0%	0.0%	15.4%
National Percent [1][2]	N/A	14.1%	N/A	24.0%	20.4%	18.9%	N/A	N/A	N/A	N/A	23.0%	26.3%	19.3%	N/A	N/A	N/A	N/A	N/A	N/A
Underrepresented Racial Minorities																			
Category Total	1	0	0	3	0	40	5	0	0	0	3	0	3	0	0	0	0	0	4
Center Percent	9.1%	0.0%	0	12.5%	0.0%	47.1%	29.4%	0	0.0%	0.0%	11.5%	0.0%	21.4%	0	0.0%	0.0%	0.0%	0.0%	30.8%
National Percent [1][2]	N/A	3.1%	N/A	4.7%	6.0%	6.4%	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	0	0	1	0	4	2	0	0	0	1	0	1	0	0	0	0	0	0
Center Percent	0.0%	0.0%	0	4.2%	0.0%	4.7%	11.8%	0	0.0%	0.0%	3.8%	0.0%	7.1%	0	0.0%	0.0%	0.0%	0.0%	0.0%
National Percent [1][2]	N/A	3.8%	N/A	6.2%	8.9%	12.1%	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	4.2%	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 - 2012, Underrepresented Racial Minorities - 2012, Hispanic or Latino - 2012, and Persons with Disabilities - 2008.
[3]The national percentages for Persons with Disabilities are for all persons, regardless of citizenship. The national percentages for Doctoral students with disabilities and Masters students with disabilities are from the national percentages for Graduate students (Masters and Doctoral students combined).

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

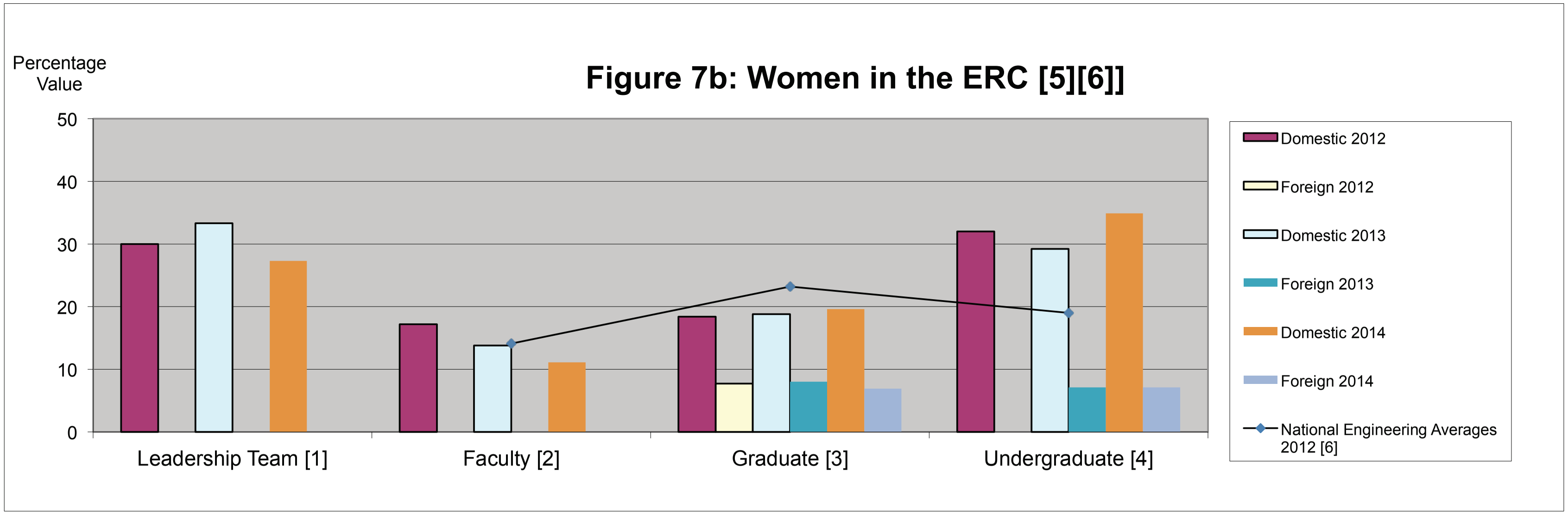
[5]Faculty includes Research - Senior Faculty, Research - Junior Faculty, Research - Visiting Faculty, Curriculum Development and Outreach - Senior Faculty, Curriculum Development and Outreach - Junior Faculty, and Curriculum Development and Outreach - Visiting Faculty.

Table 7a Summary: Count of ERC Personnel

Faculty	Community College RET	K-12 Teachers		Postdocs	Students				Young Scholars	Other [6]	Total
					Graduate		UG Non-REU	REU			
		RET	Non-RET		Doctoral	Masters					
32	0	4	10	2	54	35	112	23	0	28	279

[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.

Figure 7b: Women in the ERC [5][6]]



Averages	Leadership Team	Faculty	Graduate	Undergraduate
National Engineering Averages 2012 [6]	N/A	14.1%	23.2%	19%
All ERC's 2013 (Domestic)	29.9%	25.7%	27.1%	36.3%
All ERC's 2013 (Foreign)	15.4%	17.5%	24.6%	28.9%
Domestic Percentage for Engineering Research Center for Compact and Efficient Fluid Power at the University of Minnesota – Twin Cities 2014	27.3%	11.1%	19.6%	34.9%
Foreign Percentage for Engineering Research Center for Compact and Efficient Fluid Power at the University of Minnesota – Twin Cities 2014	0%	0%	6.9%	7.1%

[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.

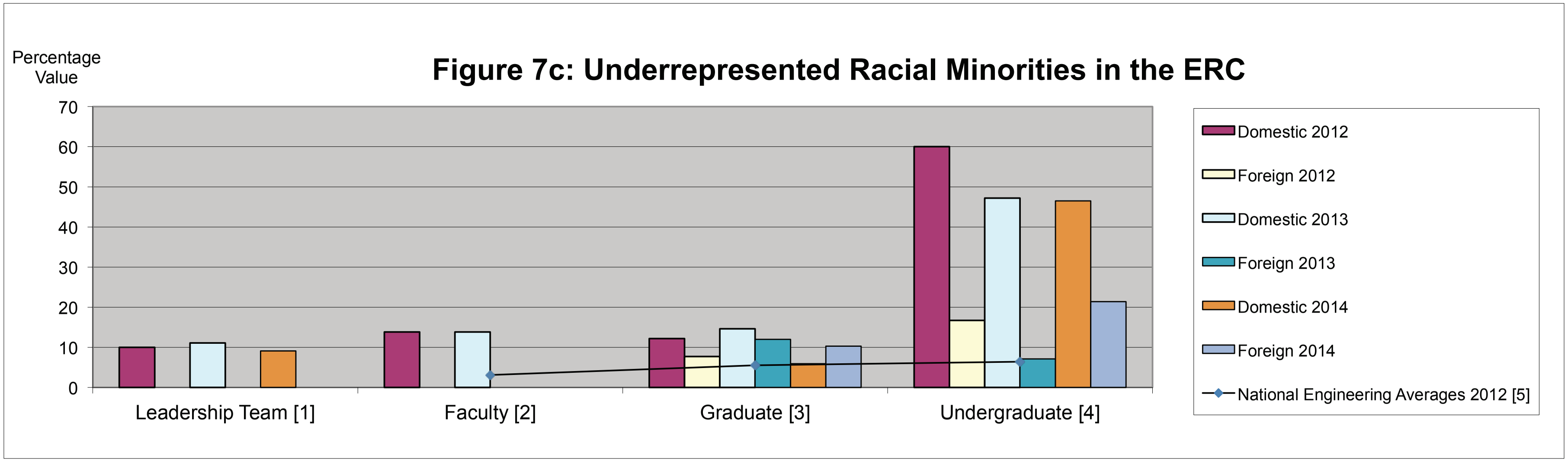


Figure 7c: Underrepresented Racial Minorities in the ERC

Averages	Leadership Team	Faculty	Graduate	Undergraduate
National Engineering Averages 2012 [5]	N/A	3.1%	5.5%	6.4%
All ERC's 2013 (Domestic)	10.2%	7.4%	11.3%	22.1%
All ERC's 2013 (Foreign)	0%	1%	4.8%	7.8%
Domestic Percentage for Engineering Research Center for Compact and Efficient Fluid Power at the University of Minnesota – Twin Cities 2014	9.1%	0%	5.9%	46.5%
Foreign Percentage for Engineering Research Center for Compact and Efficient Fluid Power at the University of Minnesota – Twin Cities 2014	0%	0%	10.3%	21.4%

[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.

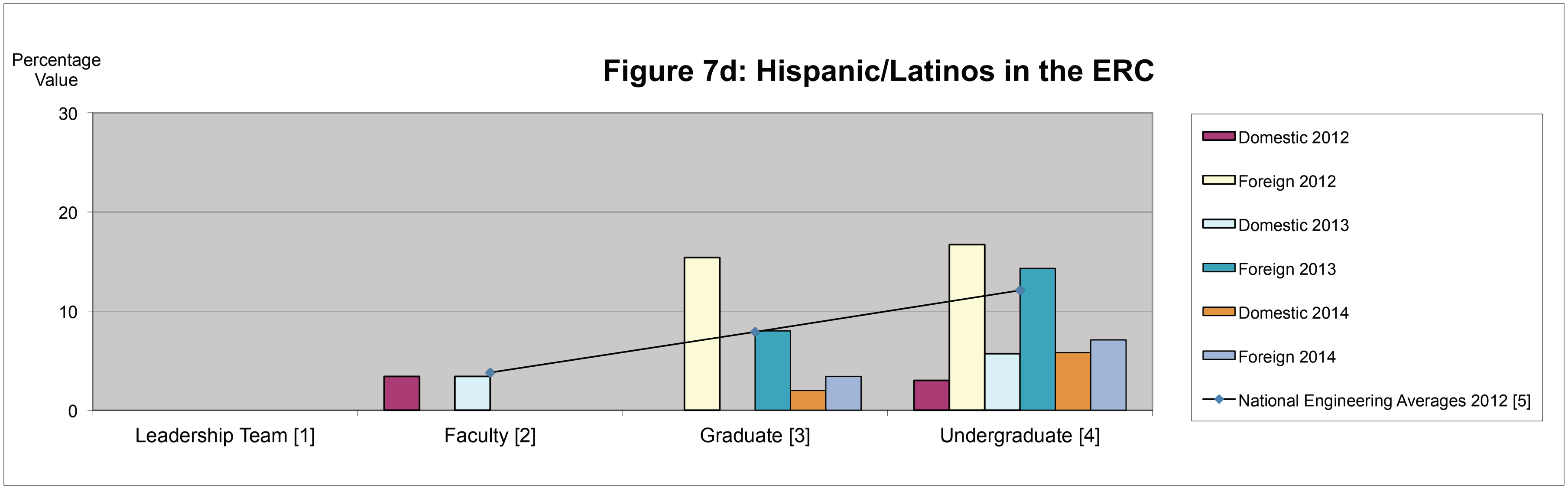


Figure 7d: Hispanic/Latinos in the ERC

Averages	Leadership Team	Faculty	Graduate	Undergraduate
National Engineering Averages 2012 [5]	N/A	3.8%	7.9%	12.1%
All ERC's 2013 (Domestic)	7.3%	6.8%	11.2%	16.5%
All ERC's 2013 (Foreign)	15.4%	7.2%	4.2%	16.7%
Domestic Percentage for Engineering Research Center for Compact and Efficient Fluid Power at the University of Minnesota – Twin Cities 2014	0%	0%	2%	5.8%
Foreign Percentage for Engineering Research Center for Compact and Efficient Fluid Power at the University of Minnesota – Twin Cities 2014	0%	0%	3.4%	7.1%

[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.

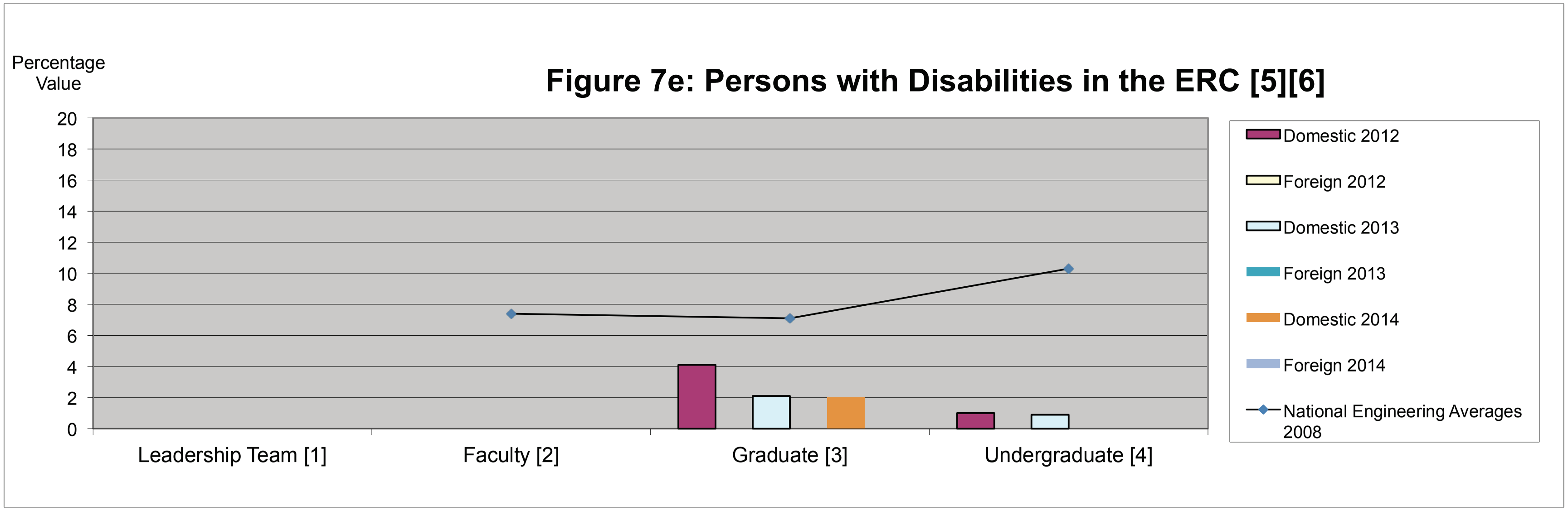


Figure 7e: Persons with Disabilities in the ERC [5][6]

Averages	Leadership Team	Faculty	Graduate	Undergraduate
National Engineering Averages 2008	N/A	7.4%	7.1%	10.3%
All ERC's 2013 (Domestic)	3.3%	2.2%	1.2%	2%
All ERC's 2013 (Domestic)	0%	0%	0%	0%
Domestic Percentage for Engineering Research Center for Compact and Efficient Fluid Power at the University of Minnesota – Twin Cities 2014	0%	0%	2%	0%
Foreign Percentage for Engineering Research Center for Compact and Efficient Fluid Power at the University of Minnesota – Twin Cities 2014	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	13	22%	9	15%	3	5%
Core Partners						
Georgia Institute of Technology	2	10%	0	0%	1	5%
Purdue University	5	29%	0	0%	0	0%
University of Illinois at Urbana-Champaign	5	28%	1	6%	1	6%
Vanderbilt University	3	27%	1	9%	0	0%
Collaborating Institutions						
Bradley University	2	33%	0	0%	0	0%
Eolos Wind Energy Research Consortium	0	0%	0	0%	0	0%
Hennepin Technical College	0	0%	0	0%	0	0%
Malaysian Ministry of Higher Education (MOHE)	0	0%	0	0%	0	0%
Milwaukee School of Engineering	2	17%	0	0%	0	0%
National Center for Earth-surface Dynamics	1	100%	0	0%	0	0%
National University of Engineering (UNI)	0	0%	0	0%	0	0%
North Carolina Agriculture and Technical State University	3	38%	5	63%	0	0%
Science Museum of Minnesota	1	20%	0	0%	0	0%
STEM Education Center	2	100%	0	0%	0	0%
Universidad Tecnológica de Querétaro	0	0%	0	0%	0	0%
University of Minnesota - Morris	15	65%	22	96%	0	0%
Non-ERC Institutions Providing REU Students						
Michigan State Univeristy	1	100%	0	0%	0	0%
Rochester Institute of Technolgy	0	0%	0	0%	1	100%
The Cooper Union for the Advancement of Science and Art	0	0%	0	0%	0	0%
University of Missouri-Columbia	0	0%	0	0%	0	0%
University of Virginia	0	0%	1	100%	0	0%
Wilkes University	1	100%	0	0%	0	0%
Yale University	1	100%	0	0%	0	0%
Precollege Partners						
Brainerd Public Schools	0	0%	0	0%	0	0%
Burnsville High School	1	100%	0	0%	0	0%
Capitol Hill Gifted and Talented Magnet	0	0%	0	0%	0	0%
Cloquet High School	0	0%	0	0%	0	0%
Cloquet Middle School	0	0%	0	0%	0	0%
Guilford Middle School	1	100%	1	100%	0	0%
Lafayette Jefferson High School	0	0%	0	0%	0	0%
McCutcheon High School	0	0%	0	0%	0	0%
North Branch Area Public Schools	0	0%	0	0%	0	0%
Orono Middle School	0	0%	0	0%	0	0%
Osakis Middle School	0	0%	0	0%	0	0%
South Ridge School (formerly Albrook School)	1	33%	0	0%	0	0%
Community Colleges						
Salish Kootenai College	0	0%	8	100%	0	0%
Louis Stokes Alliances for Minority Participation (LSAMP)						
North Star STEM Alliance	0	0%	0	0%	0	0%
NSF Diversity Program Collaborations (NSF Diversity Program Collaborations)						
Circle of Life School	0	0%	0	0%	0	0%
Leech Lake Tribal College	0	0%	1	100%	0	0%
Northstar STEM Program	1	100%	0	0%	0	0%
The National GEM Consortium	0	0%	1	100%	0	0%

[1] - This data includes U.S. Citizens and Legal Permanent Residents only.

[2] - Underrepresented Racial Minorities is a sum of all personnel entered in the following categories: American Indian or Alaska Native, Black or African American, Native Hawaiian or Other Pacific Islander, or More than one race reported, minority.

Table 8: Current Award Year Functional Budget

Function	Direct Support		Direct Support Total	Associated Projects	Total Budget
	Unrestricted Cash(Core Projects)	Restricted Cash(Sponsored Projects)			
1: Efficiency	$703,335	$0	$703,335	$1,323,162	$2,026,497
2: Compactness	$549,299	$0	$549,299	$0	$549,299
3: Effectiveness	$460,924	$0	$460,924	$398,304	$859,228
Test Beds	$386,729	$0	$386,729	$294,890	$681,619
Research Total	**$2,100,287**	**$0**	**$2,100,287**	**$2,016,356**	**$4,116,643**
Educational Program Total	$521,465	$1,000	$522,465	$0	$522,465
General Shared Equipment	$65,000	$0	$65,000	$0	$65,000
New Facilities/New Construction	$0	$0	$0	$0	$0
Leadership/Administration/Management	$656,143	$0	$656,143	$0	$656,143
Industrial Collaboration/Innovation Program	$320,000	$0	$320,000	$0	$320,000
Center Related Travel	$22,000	$0	$22,000	$498	$22,498
Indirect Cost	$1,042,865	$0	$1,042,865	N/A	$1,042,865
Functional and Educational Budget Total	**$6,318,573**	**$1,000**	**$6,319,573**	**$498**	**$6,320,071**
Support Reserved for Future Years	N/A	N/A	$0	N/A	$0
Residual Funds Remaining	$3,691,100	$0	$3,691,100	N/A	$3,691,100
Total	**$8,418,860**	**$1,000**	**$8,419,860**	**$2,016,854**	**$10,436,714**

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

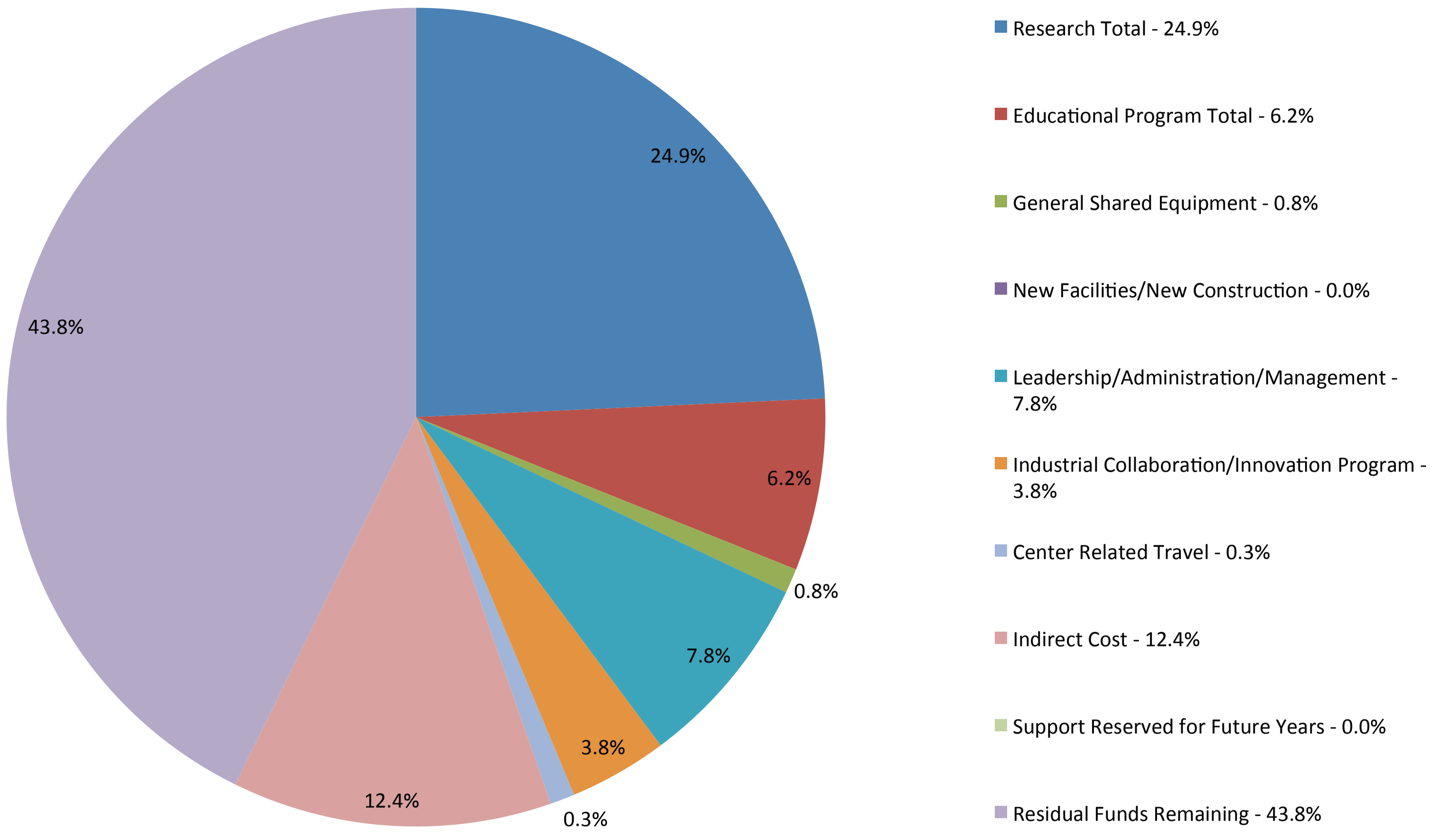


Figure 8b: Functional Budget as a percentage of Associated Project Support

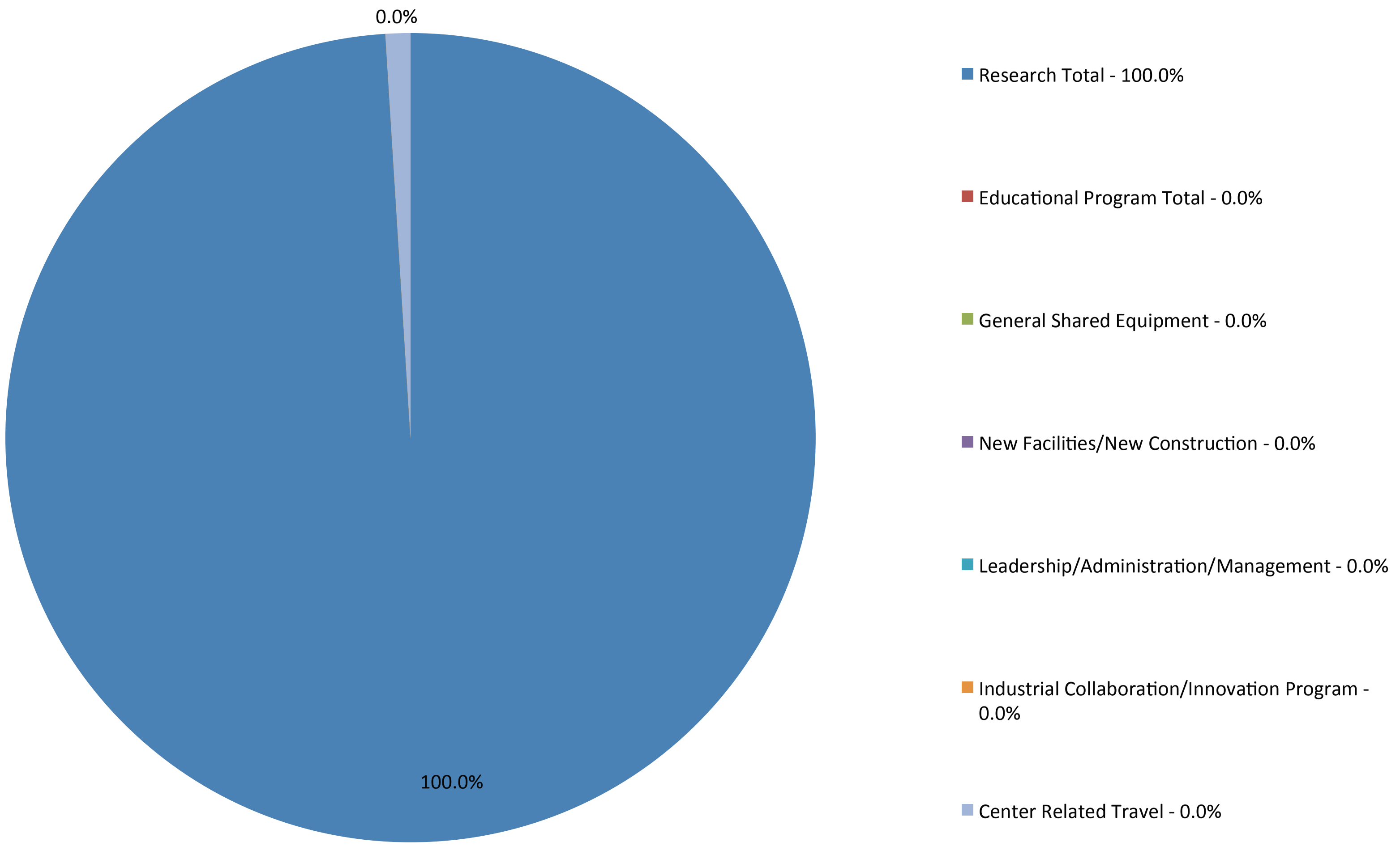


Table 8c: Current Award Year Education Functional Budget

Education Programs	Direct Support		Direct Support Total	Associated Projects	Total Budget
	Unrestricted Cash OR Core Projects	Restricted Cash OR Sponsored Projects			
Precollege Education Activities	$53,521	$1,000	**$54,521**	$0	**$54,521**
University Education	$92,540	$0	**$92,540**	$0	**$92,540**
Student Leadership Council	$24,800	$0	**$24,800**	$0	**$24,800**
Young Scholars	$1,000	$0	**$1,000**	$0	**$1,000**
REU	$159,574	$0	**$159,574**	$0	**$159,574**
RET	$34,250	$0	**$34,250**	$0	**$34,250**
Assessment	$50,000	$0	**$50,000**	$0	**$50,000**
Community College activities	$9,800	$0	**$9,800**	$0	**$9,800**
Other	$95,980	$0	**$95,980**	$0	**$95,980**
Education Program Total	**$521,465**	**$1,000**	**$522,465**	**$0**	**$522,465**

Table 9: Sources of Support

Sources of Support	Early Cumulative Total	Jun 1, 2009 - May 31, 2010	Jun 1, 2010 - May 31, 2011	Jun 1, 2011 - May 31, 2012	Jun 1, 2012 - May 31, 2013	Jun 1, 2013 - May 31, 2014			Cumulative Total [1]
						Received	Promised	Total	
Unrestricted Cash									
Government									
NSF Funding									
NSF ERC Base Award	$8,696,020	$3,750,000	$4,010,000	$4,000,000	$4,000,000	$4,000,000	$0	$4,000,000	$28,456,020
Other NSF (Not ERC Program)	$0	$0	$0	$0	$0	$390,000	$0	$390,000	$390,000
TOTAL NSF FUNDING	**$8,696,020**	**$3,750,000**	**$4,010,000**	**$4,000,000**	**$4,000,000**	**$4,390,000**	**$0**	**$4,390,000**	**$28,846,020**
Other U.S. Government (Not NSF)	$0	$0	$0	$0	$3,500	$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	**$8,696,020**	**$3,750,000**	**$4,010,000**	**$4,000,000**	**$4,003,500**	**$4,390,000**	**$0**	**$4,390,000**	**$28,849,520**
Industry									
U.S. Industry	$1,275,293	$579,415	$517,250	$583,817	$443,100	$480,267	$90,500	$570,767	$3,969,642
Foreign Industry	$261,000	$108,000	$119,000	$112,000	$102,000	$48,750	$68,000	$116,750	$818,750
Industrial Association	$0	$0	$51,000	$41,000	$41,000	$105,549	$0	$105,549	$238,549
TOTAL INDUSTRY FUNDING	**$1,536,293**	**$687,415**	**$687,250**	**$736,817**	**$586,100**	**$634,566**	**$158,500**	**$793,066**	**$5,026,941**
University									
U.S. University	$1,795,409	$913,885	$800,000	$800,000	$840,543	$600,000	$200,000	$800,000	$5,949,837
Foreign University	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL UNIVERSITY FUNDING	**$1,795,409**	**$913,885**	**$800,000**	**$800,000**	**$840,543**	**$600,000**	**$200,000**	**$800,000**	**$5,949,837**
Other									
Private Foundation	$0	$0	$1,000	$0	$0	$0	$0	$0	$1,000
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**	**$1,000**	**$0**	**$0**	**$0**	**$0**	**$0**	**$1,000**
Total Unrestricted Cash	**$12,027,722**	**$5,351,300**	**$5,498,250**	**$5,536,817**	**$5,430,143**	**$5,624,566**	**$358,500**	**$5,983,066**	**$39,827,298**
Restricted Cash									
NSF Funding									
NSF ERC Program Special Purpose Awards and Supplements	$124,934	$44,814	$281,724	$39,989	$52,000	$5,120	$0	$5,120	$548,581
Other NSF (Not ERC Program)	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL NSF FUNDING	**$124,934**	**$44,814**	**$281,724**	**$39,989**	**$52,000**	**$5,120**	**$0**	**$5,120**	**$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	$0	$500	$0	$500	$500
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**	**$500**	**$0**	**$500**	**$500**
University									
U.S. University	$0	$0	$0	$0	$0	$500	$0	$500	$500
Foreign University	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL UNIVERSITY FUNDING	**$0**	**$0**	**$0**	**$0**	**$0**	**$500**	**$0**	**$500**	**$500**
Other									
Private Foundation	$0	$0	$0	$0	$0	$0	$0	$0	$0
Medical Facility	$0	$0	$0	$0	$0	$0	$0	$0	$0
Non Profit	$0	$0	$0	$0	$0	$0	$0	$0	$0
Venture Capitalist	$0	$0	$0	$0	$0	$0	$0	$0	$0
Other	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL OTHER FUNDING	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
Total Restricted Cash - Non Translational	**$0**	**$0**	**$0**	**$0**	**$0**	**$1,000**	**$0**	**$1,000**	**$1,000**
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

Sources of Support	Early Cumulative Total	Jun 1, 2009 - May 31, 2010	Jun 1, 2010 - May 31, 2011	Jun 1, 2011 - May 31, 2012	Jun 1, 2012 - May 31, 2013	Jun 1, 2013 - May 31, 2014			Cumulative Total [1]
						Received	Promised	Total	
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 Restricted Cash - Translational	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
Total Restricted Cash	**$124,934**	**$44,814**	**$281,724**	**$39,989**	**$52,000**	**$6,120**	**$0**	**$6,120**	**$549,581**
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	$1,999,602	$316,642	$316,643	$589,405	$1,975,463	$1,975,463	N/A	$1,975,463	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	**$2,049,258**	**$316,642**	**$316,643**	**$589,405**	**$1,975,463**	**$1,975,463**	**N/A**	**$1,975,463**	**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	**$2,049,258**	**$316,642**	**$316,643**	**$589,405**	**$1,975,463**	**$1,975,463**	**N/A**	**$1,975,463**	**N/A**
Industry									
U.S. Industry	$1,671,828	$297,485	$297,485	$464,648	$455,211	$455,211	N/A	$455,211	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	**$1,671,828**	**$297,485**	**$297,485**	**$464,648**	**$455,211**	**$455,211**	**N/A**	**$455,211**	**N/A**
University									
U.S. University	$707,508	$232,525	$232,757	$184,201	$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	**$707,508**	**$232,525**	**$232,757**	**$184,201**	**$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]	**$4,428,594**	**$846,652**	**$846,885**	**$1,238,254**	**$2,430,674**	**$2,430,674**	**N/A**	**$2,430,674**	**N/A**
Associated Projects [3]									
NSF Funding									
NSF ERC Program	$0	$0	$640,109	$0	$0	$0	$0	$0	$640,109
Other NSF (Not ERC Program)	$241,492	$99,051	$640,749	$591,183	$508,500	$408,620	$226,865	$635,485	$2,716,460
TOTAL NSF FUNDING	**$241,492**	**$99,051**	**$1,280,858**	**$591,183**	**$508,500**	**$408,620**	**$226,865**	**$635,485**	**$3,356,569**
Associated Projects - Non Translational [3]									
Government									
Other U.S. Government (Not NSF)	$1,537,335	$527,447	$181,654	$13,320	$69,707	$7,086	$3,543	$10,629	$2,340,092
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

Sources of Support	Early Cumulative Total	Jun 1, 2009 - May 31, 2010	Jun 1, 2010 - May 31, 2011	Jun 1, 2011 - May 31, 2012	Jun 1, 2012 - May 31, 2013	Jun 1, 2013 - May 31, 2014			Cumulative Total [1]
						Received	Promised	Total	
Quasi-government research organization	$0	$0	$57,276	$0	$0	$0	$0	$0	$57,276
TOTAL GOVERNMENT FUNDING	**$1,537,335**	**$527,447**	**$238,930**	**$13,320**	**$69,707**	**$7,086**	**$3,543**	**$10,629**	**$2,397,368**
Industry									
U.S. Industry	$1,741,670	$1,098,877	$350,123	$0	$1,974	$61,212	$32,154	$93,366	$3,286,010
Foreign Industry	$0	$0	$52,865	$78,000	$70,417	$135,283	$32,279	$167,562	$368,844
Industrial Association	$0	$0	$71,067	$0	$0	$0	$0	$0	$71,067
TOTAL INDUSTRY FUNDING	**$1,741,670**	**$1,098,877**	**$474,055**	**$78,000**	**$72,391**	**$196,495**	**$64,433**	**$260,928**	**$3,725,921**
University									
U.S. University	$0	$0	$0	$128,550	$5,826	$500	$0	$500	$134,876
Foreign University	$0	$0	$32,000	$13,714	$3,077	$0	$0	$0	$48,791
TOTAL UNIVERSITY FUNDING	**$0**	**$0**	**$32,000**	**$142,264**	**$8,903**	**$500**	**$0**	**$500**	**$183,667**
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	$0	$527,388	$1,099,920	$1,549,850	$0	$0	$0	$3,343,778
TOTAL OTHER FUNDING	**$166,620**	**$0**	**$527,388**	**$1,099,920**	**$1,549,850**	**$0**	**$0**	**$0**	**$3,343,778**
Total Associated Projects - Non Translational	**$3,445,625**	**$1,626,324**	**$1,272,373**	**$1,333,504**	**$1,700,851**	**$204,081**	**$67,976**	**$272,057**	**$9,650,734**
Associated Projects - Translational [3]									
Government									
Other U.S. Government (Not NSF)	$0	$0	$0	$187,208	$60,667	$0	$0	$0	$247,875
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**	**$187,208**	**$60,667**	**$0**	**$0**	**$0**	**$247,875**
Industry									
U.S. Industry	$0	$0	$0	$115,701	$76,362	$128,950	$54,480	$183,430	$375,493
Foreign Industry	$0	$0	$5,000	$83,974	$37,583	$0	$0	$0	$126,557
Industrial Association	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL INDUSTRY FUNDING	**$0**	**$0**	**$5,000**	**$199,675**	**$113,945**	**$128,950**	**$54,480**	**$183,430**	**$502,050**
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	$44,750	$662,827	$263,055	$925,882	$970,632
TOTAL OTHER FUNDING	**$0**	**$0**	**$0**	**$0**	**$44,750**	**$662,827**	**$263,055**	**$925,882**	**$970,632**
Total Associated Projects - Translational	**$0**	**$0**	**$5,000**	**$386,883**	**$219,362**	**$791,777**	**$317,535**	**$1,109,312**	**$1,720,557**
Total Associated Projects	**$3,687,117**	**$1,725,375**	**$2,558,231**	**$2,311,570**	**$2,428,713**	**$1,404,478**	**$612,376**	**$2,016,854**	**$14,727,860**
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									

Sources of Support	Early Cumulative Total	Jun 1, 2009 - May 31, 2010	Jun 1, 2010 - May 31, 2011	Jun 1, 2011 - May 31, 2012	Jun 1, 2012 - May 31, 2013	Jun 1, 2013 - May 31, 2014			Cumulative Total [1]
						Received	Promised	Total	
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	$0	$39,253	$11,957	$271,466	$2,700	$274,166	$909,778
Foreign Industry	$0	$0	$0	$500	$2,300	$13,600	$0	$13,600	$16,400
Industrial Association	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL INDUSTRY FUNDING	**$584,402**	**$0**	**$0**	**$39,753**	**$14,257**	**$285,066**	**$2,700**	**$287,766**	**$926,178**
University									
U.S. University	$0	$0	$0	$0	$0	$15,550	$0	$15,550	$15,550
Foreign University	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL UNIVERSITY FUNDING	**$0**	**$0**	**$0**	**$0**	**$0**	**$15,550**	**$0**	**$15,550**	**$15,550**
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**	**$0**	**$39,753**	**$14,257**	**$300,616**	**$2,700**	**$303,316**	**$941,728**
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	$0	$1	$0	$1	$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**	**$0**	**$1**	**$0**	**$1**	**$22,501**
University									
U.S. University	$16,200	$0	$0	$8,000	$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**	**$0**	**$8,000**	**$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

Sources of Support	Early Cumulative Total	Jun 1, 2009 - May 31, 2010	Jun 1, 2010 - May 31, 2011	Jun 1, 2011 - May 31, 2012	Jun 1, 2012 - May 31, 2013	Jun 1, 2013 - May 31, 2014			Cumulative Total [1]
						Received	Promised	Total	
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 Visting Personnel	**$98,200**	**$0**	**$0**	**$8,000**	**$0**	**$1**	**$0**	**$1**	**$106,201**
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									
U.S. Industry	$0	$0	$219,621	$106,408	$0	$0	$0	$0	$326,029
Foreign Industry	$0	$0	$9,000	$62,308	$0	$0	$0	$0	$71,308
Industrial Association	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL INDUSTRY FUNDING	**$0**	**$0**	**$228,621**	**$168,716**	**$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	$0	$169,032	$0	$0	$0	$0	$0	$0	$169,032
TOTAL OTHER FUNDING	**$0**	**$169,032**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$169,032**
Total Value of Other Assets	**$0**	**$169,032**	**$228,621**	**$168,716**	**$0**	**$0**	**$0**	**$0**	**$566,369**
Total In-Kind Support, All Sources	**$1,308,193**	**$169,032**	**$228,621**	**$216,469**	**$14,257**	**$300,617**	**$2,700**	**$303,317**	**$2,239,889**
Total Cash Support, All Sources [2]	**$16,581,250**	**$6,242,766**	**$6,626,859**	**$6,815,060**	**$7,912,817**	**$8,061,360**	**$358,500**	**$8,419,860**	**$40,376,879**
Percent Non-ERC Program Cash	**35%**	**34%**	**30%**	**32%**	**24%**	**26%**	**100%**	**29%**	**28%**
Total Cash + In-Kind	**$17,889,443**	**$6,411,798**	**$6,855,480**	**$7,031,529**	**$7,927,074**	**$8,361,977**	**$361,200**	**$8,723,177**	**$42,616,768**
Grand Total (Cash + In-Kind + Associated Projects)	**$21,576,560**	**$8,137,173**	**$9,413,711**	**$9,343,099**	**$10,355,787**	**$9,766,455**	**$973,576**	**$10,740,031**	**$57,344,628**

[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
not account for any encumbrances or committed monies.

Table 10: Annual Expenditures and Budgets

Total Direct Center Cash Support	Early Cumulative Total [1]	Jun-01-2009 - May 31-2010	Jun-01-2010 - May 31-2011	Jun-01-2011 - May 31-2012	Jun-01-2012 - May 31-2013	Jun-01-2013 - May 31-2014	Proposed Budget Next Award Year
Direct Cash Support (All Sources)	**$12,152,656**	**$5,396,114**	**$5,779,974**	**$5,576,806**	**$5,482,143**	**$5,989,186**	**N/A**
Multi-year Support brought forward from Prior Year (All Sources)	**N/A**	**N/A**	**N/A**	**N/A**	**$0**	**$0**	**N/A**
Residual Funds brought forward from Prior Year (All Sources)	**$4,428,594**	**$846,652**	**$846,885**	**$1,238,254**	**$2,430,674**	**$2,430,674**	**N/A**
Total Direct Center Cash Support	**$16,581,250**	**$6,242,766**	**$6,626,859**	**$6,815,060**	**$7,912,817**	**$8,419,860**	**N/A**

Expenses	Early Cumulative Total [1]	Jun-01-2009 - May 31-2010	Jun-01-2010 - May 31-2011	Jun-01-2011 - May 31-2012	Jun-01-2012 - May 31-2013	Jun-01-2013 - May 31-2014	Proposed Budget Next Award Year
Salaries & Benefits							
A. Senior Personnel: PI/PD, Co-PIs, Faculty and Other Senior Associates	$1,054,157	$484,549	$505,207	$741,340	$354,294	$759,854	$56,989
B. Other Personnel	$4,399,432	$1,919,364	$1,853,739	$1,133,600	$1,569,030	$1,342,618	$954,847
Postdoctoral associates	$417,646	$67,797	$19,180	$0	$46,368	$79,098	$59,323
Other professionals (technician, programmer, etc.)	$387,713	$232,601	$113,991	$112,105	$0	$47,208	$3,540
Graduate Students	$1,907,440	$892,055	$1,117,358	$799,764	$816,483	$1,005,113	$753,835
Undergraduate students	$336,608	$157,422	$59,537	$43,105	$80,342	$55,510	$41,632
Secretarial - clerical	N/A	N/A	$188,104	$143,463	$104,769	$30,000	$2,250
Other	$1,350,025	$569,489	$355,569	$35,163	$521,068	$125,689	$94,267
C. Fringe Benefits	$1,259,551	$591,497	$587,333	$562,251	$440,533	$608,511	$456,383
Total Salaries & Benefits (A+B+C)	**$6,713,140**	**$2,995,410**	**$2,946,279**	**$2,437,191**	**$2,363,857**	**$2,710,983**	**$1,468,219**

Other Expenses							
D. Equipment	$736,882	$95,831	$147,311	$83,508	$91,183	$64,349	$48,262
E. Travel	N/A	N/A	$253,621	$175,231	$250,789	$302,434	$226,825
F. Participant Support	N/A	N/A	$161,046	$111,808	$160,576	$370,407	$277,805
G. Other Direct Costs	$2,145,864	$811,591	$629,139	$396,298	$830,931	$823,691	$617,768
H. Direct Costs Total (A through G)	**$9,595,886**	**$3,902,832**	**$4,137,396**	**$3,204,036**	**$3,697,336**	**$4,271,864**	**$2,638,879**
I. Indirect Costs	**$2,892,034**	**$1,262,004**	**$1,251,209**	**$993,916**	**$1,324,508**	**$1,165,236**	**$873,927**
TOTAL Expenditures and Budgets (A through I)	**$12,487,920**	**$5,164,836**	**$5,388,605**	**$4,197,952**	**$5,021,844**	**$5,437,100**	**$3,512,806**

Totals and Residuals	Early Cumulative Total [1]	Jun-01-2009 - May 31-2010	Jun-01-2010 - May 31-2011	Jun-01-2011 - May 31-2012	Jun-01-2012 - May 31-2013	Jun-01-2013 - May 31-2014	Proposed Budget Next Award Year
Total Direct Center Cash Support	**$16,581,250**	**$6,242,766**	**$6,626,859**	**$6,815,060**	**$7,912,817**	**$8,419,860**	**N/A**
J. TOTAL Expenditures and Budgets (A through I)	$12,487,920	$5,164,836	$5,388,605	$4,197,952	$5,021,844	$5,437,100	$3,512,806
K. Support Reserved for Future Years	N/A	N/A	N/A	N/A	$0	$0	N/A
L. Residual Funds Remaining	$4,278,673	$0	$1,238,254	$262,725	$2,890,973	$2,982,760	$0
Balance (Subtract J+K+L from Current Year Support)	**$-185,343**	**$1,077,930**	**$0**	**$2,354,383**	**$0**	**$0**	**N/A**

[1] - For Centers in operation for more than five years.

Explanation for Remaining Residual Funds

All funds allowed to be budgeted have been budgeted out and are committed for use. Delays in invoicing and processing of invoices contributes to carry-forward each year. In Year 8, $4 million was awarded, but only .67% was released for spending until the Engineering Research Board (ERB) meets and approves the release of $1,320,000 for spending. This money is all committed as shown in the non-ERC Web table, certified in the report.

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Table 11: Modes of Support, by Industry and Other Practitioner Organizations

Organization	Jun 1, 2012 - May 31, 2013						Jun 1, 2013 - May 31, 2014						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	$10,000
Air Logic	$2,000	$0	$0	$0	$0	$0	$1,000	$0	$0	$0	$0	$0	$0
AS Pindel	$0	$0	$0	$0	$0	$0	$667	$0	$0	$0	$0	$0	$0
Bobcat	$15,000	$0	$0	$0	$0	$0	$15,000	$0	$0	$0	$0	$0	$0
Bosch Rexroth Corporation	$50,000	$0	$0	$0	$0	$800	$0	$0	$0	$0	$0	$0	$50,000
Caterpillar, Inc.	$50,000	$0	$0	$0	$0	$0	$50,000	$0	$0	$0	$0	$0	$0
CNH America, Inc.	$40,000	$0	$0	$0	$0	$0	$40,000	$0	$0	$0	$81,446	$0	$20,361
Concentric AB/Haldex	$6,000	$0	$0	$0	$0	$0	$6,000	$0	$0	$0	$0	$0	$0
Danfoss	$50,000	$0	$0	$0	$0	$10,757	$50,000	$0	$0	$0	$6,662	$22,000	$0
Deere and Company	$0	$0	$0	$0	$0	$0	$15,000	$0	$0	$0	$24,800	$0	$12,400
Deltrol Fluid Products	$5,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$5,000
Donaldson Company	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$1	$1	$0
Eaton Corporation	$50,000	$0	$0	$0	$76,362	$0	$50,000	$0	$0	$0	$0	$333	$0
Enfield Technologies	$5,000	$0	$0	$0	$0	$0	$5,000	$0	$0	$0	$0	$0	$0
Evonik Additives, USA, Inc.	$10,000	$0	$0	$0	$0	$0	$10,000	$0	$0	$0	$0	$0	$0
Exxon Mobil	$40,000	$0	$0	$0	$0	$0	$40,000	$0	$0	$0	$0	$0	$0
Freudenberg - NOK	$6,000	$0	$0	$0	$0	$0	$6,000	$0	$0	$0	$0	$0	$0
Gates Corporation	$40,000	$0	$0	$0	$0	$0	$40,000	$0	$0	$0	$0	$0	$0
Heco Gear, Inc.	$2,000	$0	$0	$0	$0	$0	$2,000	$0	$0	$0	$0	$0	$0
Hitachi Construction Machinery	$0	$0	$0	$0	$0	$0	$13,750	$0	$0	$0	$0	$0	$0
Hoowaki, LLC	$1,000	$0	$0	$0	$0	$0	$1,000	$0	$0	$0	$0	$0	$0
Husco International, Inc.	$40,000	$0	$0	$0	$0	$0	$40,000	$0	$0	$0	$0	$0	$0
Idemitsu Kosan Co., Ltd.	$0	$0	$0	$0	$0	$0	$2,000	$0	$0	$0	$0	$0	$0
Linde Hydraulics Corp.	$5,000	$0	$0	$0	$0	$0	$5,000	$0	$0	$0	$0	$3,600	$0
Main Manufacturing Products, Inc.	$2,000	$0	$0	$0	$0	$0	$1,000	$0	$0	$0	$0	$0	$0
Master Pneumatic-Detroit, Inc.	$1,000	$0	$0	$0	$0	$0	$1,000	$0	$0	$0	$0	$0	$0
Moog, Inc.	$15,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$15,000
National Fluid Power Association	$40,000	$0	$0	$0	$0	$0	$105,549	$0	$0	$0	$0	$0	$0
National Tube Supply Company	$1,000	$0	$0	$0	$0	$0	$1,000	$0	$0	$0	$0	$0	$0
Netshape Technologies	$7,500	$0	$0	$0	$0	$0	$7,500	$0	$0	$0	$0	$0	$7,500
Nexen Group, Inc.	$1,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$1,000
Nitta Corporation	$1,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Pall Corporation	$0	$0	$0	$0	$0	$0	$21,300	$0	$0	$0	$0	$0	$0
Parker Hannifin Corporation	$0	$0	$0	$0	$0	$700	$50,300	$0	$0	$0	$0	$2,633	$50,000
Poclain Hydraulics	$15,000	$0	$0	$0	$0	$0	$15,000	$0	$0	$0	$0	$0	$0
Quality Control Corporation	$1,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$1,000
Ross Controls	$5,000	$0	$0	$0	$0	$0	$5,000	$0	$0	$0	$0	$0	$0
Shell Global Solutions	$12,000	$0	$0	$0	$0	$0	$0	$0	$0	$13,462	$0	$0	$12,000
Simerics, Inc.	$1,000	$0	$0	$0	$0	$0	$1,000	$0	$0	$0	$0	$0	$0
StorWatts Inc.	$1,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$1,000
Sun Hydraulics	$6,000	$0	$0	$0	$0	$0	$6,000	$0	$0	$0	$0	$0	$0
Takako Industries	$1,000	$0	$0	$0	$0	$0	$1,000	$0	$0	$0	$0	$10,000	$0
Tennant	$12,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
The Lubrizol Corporation	$5,000	$0	$0	$1,974	$0	$0	$5,000	$0	$0	$0	$0	$0	$0
Trelleborg Sealing Solutions	$6,000	$0	$0	$0	$0	$0	$6,000	$0	$0	$0	$0	$0	$0
Walvoil Fluid Power	$6,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$6,000
Woodward, Inc.	$16,600	$0	$0	$0	$0	$0	$15,000	$0	$0	$0	$0	$0	$0
Total Members	**$583,100**	**$0**	**$0**	**$1,974**	**$76,362**	**$12,257**	**$634,066**	**$0**	**$0**	**$13,462**	**$112,909**	**$38,567**	**$191,261**
Non-Member Organizations: Funders of Sponsored Projects, Funders of Associated Projects, and Contributing Organizations													
Casappa S.p.A.	$0	$0	$0	$55,417	$37,583	$0	$0	$0	$0	$71,821	$0	$0	$32,279
Clippard Instrument Laboratory Inc.	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Clipper Windpower Inc.	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Confidential Organization (optional use for associated or sponsored projects only)	$0	$0	$0	$1,549,850	$44,750	$0	$0	$0	$0	$0	$662,827	$0	$263,055
Cummins Engines	$0	$0	$0	$0	$0	$0	$0	$0	$0	$13,000	$0	$0	$26,000
Dae Jin Hydraulics - TECPOS	$0	$0	$0	$0	$0	$0	$0	$0	$0	$50,000	$0	$0	$0
DARPA	$0	$0	$0	$0	$60,667	$0	$0	$0	$0	$0	$0	$0	$0
DuPont	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$5,182	$0	$0
Festo Corporation	$0	$0	$0	$0	$0	$1,500	$0	$0	$0	$0	$0	$0	$0
FORCE America	$0	$0	$0	$0	$0	$0	$0	$500	$0	$0	$0	$0	$0
Funding Sources (7) kept confidential due to Intellectual Property Rights	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0

Table 11: Modes of Support, by Industry and Other Practitioner Organizations

Organization	Jun 1, 2012 - May 31, 2013						Jun 1, 2013 - May 31, 2014						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		
Hydac Corporation	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$2,500	$0
International Fluid Power Society	$1,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
John Crane	$0	$0	$0	$0	$0	$0	$0	$0	$0	$8,462	$0	$0	$6,154
Keller America, Inc.	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$244,000	$0
Mico, Inc.	$500	$0	$0	$0	$0	$0	$500	$0	$0	$0	$0	$0	$0
Midwest Precision	$0	$0	$0	$0	$0	$0	$0	$0	$0	$18,750	$0	$0	$0
National Defense Science and Engineering Fellowship Grant (NDSEG)	$0	$0	$0	$69,707	$0	$0	$0	$0	$0	$7,086	$0	$0	$3,543
NorthStar STEM Alliance	$3,500	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Precision Associates	$500	$0	$0	$0	$0	$500	$0	$0	$0	$0	$0	$0	$0
Stanadyne Corporation	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$2,700
Tol-O-matic	$1,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Total Oil Company	$0	$0	$0	$15,000	$0	$0	$0	$0	$0	$0	$0	$0	$0
Triumph Aerospace Systems	$0	$0	$0	$0	$0	$0	$0	$0	$0	$21,000	$0	$0	$0
Veraphotonics, Mistras	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$10,859	$0	$21,719
Total Non-Members	**$6,500**	**$0**	**$0**	**$1,689,974**	**$143,000**	**$2,000**	**$500**	**$500**	**$0**	**$190,119**	**$678,868**	**$246,500**	**$355,450**
Total	**$589,600**	**$0**	**$0**	**$1,691,948**	**$219,362**	**$14,257**	**$634,566**	**$500**	**$0**	**$203,581**	**$791,777**	**$285,067**	**$546,711**

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.1: Integrated Algorithms for Optimal Energy Use in Mobile Fluid Power Systems	No	No		Mr.	Jonathan	J	Meyer		University of Minnesota	Graduate Research Assistant	Mechanical Engineering	Research - Doctoral Student Curriculum - Doctoral Student
1A.1: Integrated Algorithms for Optimal Energy Use in Mobile Fluid Power Systems	No	No			Tim	O	Deppen		University of Illinois at Urbana-Champaign	Graduate Student	Mechanical Science and Engineering	Research - Doctoral Student Curriculum - Doctoral Student
1A.1: Integrated Algorithms for Optimal Energy Use in Mobile Fluid Power Systems	No	Yes		Dr.	Andrew	G	Alleyne		University of Illinois at Urbana-Champaign			Leadership/Administration - Thrust Leader
1A.1: Integrated Algorithms for Optimal Energy Use in Mobile Fluid Power Systems	Yes	Yes			Kim	A	Stelson		University of Minnesota	Professor	Mechanical Engineering	Leadership/Administration - Director Curriculum - Senior Faculty
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	No	No		Mr.	Jose	E	Gomez		Purdue University			Curriculum - Undergraduate Student
1A.2: Control and Prognostics for Hybrid Displacement Control Systems	No	No			Rohit	R	Hippalgaonkar		Purdue University	Research Assistant / Ph.D. Student	Mechanical Engineering	Research - Doctoral Student
1A.2: Control and Prognostics for Hybrid Displacement Control Systems	Yes	Yes			Monika	M	Ivantysynova		Purdue University			Leadership/Administration - Thrust Leader
1A.2: Control and Prognostics for Hybrid Displacement Control Systems	No	No		Mr.	Jose	E	Gomez		Universidad Tecnológica de Querétaro		Mechanical Engineering	Curriculum - Undergraduate Student
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.	Marco		Zecchi		Purdue University		Biological Engineering	Research - 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		Ms.	Ashley	M	Wondergem		Purdue University	Research Graduate Student	Mechanical Engineering	Research - Master's Student
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			Daniel		Mizell		Purdue University			Research - Doctoral Student
1D: Microtextured Surfaces for Low Friction / Leakage	Yes	Yes			William		King		University of Illinois at Urbana-Champaign	Engineering Bliss Professor	Mechanical Science and Engineering	Research - Senior Faculty
1D: Microtextured Surfaces for Low Friction / Leakage	No	No		Mr.	Michael		Johnston		University of Illinois at Urbana-Champaign			Research - Master's Student Curriculum - Master's Student
1D: Microtextured Surfaces for Low Friction / Leakage	No	Yes		Dr.	Randy	H	Ewoldt		University of Illinois at Urbana-Champaign	Assistant Professor	Mechanical Science and Engineering	Research - Junior Faculty Curriculum - Junior Faculty
1D: Microtextured Surfaces for Low Friction / Leakage	No	No			Jonathon	K	Schuh		University of Illinois at Urbana-Champaign			Research - Master's Student
1D: Microtextured Surfaces for Low Friction / Leakage	No	No			Richard	F	Salant		Georgia Institute of Technology			Research - Senior Faculty
quadrant Virtually Variable Displacement Pump/Motor	No	Yes			Thomas	R	Chase		University of Minnesota			Research - Senior Faculty
quadrant Virtually Variable Displacement Pump/Motor	Yes	Yes		Dr.	Perry	Y	Li		University of Minnesota			Leadership/Administration - Director Curriculum - Senior Faculty
quadrant Virtually Variable Displacement Pump/Motor	No	No		Mr.	John		Dekarski		University of Minnesota			Research - Master's Student
quadrant Virtually Variable Displacement Pump/Motor	No	No			Haink	C	Tu		University of Minnesota	Research Assistant	Mechanical Engineering	Research - 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	No		Mr.	Tyler		Helmus		Purdue University	Research Assistant	ABE	Research - Doctoral Student Curriculum - Doctoral Student
1E.3: Actively Controlled Digital Pump Motor	No	Yes			Monika	M	Ivantysynova		Purdue University			Leadership/Administration - Thrust Leader
1E.3: Actively Controlled Digital Pump Motor	No	No		Mr.	Farid		Breidi		Purdue University	Graduate Student	Biological Engineering	Research - Doctoral Student Curriculum - Doctoral Student
1E.4: Piston-by-piston control of pumps and motors using mechanical methods	No	No			Mike		Rannow		University of Minnesota			Research - Doctoral 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.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	Yes	Yes		Dr.	Perry	Y	Li		University of Minnesota			Leadership/Administration - Director Curriculum - Senior Faculty

Volume II: Project Personnel Data

Project Name	Project Leader	Project Investigator	Project Role	Title	First Name	Middle Initial	Last Name	Suffix	Institution	Title Within Institution	Department Within Institution	Personnel Types Within Institution
1E.4: Piston-by-piston control of pumps and motors using mechanical methods	No	No			Chad		Larish		University of Minnesota	Master's student		Research - Master's Student
1E.5: System Configuration & Control Using Hydraulic Transformers	Yes	Yes		Dr.	Perry	Y	Li		University of Minnesota			Leadership/Administration - Director Curriculum - 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.6: High Performance Valves Enabled by Kinetic Energy	No	Yes			Monika	M	Ivantysynova		Purdue University			Leadership/Administration - Thrust Leader
1E.6: High Performance Valves Enabled by Kinetic Energy	No	No			Daniel		Skelton		Purdue University		ABE	Research - Master's Student Curriculum - Master's Student
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			Shaoping		Xiong		Purdue University			Research - Doctoral Student
1E.6: High Performance Valves Enabled by Kinetic Energy	No	Yes		Dr.	Andrea		Vacca	PhD	Purdue University			Research - Junior Faculty Curriculum - Junior Faculty
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
1F.1: Variable Displacement External Gear Machine	No	No			Sujan		Dhar		Purdue University			Research - Doctoral Student
1G.1: Energy Efficient Fluids	No	No			Hassan		Khalid		Milwaukee School of Engineering	Graduate Research Assistant	Fluid Power Institute	Research - Master's Student
1G.1: Energy Efficient Fluids	No	No			Meghan		Miller		Milwaukee School of Engineering	Graduate Research Assistant	Fluid Power Institute	Research - Master's Student Curriculum - Master's 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	Graduate Research Assistant	Fluid Power Institute	Research - Master's Student
1G.1: Energy Efficient Fluids	No	No			Shima		Shahahmadi		Milwaukee School of Engineering	Graduate Research Assistant	Fluid Power Institute	Research - Master's Student
1G.1: Energy Efficient Fluids	No	No		Dr.	Scott	S	Bair		Georgia Institute of Technology	Regents' Researcher	Mechanical Engineering	Research - Senior Faculty
1G.1: Energy Efficient Fluids	No	No			Thomas	R	Chase		University of Minnesota			Research - Senior Faculty
1G.1: Energy Efficient Fluids	No	No			William		King		University of Illinois at Urbana-Champaign	Engineering Bliss Professor	Mechanical Science and Engineering	Research - Senior Faculty
1G.1: Energy Efficient Fluids	No	No			Frank		Cooney		Milwaukee School of Engineering			Research - Industry Researcher
1J.1: Hydraulic Transmissions for Wind Power	Yes	Yes			Kim	A	Stelson		University of Minnesota	Professor	Mechanical Engineering	Leadership/Administration - Director Curriculum - Senior Faculty
1J.1: Hydraulic Transmissions for Wind Power	No	No		Dr.	Feng		Wang		University of Minnesota	Postdoctoral associate	Mechanical Engineering	Research - Postdoc
1J.1: Hydraulic Transmissions for Wind Power	No	Yes			Brad		Bohlmann		University of Minnesota	Sustainability Director	Mechanical Engineering	Curriculum - Staff Leadership/Administration - Staff
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	K	Durfee		University of Minnesota	Professor	Mechanical Engineering	Leadership/Administration - Education Program Leader
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	No	No			Abayomi	A	Famuyiwa		University of Minnesota	Ungergraduate		Curriculum - Undergraduate Student Research - Undergraduate Student
2B.3: Free Piston Engine Hydraulic Pump	No	No		Mr.	Chen		Zhang	PhD	University of Minnesota	PhD candidate	Mechanical engineering	Research - Doctoral Student
2B.3: Free Piston Engine Hydraulic Pump	No	No			Abayomi	A	Famuyiwa		University of Virginia	Undergraduate	Mechanical Engineering	REU Student - NSF REU Site Award

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Project Name	Project Leader	Project Investigator	Project Role	Title	First Name	Middle Initial	Last Name	Suffix	Institution	Title Within Institution	Department Within Institution	Personnel Types Within Institution
2B.3: Free Piston Engine Hydraulic Pump	Yes	Yes		Dr.	Zongxuan		Sun		University of Minnesota			Research - Junior Faculty Curriculum - Junior Faculty
2B.4: Controlled Stirling Thermocompressors	Yes	Yes		Dr.	Eric	J	Barth		Vanderbilt University			Research - Senior Faculty
2B.4: Controlled Stirling Thermocompressors	No	No		Mr.	Mark	E	Hofacker		Vanderbilt University	Graduate Research Assistant	Mechanical Engineering	Research - Doctoral Student Curriculum - Doctoral Student
2B.4: Controlled Stirling Thermocompressors	No	No			Anna		Winkelmann		Vanderbilt University			Research - Master's Student
2C.2: Advanced Strain Energy Accumulator	No	No		Mr.	Daniel	N	Cramer		Vanderbilt University			Research - Master's Student
2C.2: Advanced Strain Energy Accumulator	No	No		Mr.	Josh		Cummins		Vanderbilt University			Research - Doctoral Student
2C.2: Advanced Strain Energy Accumulator	No	No			Doug	E	Adams		Vanderbilt University			Research - Senior Faculty
2C.2: Advanced Strain Energy Accumulator	Yes	Yes		Dr.	Eric	J	Barth		Vanderbilt University			Research - Senior Faculty
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
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
2G: Fluid Powered Surgery and Rehabilitation via Compact Integrated Systems	No	Yes		Mr.	Vito	R	Gervasi		Milwaukee School of Engineering			Research - Research Staff
2G: Fluid Powered Surgery and Rehabilitation via Compact Integrated Systems	No	Yes		Dr.	Eric	J	Barth		Vanderbilt University			Research - Senior Faculty
2G: Fluid Powered Surgery and Rehabilitation via Compact Integrated Systems	Yes	Yes		Dr.	Robert	J	Webster	III	Vanderbilt University			Research - Junior 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 Student	Mechanical Engineering	Curriculum - Doctoral 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			William		Gallagher		Georgia Institute of Technology	Technician- Tech temp	Mechanical Engieering	Research - Research Staff
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		Mr.	Melih		Turkseven		Georgia Institute of Technology			Curriculum - Doctoral Student
2G: Fluid Powered Surgery and Rehabilitation via Compact Integrated Systems	No	Yes		Dr.	Jun		Ueda		Georgia Institute of Technology	Assistant Professor		Research - Junior Faculty
3A.1: Teleoperation Efficiency Improvements by Operator Interface	Yes	Yes		Dr.	Wayne	J	Book		Georgia Institute of Technology			Curriculum - Senior Faculty Leadership/Administration - Thrust Leader
3A.1: Teleoperation Efficiency Improvements by Operator Interface	No	No		Mr.	Sam		Seifert		Georgia Institute of Technology		Mechanical Engineering	Research - Master's Student
3A.1: Teleoperation Efficiency Improvements by Operator Interface	No	Yes			James	D	Huggins		Georgia Institute of Technology	Research Engineer II	Mechanical Engineering	Leadership/Administration - Staff
3A.1: Teleoperation Efficiency Improvements by Operator Interface	No	Yes		Dr.	Steven	X	Jiang		North Carolina Agriculture and Technical State University	Associate Professor	Systems Engineering	Curriculum - Senior Faculty Research - Senior Faculty
3A.1: Teleoperation Efficiency Improvements by Operator Interface	No	No		Mr.	Reginald	L	White	Student	North Carolina Agriculture and Technical State University			Curriculum - Undergraduate Student Research - Undergraduate Student
3A.1: Teleoperation Efficiency Improvements by Operator Interface	No	Yes		Dr.	Eui	H	Park		North Carolina Agriculture and Technical State University			Research - Senior Faculty

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Project Name	Project Leader	Project Investigator	Project Role	Title	First Name	Middle Initial	Last Name	Suffix	Institution	Title Within Institution	Department Within Institution	Personnel Types Within Institution
3A.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		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		Ms.	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	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	No	No			Bixing		Yan		Purdue University		Mechanical Engineering	Curriculum - Undergraduate Student Research - Undergraduate Student
3B.3: Active Vibration Damping of Mobile Hydraulic Machines	No	No			Addison		Alexander		Purdue University		Mechanical Engineering	Research - Doctoral Student
3B.3: Active Vibration Damping of Mobile Hydraulic Machines	No	No			Guido Francesco		Ritelli		Purdue University			Research - Doctoral Student
3B.3: Active Vibration Damping of Mobile Hydraulic Machines	No	No		Mr.	Davide		Cristofori	PhD	Purdue University			Research - Doctoral Student
3B.3: Active Vibration Damping of Mobile Hydraulic Machines	Yes	Yes		Dr.	Andrea		Vacca	PhD	Purdue University			Research - Junior Faculty Curriculum - Junior Faculty
3D.1: Leakage/Seal Friction Reduction in Fluid Power Systems	Yes	Yes			Richard	F	Salant		Georgia Institute of Technology			Research - Senior Faculty
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
Elastohydrodynamic Lubrication to Solve Fluid Power Problems	Yes	Yes		Dr.	Scott	S	Bair		Georgia Institute of Technology	Regents' Researcher	Mechanical Engineering	Research - Senior Faculty
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			Nalin		Verma	@gatech.edu	Georgia Institute of Technology			Research - Undergraduate Student
3E.1: Pressure Ripple Energy Harvester	No	No			Aaron		Kranc		Georgia Institute of Technology			Research - Undergraduate 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		Mr.	Zachary		Koontz		Georgia Institute of Technology			Research - Undergraduate Student
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			Chong Woo		Han		The Cooper Union for the Advancement of Science and Art	Undergraduate	Mechanical Engineering	REU Student - NSF REU Site Award
3E.1: Pressure Ripple Energy Harvester	No	No			Chong Woo		Han		Georgia Institute of Technology	Undergradutae		REU Student - NSF REU Site Award Curriculum - Undergraduate Student
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	Mechanical Engineering	Research - Senior Faculty
A Characterization of the Pressure-Viscosity Response of Four lubricating Oils	Yes	Yes		Dr.	Scott	S	Bair		Georgia Institute of Technology	Regents' Researcher	Mechanical Engineering	Research - Senior Faculty
Adaptive ride control for construction machines	Yes	Yes		Dr.	Andrea		Vacca	PhD	Purdue University			Research - Junior Faculty Curriculum - Junior Faculty
Advances in modeling external spur gear machines and development of innovative solutions	Yes	Yes		Dr.	Andrea		Vacca	PhD	Purdue University			Research - Junior Faculty Curriculum - Junior 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
Design of low noise emission internal gear machines	Yes	Yes		Dr.	Andrea		Vacca	PhD	Purdue University			Research - Junior Faculty Curriculum - Junior Faculty

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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
Determining Water Content at Saturation for Three Common Wind Turbine Gearbox Oils: Mobilgear SHC XMP 320 AMSOIL EP Gear Lube ISO-320 and Castrol Optigear A320	No	No			Muhammad Shah		Ramdan		Malaysian Ministry of Higher Education (MOHE)			Research - Doctoral Student
Determining Water Content at Saturation for Three Common Wind Turbine Gearbox Oils: Mobilgear SHC XMP 320 AMSOIL EP Gear Lube ISO-320 and Castrol Optigear A320	Yes	Yes			Matthew		Whitten		University of Minnesota			Research - Master's Student
Determining Water Content at Saturation for Three Common Wind Turbine Gearbox Oils: Mobilgear SHC XMP 320 AMSOIL EP Gear Lube ISO-320 and Castrol Optigear A320	No	No			Muhammad Shah		Ramdan		University of Minnesota			Research - Doctoral Student
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
Dynamic model development for hydraulic pumps	Yes	Yes			Monika	M	Ivantysynova		Purdue University			Leadership/Administration - Thrust Leader
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
Approach for Off-shore Wind Energy Storage	No	No		Mr.	Jacob		Wieberdink		University of Minnesota			Research - Master's Student
Approach for Off-shore Wind Energy Storage	No	No			Farzad		Shirazi		University of Minnesota	Postdoctoral Research Associate	Mechanical Engineering	Research - Postdoc
Approach for Off-shore Wind Energy Storage	No	No			Terrence		Simon		University of Minnesota	Senior Faculty	Mechanical	Research - Senior Faculty
Approach for Off-shore Wind Energy Storage	No	No			Mohsen		Saadat		University of Minnesota			Research - Doctoral Student
Approach for Off-shore Wind Energy Storage	Yes	Yes		Dr.	Perry	Y	Li		University of Minnesota			Leadership/Administration - Director Curriculum - Senior Faculty
Approach for Off-shore Wind Energy Storage	No	No			Chao		Zhang		University of Minnesota			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 of a proprietary gear pump	Yes	Yes		Dr.	Andrea		Vacca	PhD	Purdue University			Research - Junior Faculty Curriculum - Junior Faculty
generating of FSTI gap design input parameters	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 Viscosity and Density Measurements on Diesel Fuels	Yes	Yes		Dr.	Scott	S	Bair		Georgia Institute of Technology	Regents' Researcher	Mechanical Engineering	Research - Senior Faculty
High Pressure Viscosity and Density Measurements on Krytox Fluids	Yes	Yes		Dr.	Scott	S	Bair		Georgia Institute of Technology	Regents' Researcher	Mechanical Engineering	Research - Senior Faculty
I-Corps: CO2 Insufflator for Minimally Invasive Procedures	Yes	Yes		Dr.	Pietro		Valdastri	PhD	Vanderbilt University		Mechanical Engineering	Curriculum - Junior Faculty
Model Predictive Control of Pneumatic Actuators	Yes	Yes		Dr.	Wayne	J	Book		Georgia Institute of Technology			Curriculum - Senior Faculty 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
Modeling and analysis of swash plate type piston motor	Yes	Yes			Monika	M	Ivantysynova		Purdue University			Leadership/Administration - Thrust Leader
MODELING OF AXIAL PISTON PUMPS AND MOTORS	Yes	Yes			Monika	M	Ivantysynova		Purdue University			Leadership/Administration - Thrust Leader
gear machines and development of quieter solutions	Yes	Yes		Dr.	Andrea		Vacca	PhD	Purdue University			Research - Junior Faculty Curriculum - Junior 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
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

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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
Highly Efficient Agricultural Machines Powered By High Pressure Water Hydraulic Technology	Yes	Yes			Monika	M	Ivantysynova		Purdue University			Leadership/Administration - Thrust Leader
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 system concept for Electrical Hydraulic Actuation system	Yes	Yes		Dr.	Andrea		Vacca	PhD	Purdue University			Research - Junior Faculty Curriculum - Junior Faculty
Transmission Power Split Hybrid Hydraulic Bus	No	Yes			Muhammad Shah		Ramdan		Malaysian Ministry of Higher Education (MOHE)			Research - Doctoral Student
Transmission Power Split Hybrid Hydraulic Bus	Yes	Yes			Kim	A	Stelson		University of Minnesota	Professor	Mechanical Engineering	Leadership/Administration - Director Curriculum - Senior Faculty
Transmission Power Split Hybrid Hydraulic Bus	No	Yes			Muhammad Shah		Ramdan		University of Minnesota			Research - Doctoral Student
optimization of valve plate to reduce noise and maintain low control effort	Yes	Yes			Monika	M	Ivantysynova		Purdue University			Leadership/Administration - Thrust Leader
Pump Dynamic Model Development	Yes	Yes			Monika	M	Ivantysynova		Purdue University			Leadership/Administration - Thrust Leader
Rheology Modeling for Mechanical Face Seals	Yes	Yes		Dr.	Scott	S	Bair		Georgia Institute of Technology	Regents' Researcher	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
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 -- Hydraulic Hybrid Passenger Vehicle	Yes	Yes		Dr.	Perry	Y	Li		University of Minnesota			Leadership/Administration - Director Curriculum - Senior Faculty
Test Bed 3: Highway Vehicles -- Hydraulic Hybrid Passenger Vehicle	No	Yes			Thomas	R	Chase		University of Minnesota			Research - Senior Faculty
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			Kathleen	A	Fitzsimons		Michigan State Univeristy	Undergraduate	Mechanical Engineering	REU Student - NSF REU Site Award
Test Bed 6: Human Assist Devices -- Fluid Power Ankle-Foot Orthosis	No	No			Yifan		Li		University of Illinois at Urbana-Champaign			Research - Doctoral Student Curriculum - Doctoral Student
Test Bed 6: Human Assist Devices -- Fluid Power Ankle-Foot Orthosis	No	No			Kathleen	A	Fitzsimons		University of Illinois at Urbana-Champaign	Undergraduate		Curriculum - Undergraduate Student Research - Undergraduate Student
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	Mechanical Science & Engineering	Curriculum - Senior Faculty Research - Senior Faculty
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			Jonathan	D	Nath		University of Minnesota	Undergraduate	Mechanical Engineering	REU Student - NSF REU Site Award Curriculum - Undergraduate Student

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
FP	fluid power
FPE	free piston engine
FPEF	Fluid Power Educational Foundation
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
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
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
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
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
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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Engineering Research Center for Compact and Efficient Fluid Power Membership Agreement

This Agreement (the "Agreement") is made this 2nd day of August, 2006, between the Regents of the University of Minnesota (hereinafter "Lead University"), on behalf of the Engineering Research Center for Compact and Efficient Fluid Power (hereinafter "Center") located at the Lead University, and ________________ (hereinafter, "Member").

WHEREAS, Lead University will operate the Center 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", and the seven universities collectively are "Universities").

WHEREAS, the parties to this Agreement, along with each of the Universities, intend to join together in a cooperative effort to support an Engineering Research Center for Compact and Efficient Fluid Power (the "Center") to maintain a mechanism whereby the Universities' environments can be used to perform research in the area of fluid power.

The parties hereby agree to the following terms and conditions:

A. The Center will be administered by certain faculty, staff and students at the Lead University. The parties understand that for the first five (5) years, the Center will be supported jointly by industrial firms, federal laboratories, the Grant and the Universities. At the end of the initial five (5) year term, the National Science Foundation (the "NSF") will conduct a review and may extend its support for an additional five (5) years. If the review is not successful, the NSF support will be phased out over a period not to exceed two (2) years after the initial five (5) year term.

B. Any individual, company, federal research and development organization, or any government-owned contractor operated laboratory may become a Member of the Center, consistent with applicable state and federal laws and statutes. Federal research and development organizations and government-owned contractor operated laboratories may become Members of the Center on terms and conditions other than those in this agreement upon approval by the Lead University and two-thirds of the Industrial Advisory Board (the "IAB"). The establishment and terms and conditions of the IAB are set forth more fully below.

C. Each of the non-lead Universities shall enter into a sub-award or subcontract with the Lead University that obligates the non-lead Universities and their researchers to comply with the obligations of Universities and researchers set forth in this Agreement.

D. Members will be required to remit a pledge at stratified levels according to Member annual U.S. Fluid Power Related Revenues. The annual fees are as follows:

Member's **Annual U.S. Fluid Power Related Revenues:**	**Sustaining Required Pledge (one lump sum)**	**Sustaining Required Pledge (each year for 5 years)**	**Principal Required Pledge (one lump sum)**	**Principal Required Pledge (each year for 5 years)**	**Supporter Required Pledge (one lump sum)**	**Supporter Required Pledge (each year for 5 years)**
Less than $25 million	$50,000	$10,000	$25,000	$5,000	$5,000	$1,000
$25 - $100 million	$150,000	$30,000	$75,000	$15,000	$30,000	$6,000
$100 -$500 million	$400,000	$80,000	$200,000	$40,000	$60,000	$12,000
Over $500 million	$500,000	$100,000	$250,000	$50,000	$75,000	$15,000

Each Member agrees to contribute the amount set forth in the above table in support of the Center and thereby will become either a Sustaining Member, Principal Member or a Supporter Member, based on the fees outlined in the table above. Payment of these membership fees shall be made to the Center as one lump sum, on a per year basis, which shall be due and payable by October 01 of each year. Checks should be made payable to University of Minnesota and mailed to Regents of the University of Minnesota, NW 5957, P.O. Box 1450, Minneapolis, MN 55485-5957. Members acknowledge that research of the type to be done by the Center takes time and research results may not be immediately obvious. The pledge of support is for a period of five years; however, a Member may withdraw from the Center on one year's prior written notice to the Lead University.

The Center shall provide each Member with periodic reports of the progress of research supported by the Center. The Center shall invite each Member to attend an annual meeting of the Center, at which the results of Center research will be presented and displayed. The Center shall produce a Newsletter which periodically informs each Member of noteworthy research and developments. In addition, Members will be invited to actively interact with researchers conducting projects of particular interest to them, and such Members will receive early, confidential information directly from the researchers about the progress of those projects.

E. The IAB is an advisory board. The organization, governance and operation of the IAB within the Center will be specified in detail by Center bylaws that will be adopted at the first IAB meeting. The bylaws, when adopted, shall control the functions of the IAB, shall reflect the terms of this Agreement, and shall be consistent with the NSF grant and applicable federal regulations and policies.

F. The IAB will be comprised of one representative from each Sustaining Member and Principal Member. The IAB will effect all changes in the Center bylaws. The IAB will make recommendations to the Universities and Center researchers concerning (a) the research projects to be carried out by the Center, (b) the apportionment of resources to such research projects, and (c) other matters specified in the Center bylaws. The organization and function of the IAB will be specified in the Center bylaws. The overall administrative functions and operations of the Center shall be the responsibility of the Lead University. The Lead University's Center Director retains final authority and will not be bound by IAB recommendations specific to selection of research projects and apportionment of resources.

G. The students, faculty and staff conducting research through the Center (the "Researchers") shall have the right to publish the results of any research performed through the Center, subject to the limitations set forth in this Paragraph. In order to protect potentially patentable Intellectual Property, the Center shall notify all Members in writing of the potential publication of any paper or presentation containing information on the research performed through the Center ("Publication Materials") and shall provide all Members with an opportunity to review, on a confidential basis (e.g., on a secure website), any Publication Materials. The Center shall effect such notification and make all Publication Materials available for review not less than forty-five (45) days prior to the expected date of publication. Members shall have the right to delay publication for a period not to exceed ninety (90) days from the date the publication or presentation is made available to each Member, provided that Member submits to the publishing University and Researcher a written request to delay publication in order to consider obtaining patent protection within thirty (30) days from the date the proposed publication or presentation is made available to the Member.

H. Each University hereby grants all Members a perpetual, irrevocable, non-exclusive, royalty-free license to use any non-patented discovery or invention developed under the Center.

I. 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 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. If any Member exercises its rights under Paragraph K of this Agreement, the Inventing University or Inventing Universities shall exercise its right to retain title.

J. University employees shall promptly disclose to their University (which shall promptly notify the Center) any invention made with support of the Center. The Center shall promptly provide all Members with confidential notice of the invention and of their right to exercise the options provided under this Paragraph K. Within 90 days of receipt of notice, any Member may direct that a patent application or application for other intellectual property protection be filed. If a Member so directs, other Members shall then be provided an additional 60-day option period to elect whether to share equally, among those who elect to exercise the option, all costs incurred in connection with such preparation, filing, prosecution, and maintenance of U.S. and foreign application(s) directed to said invention.

Those Members that elect to share such costs shall cooperate with Inventing University to assure that such application(s) will cover, to the best of Members' knowledge, all items of interest and importance. The Inventing University shall keep the Members that are sharing in payment of costs advised as to all developments with respect to such application(s) and shall promptly supply to those Members copies of all papers received and filed in connection with the prosecution thereof in sufficient time for those Members to comment thereon.

K. If a Member elects not to exercise its option described above in Paragraph J, or decides to discontinue the financial support of the prosecution or maintenance of the protection, the Member shall have no rights in the invention. If no Members elect to exercise their option, or if all Members discontinue their support, then the Inventing University shall be free to file or continue prosecuting or maintaining any such application(s), and to maintain any protection issuing thereon in the U.S. and in any foreign country at that University's sole expense.

If only one Member bears the costs of protection, the Inventing University shall grant that Member the first option to a royalty bearing exclusive license to the invention. If only one Member is interested in a license for a particular field of use, the Inventing University shall grant that Member an option to a royalty bearing exclusive license for that field of use. In either case, if the Member is a Sustaining Member, then the Sustaining Member shall have an option to obtain a royalty-free, non-exclusive license, without a right to sublicense, rather than a royalty bearing exclusive license; further, when a Sustaining Member elects to obtain an exclusive license, the royalty shall be at a reduced rate to be negotiated at a discount from a commercially reasonable royalty. If the Member is either a Supporter Member or a Principal Member, the exclusive license shall bear a full reasonable royalty to be negotiated on commercially reasonable terms. Any exclusive licensee under this Paragraph will have a right to sublicense on terms and conditions to be mutually agreed upon. The option shall extend for a time period of (180) days from the date of filing the first patent application, which period may be extended by mutual agreement.

If more than one Member bears the costs of prosecution, the Inventing University shall grant to each of those Members options to a license to the invention on terms and conditions to be mutually agreed upon. The license shall be exclusive as to the rest of the world, but non-exclusive as among those Members which bear the cost of prosecution, provided that, where only one Member seeks a license for a particular field of use, the preceding paragraph, and not this paragraph, shall apply. The Inventing University shall grant all Sustaining Members that have borne the cost of prosecution of the patent a royalty-free license. The Inventing University shall grant all Principal Members that have borne the cost of prosecution a royalty-bearing license, but the royalty amount will be a reduced rate. The Inventing University shall grant all Supporter Members that have borne the cost of prosecution a royalty-bearing license, the royalty to be negotiated on commercially reasonable terms, but in any event the royalty amount will be higher than the amount paid by Principal Members. Except in cases of fully exclusive licenses as provided in the preceding paragraph (either for all uses or for particular fields of use), there shall be no right to sublicense; provided, however, that with the consent of the Inventing University and of all Members that have entered into licenses, either the University or a Member may sublicense the invention on such terms as the parties may agree.

L. Background Patent Rights means patent rights that result from research conducted at any of the Universities before the creation of the Center, but that are used, in whole or in part, in the research to be conducted through the Center. To the extent necessary to practice an invention conceived or first reduced to practice with funding from the Center, and to the extent that a University has legal authority to do so, a University that owns Background Patent Rights shall offer Members that have exercised the option to obtain a license to the invention, a non-exclusive, royalty-bearing license to use such Background Patent Rights, the terms of which will be negotiated in good faith on commercially reasonable terms.

M. Each University shall ensure that it has obtained all necessary rights to the Intellectual Property from its Researchers to grant the rights provided under this Agreement.

N. Any royalties and fees received by any of the Universities under this Agreement, over and above expenses incurred, will be distributed as or in accordance with the policies of the University or Universities that have taken title to the invention. A portion of net income from inventions will be devoted to research in the Center's fields of research.

O. Each party recognizes that the Center will be funded by NSF for, at the most, ten (10) years, subject to NSF continued approval and support. It is hoped that, during that 10 year period, the Center may become self-supporting. Any disposition of funds and Intellectual Property upon the conclusion of the funding, or upon the possible termination of operations of the Center shall be the responsibility of the Lead University and of any Universities that have taken title to Center inventions, and shall be in full compliance with the laws, regulations and rules governing NSF supported research programs.

P. CONTACTS for this Agreement are as follows:

Lead University Addresses	**LEAD UNIVERSITY** (Name, phone, email)	**MEMBER** (Name, phone, email)
Technical: Mechanical Engineering 111 Church Street SE Minneapolis, MN 55455	Prof. Kim Stelson 612-625-6528 kstelson@umn.edu	
Contractual/Administrative: 200 Oak Street SE, Suite 450 Minneapolis, MN 55455	Sponsored Projects Admin- Amy Rollinger 612-625-1359 amyg@umn.edu	
Financial: Mechanical Engineering 111 Church St. SE Minneapolis, MN 55455	Lisa Wissbaum 612-624-4993 mailto:lwissbaum0022@umn.edu	

Q. 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.

R. This Agreement shall be governed and construed in accordance with the laws of the State of Minnesota.

REGENTS OF THE

UNIVERSITY OF MINNESOTA

on behalf of
The Engineering Resource Center

Name Kevin McKoskey, CRA
Senior Associate Director

Title

Date: ______________________

MEMBER

Name

Title

Date: ______________________

---------- Forwarded message ----------
From: <irb@umn.edu>
Date: Thu, Aug 22, 2013 at 11:16 PM
Subject: 0906S67382 - PI Stelson - IRB - APVD Continuing Review
To: kstelson@umn.edu

TO : kstelson@umn.edu,

The IRB: Human Subjects Committee renewed its approval of the referenced study listed below:

Study Number: 0906S67382

Principal Investigator: Kim Stelson

Expiration Date: 08/20/2014

Approval Date: 08/21/2013

Title(s):
Center for Compact and Efficient Fluid Power

This e-mail confirmation is your official University of Minnesota HRPP notification of continuing review approval. You will not receive a hard copy or letter. This secure electronic notification between password protected authentications has been deemed by the University of Minnesota to constitute a legal signature.

You may go to the View Completed section of http://eresearch.umn.edu/ to view or print your continuing review submission.

For grant certification purposes you will need this date and the Assurance of Compliance number, which is FWA00000312 (Fairview Health Systems Research FWA00000325, Gillette Childrens Specialty Healthcare FWA00004003). Approval will expire one year from that date. You will receive a report form two months before the expiration date.

In the event that you submitted a consent document with the continuing review form, it has also been reviewed and approved. If you provided a summary of subjects' experience to include non-UPIRTSO events, these are hereby acknowledged.

As Principal Investigator of this project, you are required by federal regulations to inform the IRB of any proposed changes in your research that will affect human subjects. Changes should not be initiated until written IRB approval is received. Unanticipated problems and adverse events should be reported to the IRB as they occur. Results of inspections by any external regulatory agency (i.e. FDA) must be reported immediately to the IRB. Research projects are subject to continuing review.

If you have any questions, please call the IRB office at (612) 626-5654.

The IRB wishes you continuing success with your research.

NC A&T DIVISION OF RESEARCH AND ECONOMIC DEVELOPMENT
1601 East Market Street
Greensboro, NC 27411
(336) 334-7314
Web site: http://www.ncat.edu/~divofres/compliance/irb/index.php
Federalwide Assurance (FWA) #00000013

To: Yogeeta Desai

From: Behavioral IRB

Cat Collins
Authorized signature on behalf of IRB

Approval Date: 5/29/2013
Expiration Date of Approval: 5/28/2014

RE: Notice of IRB Approval by Expedited Review (under 45 CFR 46.110)
Submission Type: Initial
Expedited Category: 7.Surveys/interviews/focus groups,4.Noninvasive clinical data
Study #: 13-0151
Study Title: The Effect of Auditory Cues on Excavator Operator Performance
Sponsors: National Science Foundation (NSF)

This submission has been approved by the above IRB for the period indicated. It has been determined that the risk involved in this research is no more than minimal.

Study Description:
The purpose of this study is to assess the impact of auditory cues on operator performance and provide design recommendations for excavators.

Investigator's Responsibilities:
Federal regulations require that all research be reviewed at least annually. It is the Principal Investigator's responsibility to submit for renewal and obtain approval before the expiration date. You may not continue any research activity beyond the expiration date without IRB approval. Failure to receive approval for continuation before the expiration date will result in automatic termination of the approval for this study on the expiration date.

Stamped copies of approved consent forms and other documents will arrive under a separate email. You must use the stamped forms with subjects unless you have approval to do otherwise.

You are required to obtain IRB approval for any changes to any aspect of this study before they can be implemented. Any adverse event or unanticipated problem involving risks to subjects or others should be reported to the Office of Research Compliance and Ethics.

This study was reviewed in accordance with federal regulations governing human subjects research, including those found at 45 CFR 46 (Common Rule), 45 CFR 164 (HIPAA), 21 CFR 50 & 56 (FDA), and 40 CFR 26 (EPA), where applicable.

CC: Steven Jiang, Industrial And Systems Engineering Department

INFORMED CONSENT FORM

Title: The Effect of Auditory Cues on Excavator Operator Performance

Principal Investigator: Yogeeta Desai

You have been asked to participate as a participant in a research project that involves assessing the impact of auditory cues on operator performance with the use of a haptic device by performing tasks using simulation software associated with operating mobile heavy machinery. Participants of this study need to have normal hearing and vision. Please take your time to make your decision and ask the person presenting you with this form to explain any words or information that you do not understand.

PURPOSE

Excavator operators are required to perform blind operations when operating mobile heavy machinery. This task can be quite complex and unsafe. The purpose of this project is to assess the impact of auditory cues on operator performance for mobile heavy equipment using simulation software and a haptic device.

SOURCE OF FUNDING

This project is funded by National Science Foundation Engineering Research Center for Compact Efficient Fluid Power.

PROCEDURES

If you choose to participate in the project, you will be seated in front of the computer that runs the interface simulation. You will be given a training session to become familiar with the simulation and haptic device. After all of your questions are answered by the experimenter, testing will start. You will be asked to perform several tasks within the simulation. There will be a 5-minute break after twenty minutes. After you have completed the test, you will be debriefed, and asked for any feedback that you might have. Your participation for the entire study will last approximately 40 minutes.

RISKS AND BENEFITS

Your participation in the project will involve minimal to no risk. There is no foreseeable risk in participating in this study. The participants might experience the same visual fatigue whenever someone is using the computer.

Approved: 5/29/13
Expires: 5/28/14

COSTS TO STUDY PARTICIPANTS

There are no costs to you while participating in this study other than your time. It will take approximately 40 minutes for you to complete the entire study.

COMPENSATION

You will not be paid for participating in this study.

CONFIDENTIALITY AND DISCLOSURE

The following procedures will be followed to keep your personal information confidential in this study. The data collected about you will be kept private to the extent allowed by law. The investigators guarantee that data will not be identified with you by name. A report of general and combined results from all participants will be prepared and may be submitted to a technical journal or professional conference at a later time. The consent form will be the only document that will contain the names of the participants and will be stored in a safe secured cabinet and will remain confidential. To make sure that this research is being carried out in the proper way, the North Carolina A&T State University's IRB may review study records.

QUESTIONS ABOUT THE STUDY

The investigators, Yogeeta Desai, Dorian Davis and Alexandria Ward are available to answer any questions that you may have about your involvement in this project. Please contact Yogeeta Desai at 336-285-4524 or by email, ysdesai@aggies.ncat.edu. You may also contact our advisor, Dr. Steven Jiang, at 336-2853726 or by email at xjiang@ncat.edu.

RIGHTS AS A RESEARCH PARTICIPANT

Your participation is voluntary. You may end your participation at any time. Refusing to participate or leaving the study at a later time will not result in any penalty or loss of benefits to which you are entitled. If you have a question about your rights as a research participant, you can contact the Compliance Office at (336) 334- 7995.

You will be given a copy of this form.

Approved: 5/29/13
Expires: 5/28/14

SIGNATURES

A signed statement of informed consent is required of all participants in this project. Your signature indicates that you voluntarily agree to the conditions of participation described above, and that you have received a copy of this form.

I agree to take part in this study. I have had a chance to ask questions about being in this study and have those questions answered.

Signature of Subject

Date

Using language that is understandable and appropriate, I have discussed this project and the items above with the subject and/or authorized representatives.

Signature of Principal Investigator

Date

North Carolina A&T State University Institutional Review Board
Approved: 5/29/13
Expires: 5/28/14

CCEFP INDUSTRY MEMBERSHIP LIST

Private Sector Firms

A.S. Pindel Corp
Afton Chemical Corp.
Air Logic
Bobcat
Bosch Rexroth Corp
CNH America, LLC
Caterpillar Inc
ConcentricAB
Danfoss
Deere & Company
Deltrol Fluid Products
Eaton Corporation - Hydraulics Operations
Enfield Technologies
Evonik Additives, USA, Inc.
ExxonMobil
Freudenberg-NOK
Gates Corporation
HECO Gear, Inc.
Hitachi America, Ltd
Hoowaki, LLC
HUSCO
Idemitsu Kosan Co.,
Linde Hydraulics
Main Manufacturing
Master Pneumatic-
National Fluid
National Tube
Netshape
Pall corporation
Parker Hannifin
Poclain Hydraulics
Ross Controls
Shell Global
Simerics
Sun Hydraulics Corp
Takako Industries
The Lubrizol
Trelleborg Sealing
Woodward, Inc

Kevin McKoskey, Sr Associate Director
Sponsor Projects Administration

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 Commitment
Institution	**Committed**	**Actual**	**Committed**	**Actual**	
U. of Minnesota	$339,537	$602,309	$339,537	-	$2,070,294
Georgia Tech	$130,232	$61,944	$130,232	-	$1,060,551
MSOE	$0	-	$0	-	$10,800
Purdue	$152,557	$56,262	$152,557	-	$1,127,526
UIUC	$92,093	$84,695	$92,093	-	$899,740
Vanderbilt	$85,581	$35,335	$85,581	-	$692,630

Kevin McKoskey
Senior Associate Director
Sponsored Projects Administration

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	$2,170,383	$3,723,347
Committed, Encumbered, Obligated funds (obligated = planned for)	$2,170,383	$3,723,347
Residual Funds Without Specified Use	$0	$0

Response of the University of Minnesota to NSF's Request for Conflict of Interest Related Information

NSF has requested specific conflict of interest policy information from the ERC lead institution regarding ERC faculty or student involvement in start-up firms or small businesses. In particular, NSF requests that the lead university's oversight policies with respect to COI for the following circumstances be explained:

- Situations where ERC faculty or students spin-out start-up firms;
- Situations where it is necessary for the ERC to purchase products from a firm for which ERC faculty (or hi/her spouse or children") have fiduciary interests.

The following is the University of Minnesota's response.

The University has recently revised its conflict of interest policy, now titled: *Individual Conflicts of Interest***.** This policy has University wide application. The policy is risk based. More restrictive standards apply to individuals who are involved in one or more of the five higher risk areas which include individuals:

1. involved in human subjects research subject to review by the Institutional Review Board (IRB) where the IRB has determined that research conducted by the covered individual involves "more than minimal" risk to subjects;
2. involved in clinical health care;
3. involved in technology commercialization;
4. in a position to exert control over the content of University curriculum that could benefit the commercial interests of a business entity and, at the same time, create opportunity for or further an existing financial relationship between the covered individual and that business entity; or
5. in a position to take any other action on behalf of the University that could benefit the commercial interests of a business entity and, at the same time, create opportunity for or further an existing financial relationship between the covered individual and that business entity.

The University has an annual mandatory reporting process that applies to all faculty and staff, those responsible for the design, conduct and reporting of research, as well as those who are considered "key personnel" on research protocols. These individuals are required to annually report all business and financial interests and engagement in outside consulting and other outside commitments. In addition to annual reporting, these individuals are also required to prepare a new report within 30 days of a substantial change in a business or financial interest that relates to the individual's university expertise or responsibilities, or a change in their University responsibilities that relates to an existing business or financial interest.

The report form is called the Report of External Professional Activities (REPA). The REPA asks a number of detailed questions to include:

- whether the individual completing the form will take administrative action on behalf of the University related to the business in which the individual has a business or significant financial interest. This question elicits information regarding purchasing relationships.

The questions on the REPA also inquire about the filer's equity interests. Where faculty spin-out start up firms, they typically have an equity interest in the firm that equals or exceeds the University's thresholds for reporting.

When REPA filers report the circumstances described above, a conflict of interest review is initiated. That review begins with an administrative review and ends with review and consideration by a formally convened conflict of interest committee. If the committee determines that a conflict of interest exists, a conflict management plan is developed and that plan remains in effect so long as the conflict exists. Throughout the review process, coordination takes place between the Conflict of Interest Program and the Office for Technology Commercialization.

Students are covered by the University's conflict of interest policies and procedures if they:

- have a leadership role on University research (PI or CoI); or
- have responsibility for the design, conduct or reporting or University research, or are considered "key personnel" on University research.

The following are links to the:

- University's of Minnesota's Board of Regents Policy: *Individual Conflicts of Interest.*

  http://www1.umn.edu/regents/policies/administrative/Individual_COI.htm.

- University of Minnesota's administrative policy: *Individual Conflicts of Interest.*

  http://www.policy.umn.edu/Policies/Operations/Compliance/CONFLICTINTEREST.html.

- *Appendix to policy: Conflicts of Interest Categories.*

  http://www.policy.umn.edu/Policies/Operations/Compliance/CONFLICTINTEREST_APPD.html. See item 4A.

Administrative

UNIVERSITY OF MINNESOTA
BOARD OF REGENTS POLICY

INSTITUTIONAL CONFLICT OF INTEREST
Adopted: June 10, 2005

INSTITUTIONAL CONFLICT OF INTEREST

SECTION I. SCOPE.

This policy governs institutional conflict of interest at the University of Minnesota (University) and applies to members of the Board of Regents (Board), University officials, department/unit heads, and other individuals as required by administrative policies and procedures.

SECTION II. DEFINITIONS.

Subd. 1. Institutional Conflict of Interest. *Institutional conflict of interest* shall mean a situation in which the research, teaching, outreach, or other activities of the University may be compromised because of an external financial or business relationship held at the institutional level that may bring financial gain to the institution, any of its units, or the individuals covered by this policy. **Subd. 2. University Official.** *University official* shall mean persons holding the following positions, including those holding these positions in a temporary capacity:

(a) chancellors and vice chancellors;
(b) deans, associate deans, and assistant deans;
(c) division I athletic director;
(d) general counsel;
(e) president and president's chief of staff;
(f) provosts, vice provosts, associate vice provosts, and assistant vice provosts; and
(g) senior vice presidents, vice presidents, associate vice presidents, and assistant vice presidents.

SECTION III. GUIDING PRINCIPLES.

The following principles shall guide the University in addressing institutional conflict of interest:

(a) Because it is critical to the mission and reputation of the University to maintain the public's trust, University research, teaching, outreach, and other activities must not be compromised or perceived as biased by financial and business considerations.

(b) Because of its numerous and complex relationships with public and private entities, the University must be aware of any relationships involving financial gain that may compromise or

appear to compromise its integrity.
(c) The University shall establish and maintain an oversight process to manage, reduce, or eliminate institutional conflict of interest.

SECTION IV. RESERVATION OF AUTHORITY.

The Board reserves authority to review and approve plans for managing, reducing, or eliminating institutional conflict of interest involving:

(a) external relationships with an unusually significant financial impact that present a potential conflict;
(b) potential conflicts involving the president;
(c) potential conflicts that raise serious policy issues or have a significant public impact on the mission and reputation of the University; or
(d) potential conflicts arising in matters that otherwise require Board review and action under Board of Regents Policy: *Reservation and Delegation of Authority*.

In these instances of conflict of interest, the president shall consult with the Board.

SECTION V. ASSURANCE, DELEGATION OF AUTHORITY, AND REPORTING.

The president or delegate shall:

(a) implement an oversight process and administrative policies and procedures to address institutional conflict of interest and to identify situations in which institutional conflict of interest may arise;
(b) recommend and implement plans to manage, reduce, or eliminate institutional conflict of interest;
(c) develop and present conflict of interest plans to the Board for review and action as required under Section IV;
(d) ensure that individuals covered by this policy who act on behalf of the institution adhere to these policies and procedures, follow applicable conflict management plans, and do not engage in activities in which there is an actual conflict of interest; and
(e) report to the Board annually all institutional conflict of interest matters that do not meet the thresholds identified in Section IV.

SECTION VI. DISCLOSURES.

Subd. 1. Regents. Regents shall file a financial disclosure statement annually and report conflicts of interest as required by Board of Regents Policy: *Code of Ethics*.

Subd. 2. University Officials. University officials shall, upon appointment and annually on September 30 thereafter, file a financial disclosure statement with the president or delegate, disclosing significant economic interests and how those interests may relate to their institutional responsibilities. Such disclosure shall be made in addition to any reporting requirement for individual conflicts of interest.

Subd. 3. Department/Unit Heads. Annually and under circumstances described in administrative policy, department/unit heads shall disclose relevant financial and business interests by filing a *Report of External Professional Activities*.

Subd. 4. Other Individuals. The president or delegate may designate other individuals who shall file a financial disclosure statement.

SUPERSEDES: FINANCIAL DISCLOSURE FOR SENIOR UNIVERSITY OFFICIALS, DATED NOVEMBER 10, 1995.

CERTIFIED BY AOR

Kevin McKoskey, CRA
Senior Grants Manager
Office of Sponsored Projects Administration

APPENDIX IV

Center Diversity Plan

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DIVERSITY STRATEGIC PLAN

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.

The mission of the Diversity Strategic Plan of the Center for Compact and Efficient Fluid Power, through its active and diverse research and educational agenda--directed from its headquarters, amplified through its seven academic institutions, and extended through its partnerships in the education and outreach communities--is to change the face of fluid power 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 and 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, education and outreach 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 and AGEP programs and partners). Still other efforts are designed, launched, and coordinated by the CCEFP staff. The Center’s diversity strategy continues to focus on building a network of recruiting partners across the country.

The objectives of the CCEFP research, education and outreach program are to:

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.
3. Infuse new fluid-power research and innovative, evaluated, fluid power curricula and programs into informal, K-12, and college level course offerings.
4. Creating a culture that integrates research and education for undergraduate and graduate students across all partner institutions.

The objectives of the CCEFP diversity strategic plan are to:

1. The Center aims to provide a welcoming and inclusive environment for all persons, especially those who are underrepresented in engineering, in which 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 aims to reach these objectives through a variety of approaches. Key among them are:

- Successfully pilot an innovative membership model between Engineering Research Centers and the National GEM Consortium--a well established and highly regarded program aimed at increasing the participation of underrepresented groups--and the mutual corporate members of each organization. Receive NSF buy-in and support.
- Develop a supplemental award program modeled after the NSF Research Diversity Supplement. CCEFP currently supports up to six undergrads and two graduate students per year through the CCEFP Research Diversity Supplement award for CCEFP faculty who recruit and retain underrepresented students in engineering.
- Work and support efforts at partner schools and other ERCs to recruit and fund underrepresented students in CCEFP-related undergraduate and graduate research. This includes building relationships with outreach and diversity offices across partner institutions as well as others nationwide to bridge learning and teaching opportunities. Such partners include the National Society for Black Engineers (NSBE); Society of Women Engineers (SWE); the Society of Hispanic Professional Engineers (SHPE); Society for Advancing Chicanos/Latinos and Native Americans in the Sciences (SACNAS); American Indian Science and Engineering Society (AISES); and the Louis Stokes' Alliances for Minority Participation (LSAMP).
- Develop a large and vigorous Research Experiences for Undergraduates (REU) Program to bring highly qualified underrepresented students from across the country to CCEFP universities for summer research. CCEFP was awarded NSF's REU Site Award in Y8.
- In order to build a strong recruiting network for Center-wide programs, one that insures widespread awareness of opportunities within the CCEFP and the fluid power industry itself, establish relationships with engineering faculty in ABET-accredited colleges and universities from across the country, with an emphasis on those in minority-serving institutions and those engaged in fluid power and related engineering curricula.
- In collaboration with local communities and the Fond du Lac Tribal and Community College, increase the number of Native Americans in engineering professions through support of Native American undergraduate and youth STEM enrichment programs. These include weekend and summer camps, a robotics curriculum, and local, regional, and national science fairs.
- Facilitate a partnership between the American Indian Science and Engineering Society (AISES) and the Northstar STEM LSAMP Alliance in order to bring academic, research, and industrial opportunities to Native American undergraduate students in STEM fields throughout Minnesota.
- Identify new partners to work with in the implementation of this agenda. As an example, see the account of the CCEFP's new partnership with BRIDGE (Project B.5) and Innovative Engineers (Project C.11).

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.

Pre-College: An essential part of the CCEFP strategic plan is to promote the study of science, technology, engineering, and math (STEM), and to encourage a diverse group of young students to enter these fields. A special focus in these efforts lies in Center-supported work to increase the number of Native Americans choosing STEM-related study tracks through its gidaa STEM and robotics programs. For now, the CCEFP's Native American programs are centered at the University of Minnesota because of the large number of tribal colleges in the upper Midwest as well as the large population of Native Americans in Minnesota and surrounding states. In these initiatives, the Center envisions that project successes will be duplicated within larger networks. At the national level, the Center's partnership with Project Lead The Way (PLTW), and its work with the Science Museum of Minnesota (SMM), a recognized leader in museum-based education, support STEM initiatives that involve diverse student populations. Years 3 - 5 marked progress in developing fluid power content for selected PLTW courses and in creating the prototype of a pneumatics workshop that can be used by many students including FIRST Robotics teams. In year 7, our focus is on helping teachers to effectively understand and teach this content. Further, our partnership with PLTW and our RET program continues; several RETs are also PLTW teachers, five in 2009, three in 2010, four in 2011, four in 2012 and 2013.

College: At the university level, the Center continues to build the communications and database networks needed to recruit undergraduate and graduate students, faculty, and researchers from a diverse population. To accomplish this, the Center has identified key schools and programs at institutions that cater specifically to these target populations, creating formal and informal relationships that will support recruitment efforts. The Center is also driving its diversity and recruiting efforts by developing formal alliances and collaborations among several other National Science Foundation-funded organizations and with professional and national organizations. The CCEFP's outreach database grew to over 1000 direct and unique contacts.

At the grass-roots level: members of the Center's faculty research network help in recruiting within their universities. The Center has also formed partnerships for outreach programs that are led by its seven partner institutions. In casting this wider net, both the Center's website and its presence on Internet job boards (for its Fluid Power Scholars and REU programs) inform and promote the work of the CCEFP, thereby extending its outreach opportunities.

Within the Center network: The Center works through the various student-centered organizations, including LSAMP and the diversity organizations and programs of its collaborating institutions. CCEFP also works with associated Deans and Department Chairs to increase diversity through faculty hiring.

Major Initiatives

Each research and education project at CCEFP institutions is committed to actively recruiting underrepresented and minority students to participate as the following examples illustrate.

Research Experiences for Undergraduates - REU (Project C.1)

REU is an NSF program whose purpose is to provide undergraduate STEM students with summer experiences in university research labs. An objective of the program is to increase the number of top students, reflecting the racial, ethnic, and gender composition of our country, who attend graduate schools in STEM areas. Every summer the CCEFP hosts an average of 15 REU students. Within this total, the number of participants from outside the Center's network should be greater than the number of students admitted from its seven universities. The CCEFP's REU students begin the summer with a Fluid Power Boot camp and instruction in fluid power technology, its applications and the research activities of the CCEFP. Continuing interaction among CCEFP REU students at the seven sites occurs weekly during the summer through a research blog where REU students submit descriptions and updates of their own research activities. The CCEFP actively recruits underrepresented students in STEM including racial and ethnic minorities, women, persons with disabilities, and recent war veterans for its REU program.

Fluid Power Scholars Program (Project D.1)
As interns, students gain hands-on experience in fluid power technology. Companies hosting interns benefit as well, as students bring fresh insights learned in the classroom. Recognizing these benefits, the CCEFP has enhanced the traditional internship model by adding an intensive orientation to fluid power at the outset of the internship experience in order to expedite knowledge transfer while enabling student interns to make more immediate and effective contributions to their host companies. This program was launched in 2010. (Note that host companies select their scholar/interns from a pool of applicants recruited by the CCEFP.)

CCEFP Research Diversity Supplement (Projects C.9 and C.10)
Recognizing the need for additional programs to strengthen its efforts to recruit and retain a diverse student population, the CCEFP launched a new supplemental program in year 6. The short and long-term goals of these programs are: 1) to provide CCEFP faculty with the means to involve additional graduate students on CCEFP research projects; 2) to identify a graduate student who might not otherwise consider a research opportunity in CCEFP laboratories; 3) to encourage students to consider graduate study or an employment position in the fluid power industry by fostering a learning and career advancement centered environment; 4) to further provide exposure to fluid power technology to a diverse audience; 5) to answer the country's need of greater retention of underrepresented students in engineering.

Expanding on this effort is the novel partnership between NSF ERC's, members of Industry and the National GEM Consortium. CCEFP has received NSF interest and support in creating a new fellowship model through the National GEM Consortium to increase the number of GEM Fellows advised and supported by Engineering Research Centers. The CCEFP will attempt to pilot the new GEM-ERC Fellows model for a second year in 2014/15. NSF has expressed interest in supporting, financially, a pilot of this proposed program at other ERCs.

Research Experiences for Teachers (Project B.1)
RET is an NSF program whose purpose is to improve science, technology, engineering, and mathematics (STEM) education in schools by funding high school teachers to spend the summer in a university research lab. During that time, participating teachers complete a research project and develop curriculum to be used in their classes. Every summer the CCEFP hosts at least four RET teachers at least three CCEFP universities. A special CCEFP RET focus is recruiting teachers from area high schools participating in the PLTW program.

Gidaa Robotics Program (Project B.4)
Under the *gidaa* STEM Program umbrella, staff and teachers have drawn on lessons learned through FIRST robotics and introduced K-12 robotics day and after-school curricula using Lego Wedo-Webots, Lego Mindstorms robots, and software. The *odaangiina anaangoog* Shooting for the Stars Robotics Program enables students in and around the Fond du Lac Indian Reservation to use concrete learning experiences with robotics to better understand physics concepts; develop mathematical thinking, problem solving, and programming skills; and participate in team-building exercises through hands-on engineering construction. This program currently engages challenged students at the elementary, middle and high school levels.

giiwed'anang North Star AISES Alliance (Project C.5)
The American Indians in Science and Engineering Society (AISES) is a national organization with the goal to increase the number of Native American college students in STEM fields. In conjunction with the University of Minnesota College of Science and Technology Office of Diversity and Outreach, and the North Star (LSAMP) STEM Alliance, and the North Star AISES Professional Chapter, the CCEFP is coordinating, sponsoring, and hosting all activities of the giiwed'anang North Star Alliance. This alliance has formed partnerships between the AISES student chapters in Minnesota. It exists to provide tools and resources to assist students of AISES Chapters. Goals of the Alliance include: engaging students in STEM-related activities; encouraging students to pursue their education in STEM-related fields; developing a Minnesota student cohort network; increasing the number of AISES chapters; and encouraging a greater representation of Native Americans in STEM fields and disciplines.